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16. Abstract

A review of ride-quality technology in the United States is given in the thirteen papers presented at the symposium. Although emphasis is directed toward criteria for passenger air travel, information on ground and water modes of transportation is also presented. The papers include an overview of the present state of knowledge, results of various recent studies involving people, vehicles, and simulators, discussion of mechanisms underlying motion discomfort, and description of ongoing activities.

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PREFACE

A symposium on Vehicle Ride Quality, sponsored by NASA, was held at the Langley Research Center, Hampton, Virginia, July 6-7, 1972.

The purpose of the symposium was to apprise the Government, transportation industry, and university community of the current state of the art of passenger ride-quality technology and to improve the degree of complementary effort between investigators. The symposium consisted of a review of technology covering ride quality and ride-quality criteria for passenger-carrying vehicles including surface vehicles as well as aircraft. Also included were several panel discussions directed toward how best to structure and implement experiments so that findings relate to real-world situations of public transportation. The deliberations of these panels are not included in this publication.

Contributions to this publication were made by representatives from NASA Langley and Flight Research Centers, Naval Aerospace Medical Institute, USAF Aerospace Medical Research Laboratory, The Boeing Company, McDonnell Douglas Corporation, United Aircraft Corporation, United Aircraft Research Laboratories, Princeton University, University of Dayton, and University of Virginia.

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CONTENTS

RIDE-QUALITY OVERVIEW

By Ralph W. Stone, Jr.
NASA Langley Research Center

INTRODUCTION

It is not my purpose today to justify the need for research in ride quality. I presume that those of us here recognize and are concerned for this need. It is sufficient to say that progress in air travel, as indicated by the recent Civil Aviation Research and Development Policy Study (ref. 1), is such that the problems of noise and congestion and the need for short haul transportation will lead to conditions of flight at lower altitudes and requiring more acute maneuvering than we currently experience. Such conditions will tend to make ride comfort less acceptable than is offered by our current jets.

I should like to review very briefly today
(a) What the problem of ride quality seems to be
(b) What the current state of knowledge is
(c) What the deficiencies in this knowledge are
(d) What information seems to be required to overcome these deficiencies

and

(e) Some thoughts on ride quality criteria

HUMAN FACTOR ELEMENTS IN RIDE QUALITY

One first asks what is ride quality or what is passenger acceptance of a ride? I have seen no clear definition. I assume that what we are talking about is the passenger's feeling of well being in the current situation of the ride and his contentment with his accumulated experience during the entire ride.

Figure 1 lists the various elements that relate to the fundamental problems of ride acceptance. There are the basic physical factors that define the total environment that the passenger experiences and those that define his intended activity.

The physical factors define the dynamics of motions involved as well as other environmental factors and the cabin arrangements.

There are also, of course, psychological factors; such as the fear of flying, the purpose of flying, and many others. These I will not discuss today, although they are highly significant.

In the course of the next two days, programs will be presented that relate to most of the elements listed for, as you know, considerable effort has been applied to many of them. The area of greatest concern, however, as it is being brought into predominance by the trends and needs for airplane transportation that were mentioned earlier, is the area of the dynamics of the ride.

CURRENT KNOWLEDGE

Let us then, examine very briefly and only partially, because of time limitations, the current knowledge relative to the dynamics of the flight environment and how it applies to passenger acceptance.

In general, because of maneuvering, turbulence, buffet, and aircraft systems operations; oscillations ranging from fractions of a Hertz to 60 or more Hertz can be experienced by most aircraft (fig. 2). At the low range vestibular-visual disturbances are expected and motion sickness is possible. In a range above 1 Hertz, resonance of body components and relative motions of them may occur and cause annoyance and even pain. At frequencies generally above 10 Hertz, body vibrations occur and these too can be most annoying.

A great number of studies have been made over the last several years (these are to a great extent summarized in reference 2) and a brief summary will be shown in the next three figures.

Figure 3 is a limited summary of representative information about the effects of oscillations along (parallel to) the long body axis. The dotted lines show some typical experimental results and represent a progressive intolerance to oscillations as their magnitude increases. Also shown are some current criteria for U. S. Military aircraft and those proposed by the British and Japanese for passenger acceptance primarily for railroad comfort. It is interesting to note that these criteria are relatively near the experimental data representing unpleasantness.

The lower set of curves shown were suggested by Dr. von Gierke and his colleagues some years ago (ref. 3) and still represent potential criteria. They are appreciably lower than the other criteria.

The hatched area in the frequency range from 0.1 to 1 Hertz is where motion sickness may occur. The magnitudes of motion required to elicit sickness are not defined. Motion sickness is a complex psychophysiological process which runs the gamut from sweating to vomiting (see for example ref. 4). The magnitudes of oscillations required to elicit a first level of nonacceptance are not known.

As noted previously, this information deals with vertical motions. Figure 4 is for lateral or transverse oscillations.

Much less information exists for the transverse situation than for the vertical. Shown only are some proposed criteria of the British and Japenese which are companion criteria to those shown in figure 3. It is apparent that there is not unanimity as to what the criteria should be. It is also evident that tolerance for lateral oscillations is lower than for vertical oscillations, possibly being about one half as great.

Another point not distinguished in these two previous figures is the influence of the length of exposure and the frequency of exposure to oscillatory motion on the acceptability of a ride.

Figure 5 shows the influence of time of exposure on the magnitude of acceptable oscillations. This is rather limited information but shows a rapidly decreasing acceptability with "flight time"(see refs. 2 and 5). These proposals show some differences of opinion relative to what the real criteria might be.

In addition to the information shown, it must be pointed out that the International Standards Organization has for a number of years been endeavoring to establish a unified standard for the effects of vibrations on man. Recommendations will be made treating the problems of safe exposure, fatique decreased performance, and reduced comfort (ref. 6). Dr. Ashley of England has introduced an interesting contribution for the study of vibrations on man in connection with the International Standards Studies (ref. 7). He suggests using a random vibration spectrum as a datum for matching with sinusoidal vibrations to establish contours of constant annoyance. He shows for a standing man minimum sensitivity near 1.7 Hertz with increasing sensitivity at lower frequencies where motion sickness has been suggested to be a problem. He shows also an extension of maximum sensitivity out to about 15 Hertz, which is different than has been suggested in the past.

This has been a very cursory review of the state of current knowledge. What are the deficiencies in this state of knowledge.

Figure 6 lists some of these deficiencies.

(a) The data generally available, are primarily for males of flight crew type, hardly representative of the general riding population for which we are concerned.

(b) The sensitivity to motion of the subjects used is generally not available.

(c) The results to date are generally for vertical oscillations and for exposures to discrete frequencies, not at all representative of the random character of natural flight phenomena.

(d) There is little available information of acceptable maneuvering limits. That is, the rates of rolling, turning and pitching and the magnitudes of the attitudes of roll or pitch.

and finally,

(e) There is only a limited amount of data correlating flight data on the dynamics of flight with subjective impressions of the flight.

STUDY REQUIREMENTS FOR HUMAN FACTORS IN RIDE QUALITY

What, then, are the requirements for study relative to the human factors aspects of ride quality in view of the deficiencies just seen.

On figure 7 are listed a number of possible study requirements.

(a) First, it is felt that the subjects used to study the problems of ride quality should be representative of the population who will ride. Also, as they will be the instruments whereby ride quality is measured, their characteristics particularly their sensitivity to motion should be known. Further, as exposure of humans to environmental stress tends to brings about habituation, this effect should be understood in the subjects used.

(b) The only source of the real motions of concern is found in real flight and therefore, studies in flight are required. The actual random disturbances and maneuvers and the corresponding subjective responses are necessary. The influence of airline route structures, seasons, and weather conditions as they influence the frequency of disturbance encounters needs also to be understood. In addition, proper instruments to measure the real environment experienced and the subjective responses to the environment along with the improved computer programs to reduce and analyze these data are required. Tests on airborne simulators; that is, aircraft on which specific disturbances can be tested and evaluated, are necessary to validate knowledge gained in laboratory tests and to verify criteria established.

(c) Laboratory tests, it is felt, are necessary from the standpoint of economics and for the ability to readily vary tests conditions and to identify and isolate the components, magnitudes, and frequencies which are important.

Papers to be presented later today will delineate current programs and plans for laboratory and field tests.

(d) For the design of aircraft having acceptable ride quality, what is required are criteria which can be translated into specific requirements for airplane and control systems characteristics, seat and cabin design, and airline schedules and route structures. Such criteria as in all areas of research must be based on sound, substantial hypotheses, which for the case in point, must relate to human responses to the environmental conditions expected. It is felt that this development must be pursued and should include the development of models involving the dynamic responses of human bodily systems. Also in all experimental processes where subjective data are obtained it must be remembered that the quantification of subjective attitudes, the variability among persons in the interpretation of what the experimenter desires when recording subjective attitudes, and the variability of each person's attitudes with time is a most difficult and complex art.

(e) Finally, studies to determine the processes by which the general public chooses its modes of transportation should be helpful. In this selection process, all the elements of cost, time saving, safety (both real and imagined) and comfort enter the picture.

As was noted earlier, the criteria that exist are based on limited data, usually on exposures to a single degree of freedom and to discrete frequencies.

Figure 8 lists some of the requirements for improved criteria. These are:
(a) The influence of transverse motions, particularly lateral motions
(b) The second point relates to whether the existence of a lateral (or fore and aft) motion reduces the level of acceptability of a vertical motion and vice versa
(c) The influence of a spectrum of frequencies in single and multiple degrees of freedom needs definition

and

(d) finally the buildup and decay of annoyance as a function of the time course of disturbance encounters must also be defined.

I should like now to briefly discuss a few thoughts on the subject of criteria and then to suggest some criteria which may be points of departure for future work.

Mathematical models using damped-spring mounted masses have been developed in the past for studying the responses of body systems to oscillations. All such models of course show a maximum response (or stress) at the damped natural frequency. This implies that larger disturbances are required at frequencies other than the natural frequency to create the same response (or stress) as occurs at the natural frequency. Curves of equal response (fig. 9) over a frequency range are surprisingly similar in form to the experimental data and criteria presented earlier.

Relative to transverse oscillations some interesting information has been obtained by Nickerson on the response of animal organs to oscillations (ref. 8). He noted that the natural frequencies of the internal body systems to transverse oscillations (front to back and sideways) were about twice as large as for vertical oscillations, although the damping was only slightly different.

These results suggest a considerably modified damped spring model that is multiply supported in the transverse motions while only singly supported in vertical motions. Such a model may have higher natural frequencies and larger stresses in the transverse motion as compared to the vertical.

Relative to the influence of multiple disturbances and of a spectrum of frequencies as is normally encountered in turbulence, one can only intuitively feel that the presence of a second disturbance (or more) must reduce the general tolerance. Studies using multiple disturbances and power spectral densities of the disturbances with the corresponding subjective responses are of course in order and subsequent papers will discuss such plans.

Finally we are concerned with the frequency of disturbance encounters. Clearly one disturbance in an hour's flight is much less annoying than 60 identical disturbances in the same flight.

On figure 10 is suggested a mechanism whereby the frequency of disturbance may be evaluated. It assumes that annoyance of the disturbance has an immediate onset and decays exponentially with time, much like other psychophysiological mechanisms. In the top figure the dotted disturbance is below the annoyance level and would presumably not influence the opinion of a ride, whereas the solid disturbance would. In the lower figure, the solid disturbances are spaced such that the full decay of one disturbance occurs before the next disturbance is encountered and the acceptable annoyance level is unchanged. If, however, as illustrated by the dotted lines, the disturbances superpose on each other, the acceptable annoyance level may decrease as shown. Possibly the integral of annoying accelerations(above the acceptable level) with time and decay would be indicative of the influence of the frequency of disturbance encounters an acceptance.

This is only a suggested mechanism which may help in the interpretation of data. Any other such concepts are much desired.

POSSIBLE CRITERIA FOR HUMAN FACTOR IN RIDE QUALITY

I would now like to present some possible criteria which, as I noted before, may be considered as points of departure for real criteria which, hopefully, will evolve from programs in progress and planned.

Figures 11 and 12 treat the oscillatory environment. Figure 11 is for vertical motions and oscillations and figure 12 is for transverse motions.

The very low frequencies (about 0.1 Hz) are really representative of maneuvering conditions, except for the longitudinal phugoid, oscillations at such low frequencies may not be encountered. On figure 11, the upper curve represents positive accelerations and the lower represents negative accelerations. They are mirror images except for the maneuvering situation just mentioned, where I believe that maneuvers causing accelerations of less than 1g are less acceptable than maneuvers causing positive g's. The motion sickness area which is not at all well defined, as shown in figures 11 and 12, depresses the boundaries in the region below 1 Hz. Whether this is a true representation is not known, but nausea remains as a concern for future aircraft and it will occur in this frequency range. The rest of the boundaries are somewhat representative of criteria suggested in the past, except they are depressed somewhat because of concern for disturbances in multiple degrees of freedom and with random inputs.

Much of what has been discussed deals with oscillatory disturbances. As you recall, it was noted at the onset that maneuvering conditions, that is, rates of motions and attitudes of the aircraft, are also factors that may influence the acceptance of a ride.

Figure 13 is a plot of roll and pitch rates as a function of altitude. Shown are possible boundaries above which the rates of motion may become objectionable. These boundaries show a variation with altitude, as it is believed that the closer to the ground the aircraft is the less tolerant of angular motions people may become. There is little data to justify the boundaries except possibly the maximum roll rate. It is felt that pushovers (motions causing less than 1g condition) are less tolerable than pullups, a point mentioned earlier.

The attitudes of an aircraft, that is, the roll and pitch attitudes, particularly near the ground, may be of concern to passengers as well as the rate of motion. Again, probably as the altitude decreases, this tolerance may also decrease. No criteria are shown but they probably are needed. No specific hypothesis has, as yet, been devised, although rolling such that the horizon disappears from view above or below your window and pitching forward in descent such that your belt is necessary may be causes for concern.

An explanation for the possible limitation in roll rate just discussed is shown on figure 14. Plotted is the rate of head motion as a function of airplane angular velocity. The curves shown are curves of constant cross-coupled angular accelerations, which occur when the head is moved in a rotating environment. This factor has occurred in flights and has caused confusion and accidents. Such plots as this have been used in considering problems of artificial gravity (ref. 9). It is clear that rapid head movements in a rapidly maneuvering aircraft can cause disturbances. The 20 degrees per second line shows that a rapid head motion may cause a disturbance near but below the tolerable boundary. Any greater value could cause annoyance and disorientation.

CONCLUSIONS

In conclusion, the status of ride quality, as it relates particularly to the dynamics of the flight environment, has been briefly reviewed. Areas of research necessary for the attainment of proper criteria for acceptable ride quality have been suggested and finally some possible criteria also have been suggested as points of departure for future criteria development.

REFERENCES

1. DOT TST-10-4, NASA SP-265. Joint DOT-NASA Civil Aviation Research and Development Policy Study, March 1971.

2. NASA CR-1205(II). Compendium of Human Responses to the Aerospace Environment. Volume II, Section 8. By E. M. Roth and A. N. Chambers, November 1968.

3. AMRL - TR-66-194. Reactions to Mechanical Vibrations. By Mohr, G. C, and von Gierke, H. E. Man in Environmental Biology. By Altman, P. L., and Dittmer, D. S. (eds.), November 1966, pp. 217-221.

4. Miller, E. F.; and Graybiel, A. Comparison of Five Levels of Motion Sickness Severity as the Basis for Grading Susceptibility. NAMI-1098, February 1970. Naval Aerospace Medical Institute. NASA Joint Report.

5. AMRL-TR-65-84. On Noise and Vibration Exposure Criteria. Von Gierke, H. E. September 1963. Aerospace Medical Research Laboratory. Aerospace Medical Div. Air Force Systems Command.

6. ISO Dcoument ISO/TC 108/WG7 (Secretarial 19) 39, June 1970. Guide for the Evaluation of Human Exposure to Whole Body Vibration.

7. Ashley, C. Equal Annoyance Contours for the Effect of Sinusoidal Vibration on Man. Presented at the 41st Symposium on Shock and Vibration. USAF Academy, Colorado, October 27-29, 1970. Bulletin 41, part 2, pp. 13-20. Published by the Shock and Vibration Information Center NRL, Washington, D.C.

8. AMRL-TR-66-102. Internal Body Movement Along three Axes Resulting From Externally Applied Sinusoidal Forces. By Nickerson, John L., and Drazic, M. The Chicago Medical School, July 1966. Aerospace Medical Research Laboratory, Aerospace Medical Division, Air Force Systems Command.

9. (SP-77). Some Observations on the Stimulation of the Vestibular System of Man on a Rotating Environment. R. W. Stone, Jr., and W. Letko, pp. 263-278. NASA SP-77. The Role of the Vestibular Organs in the Exploration of Space, January 20-22, 1965.

PHYSICAL FACTORS

DYNAMIC
MOTION AND VISION IN TURBULENCE
MANEUVERS AND VIBRATIONS

ENVIRONMENTAL
NOISE, TEMPERATURE, HUMIDITY, AND ODORS

HABITABILITY
SEAT SIZE AND SPACING
WINDOW SIZE AND LOCATION

ACTIVITY FACTORS

READING, TALKING, WRITING, AND THINKING
DRINKING AND EATING
DOZING AND SLEEPING
WALKING

Figure 1.- Probable human factors elements in ride quality.

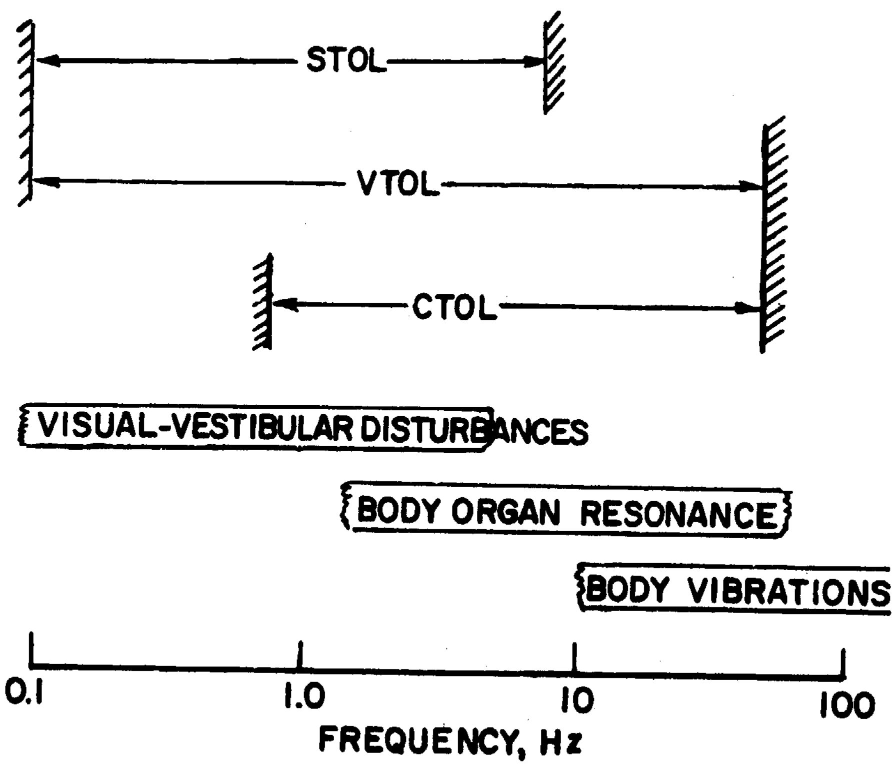


Figure 2.- The motion environment.

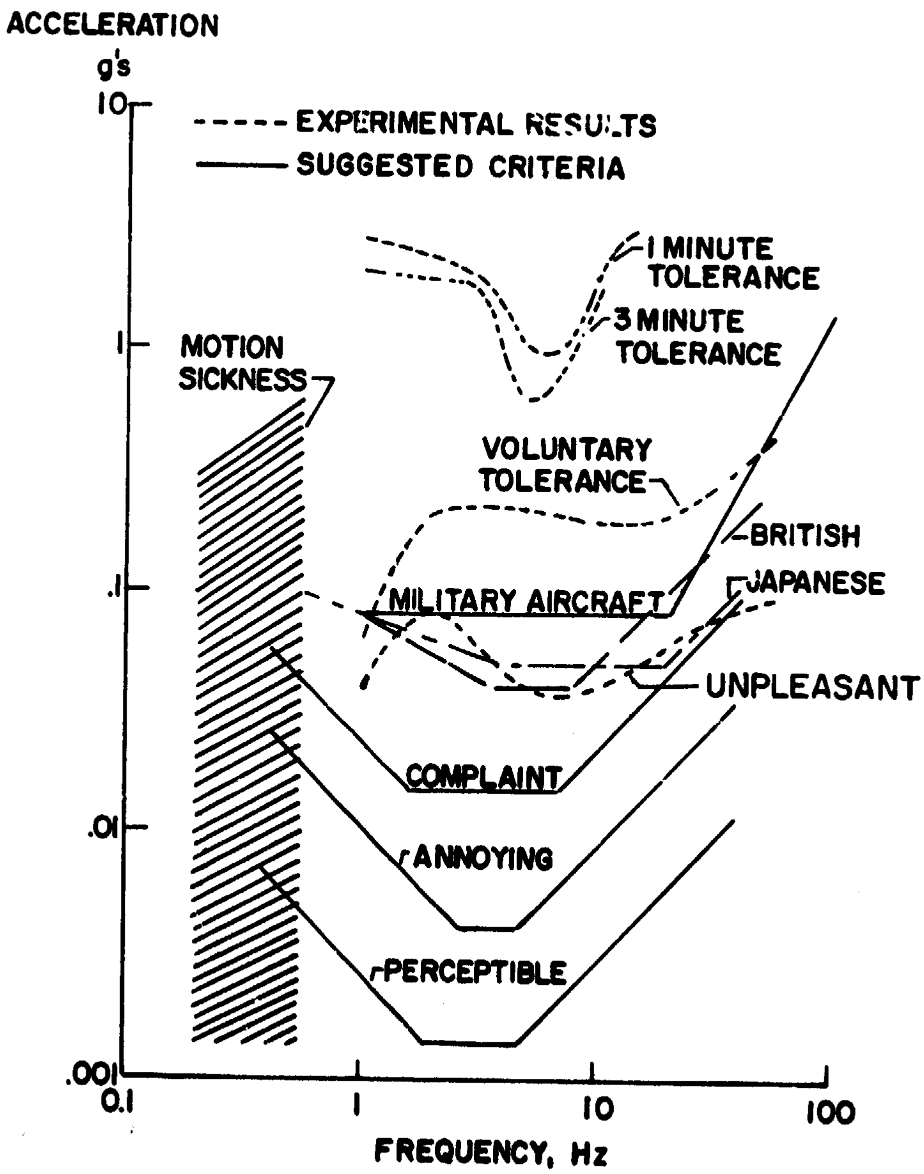


Figure 3.- Current ride quality boundaries based on exposure to discrete frequencies (vertical motions).

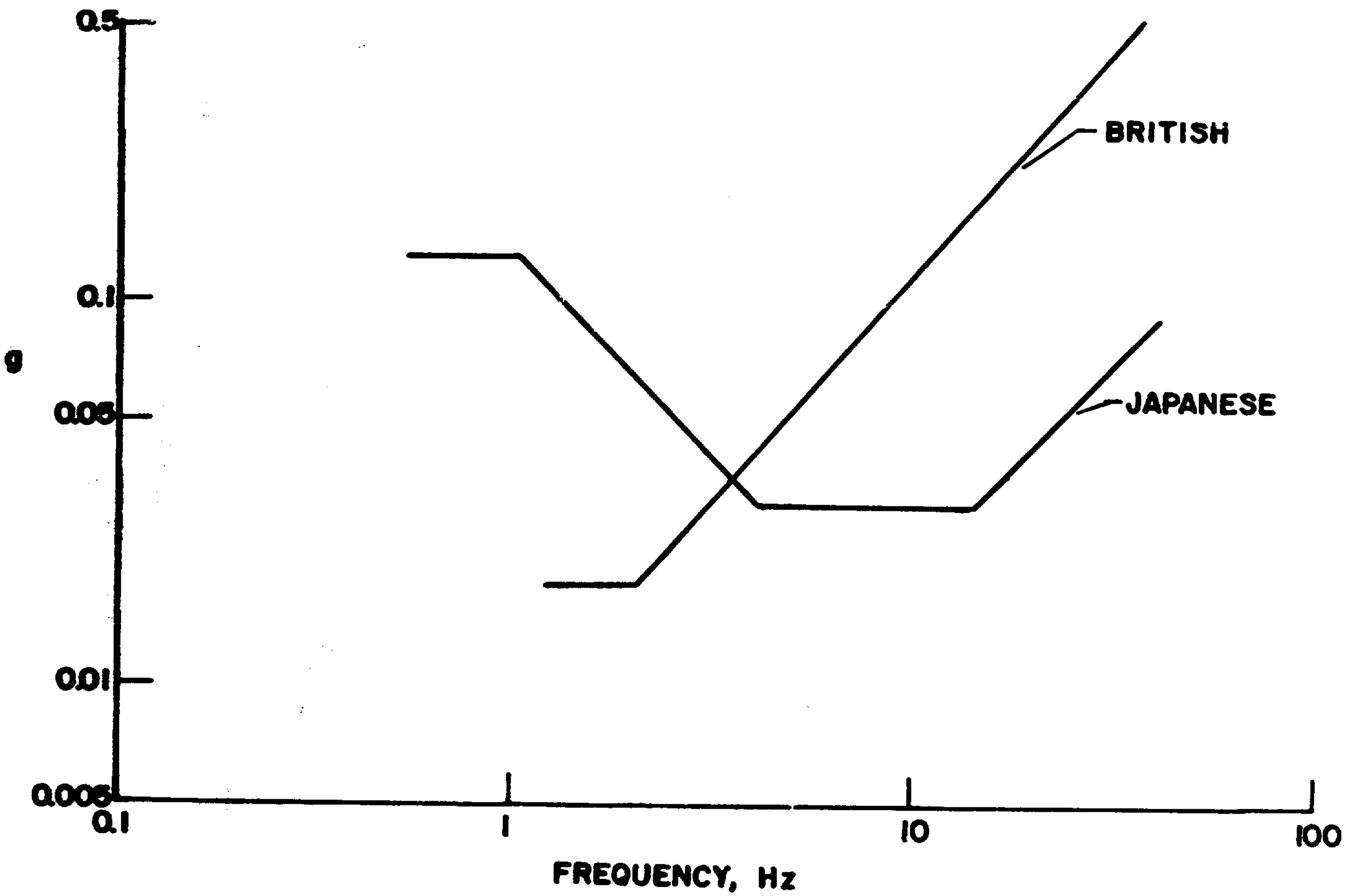


Figure 4.- Current ride quality boundaries based on exposure to discrete frequencies (lateral motions).

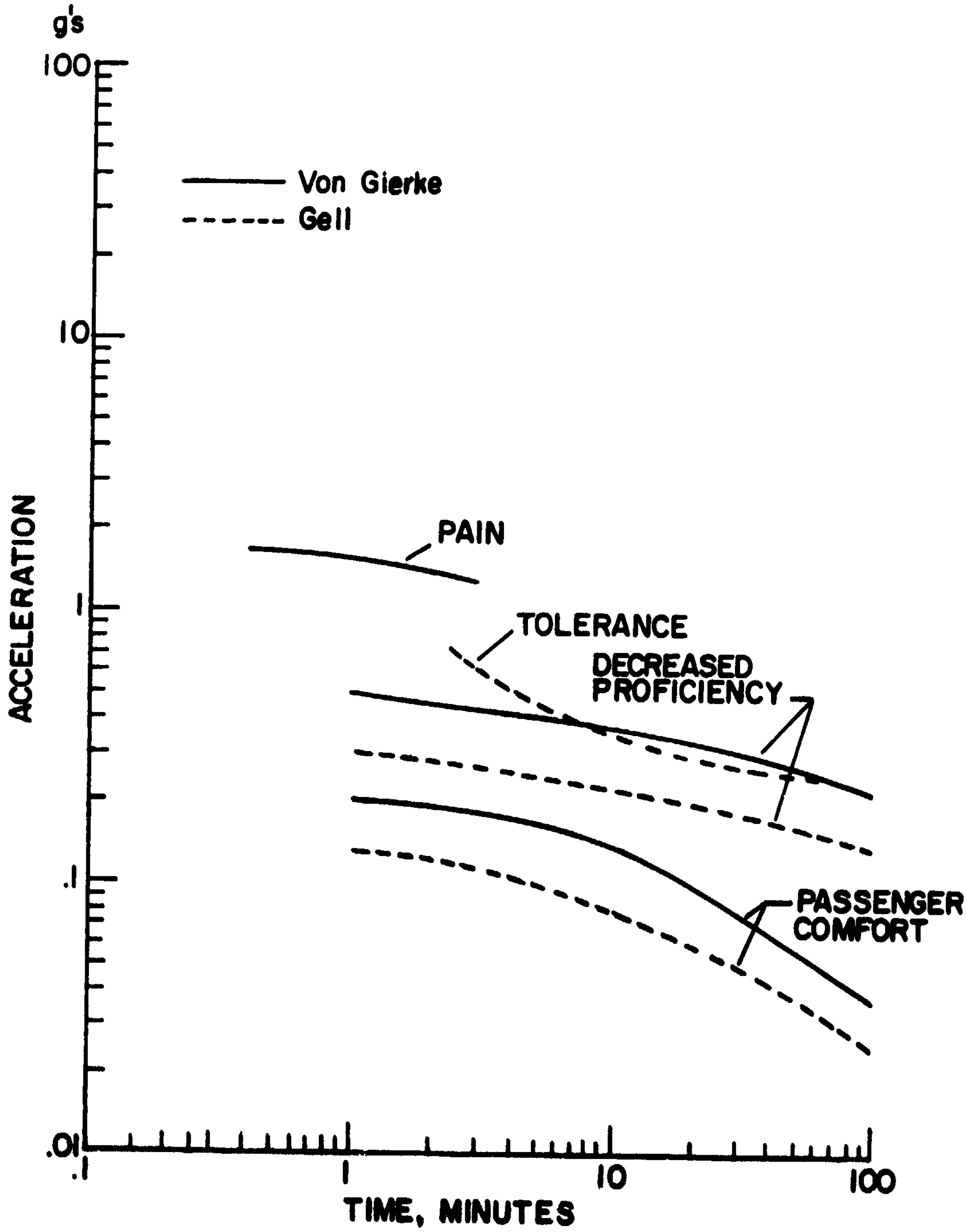


Figure 5.- The influence of time of exposure on acceptability.

LIMITED SUBJECT TYPE

SUBJECTS NOT CALIBRATED FOR MOTION SENSITIVITY

DATA AND CRITERIA LIMITED GENERALLY TO VERTICAL MOTIONS

DATA AND CRITERIA LIMITED TO DISCRETE FREQUENCIES NOT TO RANDOM CONCURRENT FREQUENCIES AS IS COMMON TO NATURAL PHENOMENA

DATA AND CRITERIA FOR MANEUVERING LIMITS (ATTITUDES AND RATES) NOT AVAILABLE

LIMITED QUANTITATIVE AND SUBJECTIVE DATA FROM ACTUAL FLIGHT CONDITIONS

Figure 6.- Deficiencies of current knowledge.

SUBJECT

- SELECTION REPRESENTATIVE OF RIDING POPULATION
- CALIBRATION FOR MOTION SENSITIVITY
- TESTS FOR HABITUATION AND ITS PERSISTENCE

FIELD TESTS

- FLIGHT EXPERIENCE TO OBTAIN DATA ON ACTUAL RANDOM DISTURBANCES, MANEUVERS, AND SUBJECT RESPONSES
- FLIGHT EXPERIENCE TO OBTAIN DATA ON FREQUENCY OF DISTURBANCE ENCOUNTERS AS RELATED TO AIRLINE ROUTE STRUCTURES, SEASONS, AND WEATHER CONDITIONS
- AIRBORNE SIMULATOR STUDIES TO ISOLATE CRITICAL FACTORS PERTINENT TO RIDE QUALITY
- DEVELOPMENT OF SIMPLE LIGHTWEIGHT INSTRUMENTATION
- DEVELOPMENT OF EFFICIENT COMPUTER PROGRAMS FOR DATA REDUCTION AND ANALYSES

LABORATORY TESTS

- STUDIES WITH THE SAME REPRESENTATIVE SUBJECT POPULATION AND RANDOM DISTURBANCES AND MANEUVERS TO DEVELOP AND VERIFY SIMULATION TECHNIQUES
- STUDIES TO ISOLATE MOTION COMPONENTS MOST PERTINENT TO RIDE QUALITY

CRITERIA

- MATHEMATICAL MODELING OF HUMAN VISION MOTION RESPONSES
- HYPOTHESIS AND CRITERIA DEVELOPMENT
- VALIDATION WITH FLIGHT PROGRAMS

GENERAL

- STUDIES OF THE TRADEOFF OF PROCESSES USED BY THE GENERAL TRAVELING PUBLIC IN THE SELECTION OF MODES OF TRANSPORTATION

Figure 7.- Ride quality study requirements.

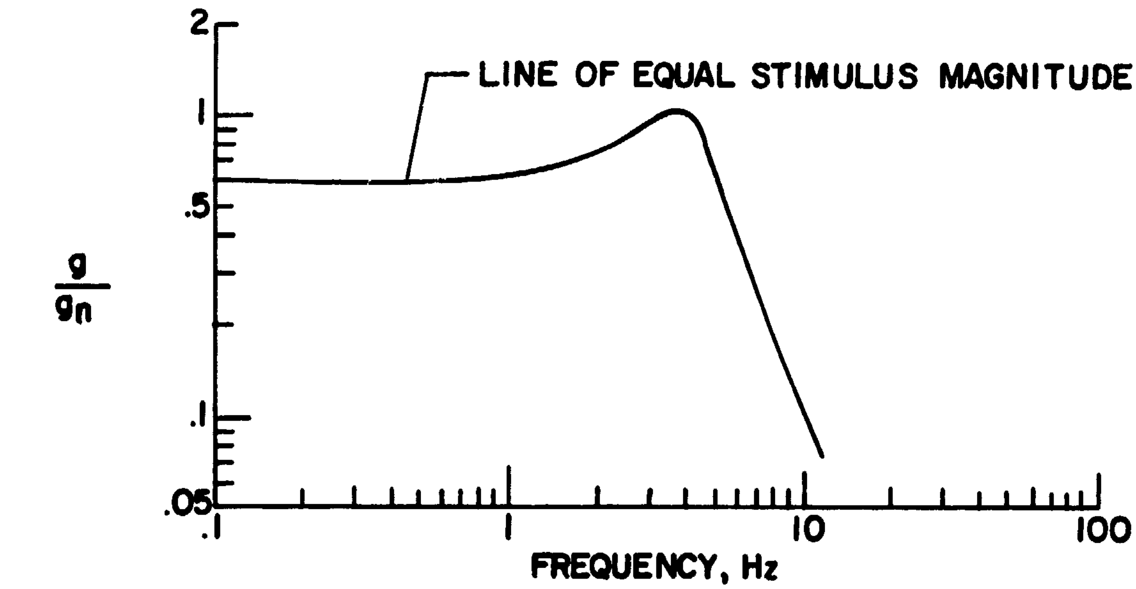
THE INFLUENCE OF TRANSVERSE MOTIONS AND OSCILLATIONS

THE INFLUENCE OF SIMULTANEOUS OSCILLATION IN MULTIPLE DEGREES OF FREEDOM

THE INFLUENCE OF A SPECTRUM OF FREQUENCIES IN SINGLE AND MULTIPLE DEGREES OF FREEDOM

THE INFLUENCE OF THE TIME COURSE OF DISTURBANCE ENCOUNTERS AND THE THE BUILDUP AND DECAY OF ANNOYANCE

Figure 8.- Information requirements for ride quality criteria.



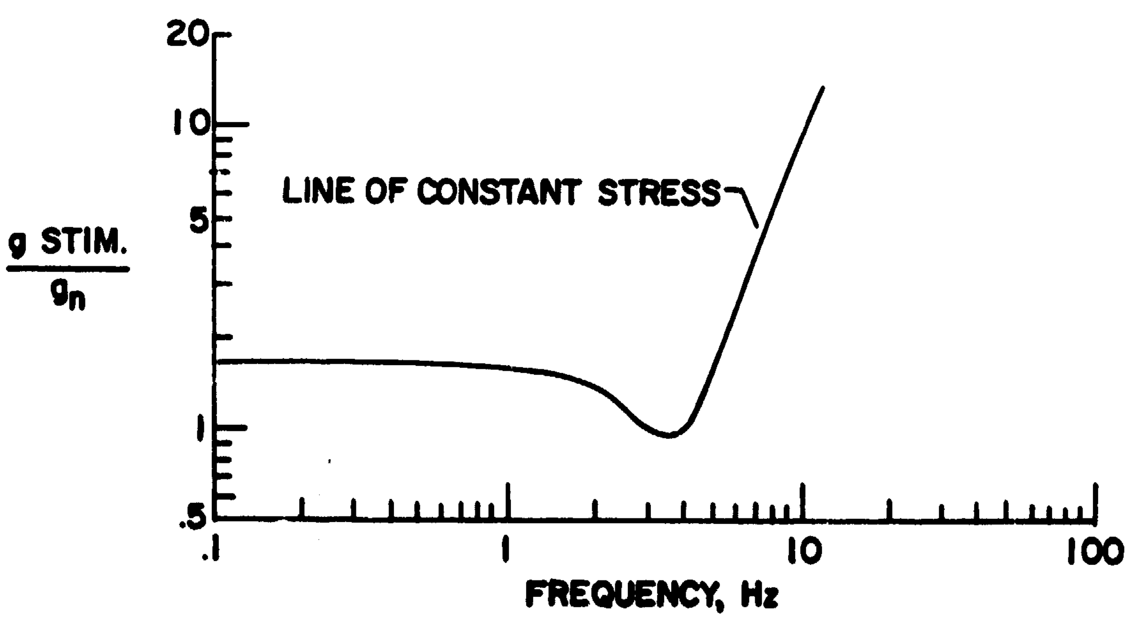


Figure 9.- Potential stress ratio in vertical oscillations.

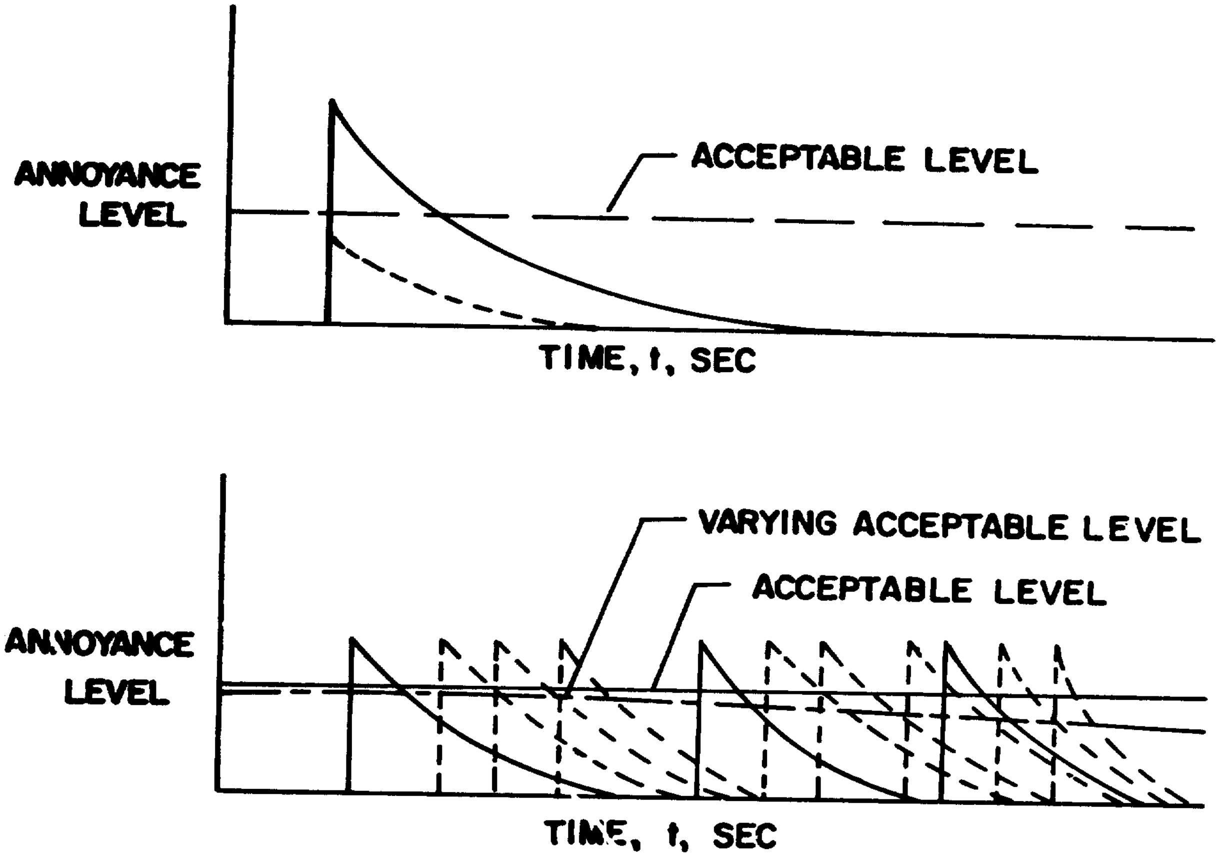


Figure 10.- A possible effect of frequency of disturbance encounter.

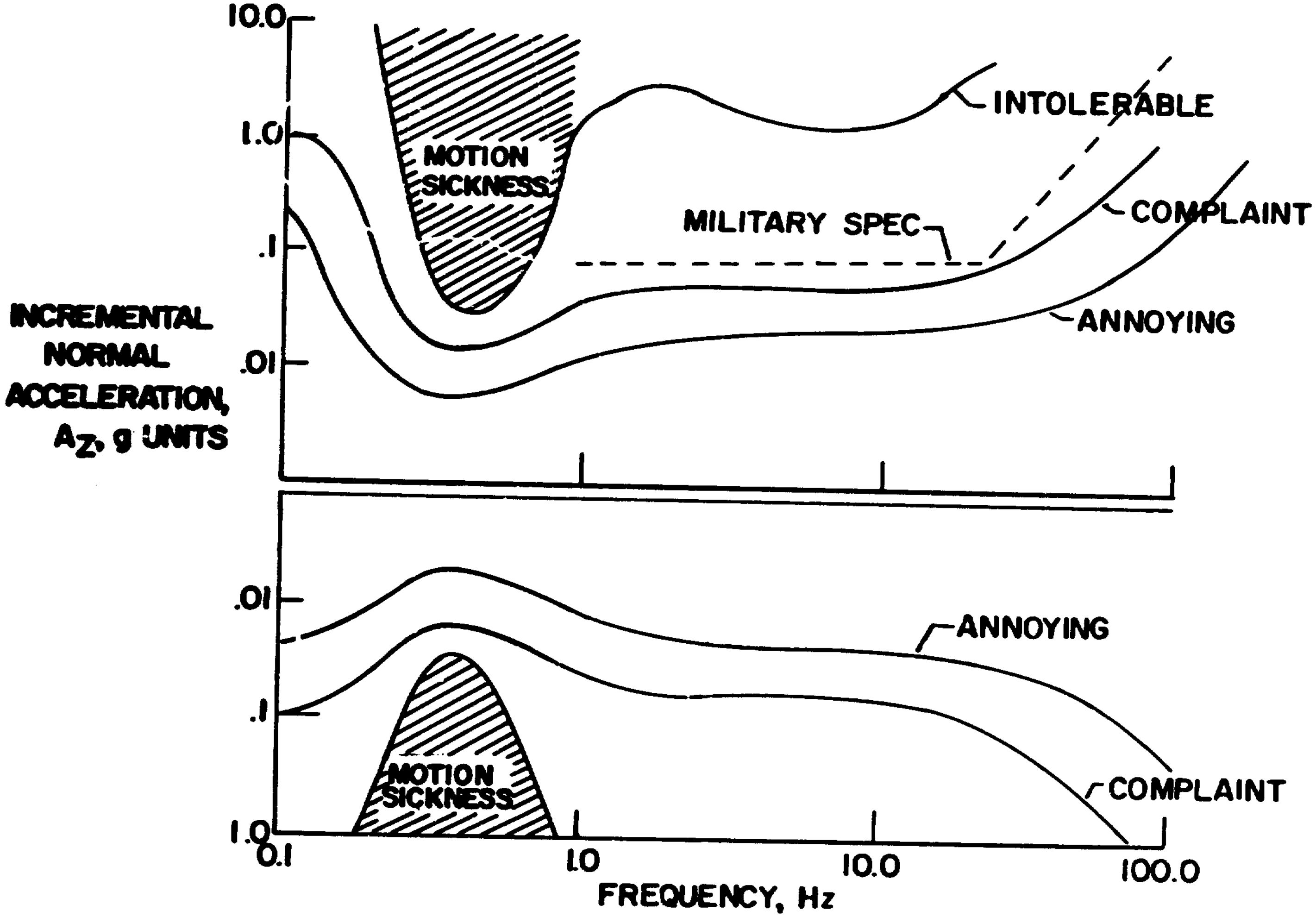


Figure 11.- Possible general ride quality criteria (vertical motions).

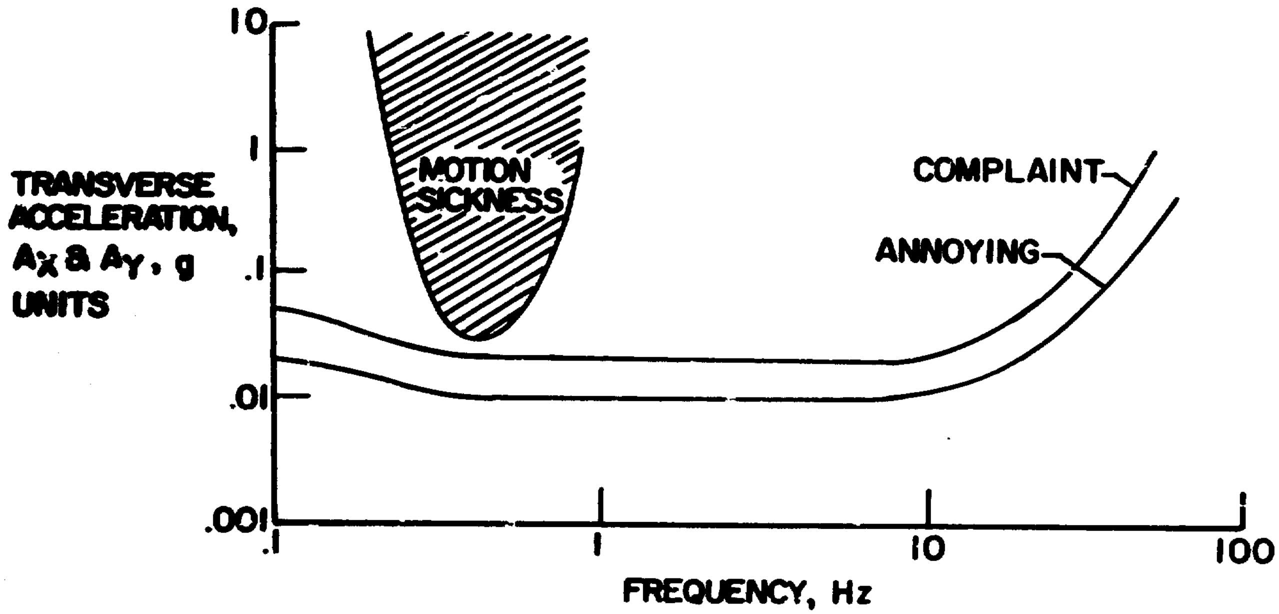


Figure 12.- Possible general ride quality criteria (transverse motions).

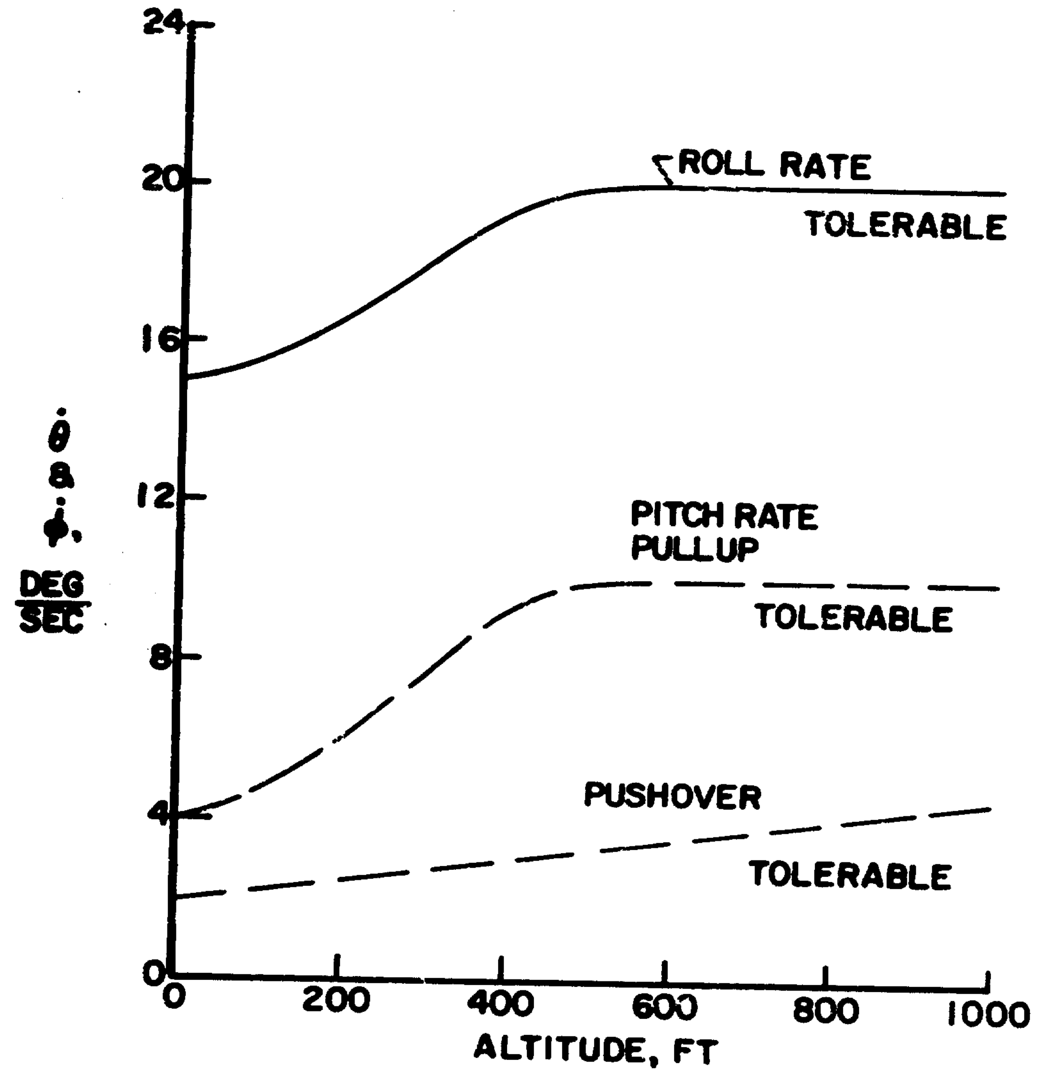


Figure 13.- Possible angular velocity criteria for ride acceptance.

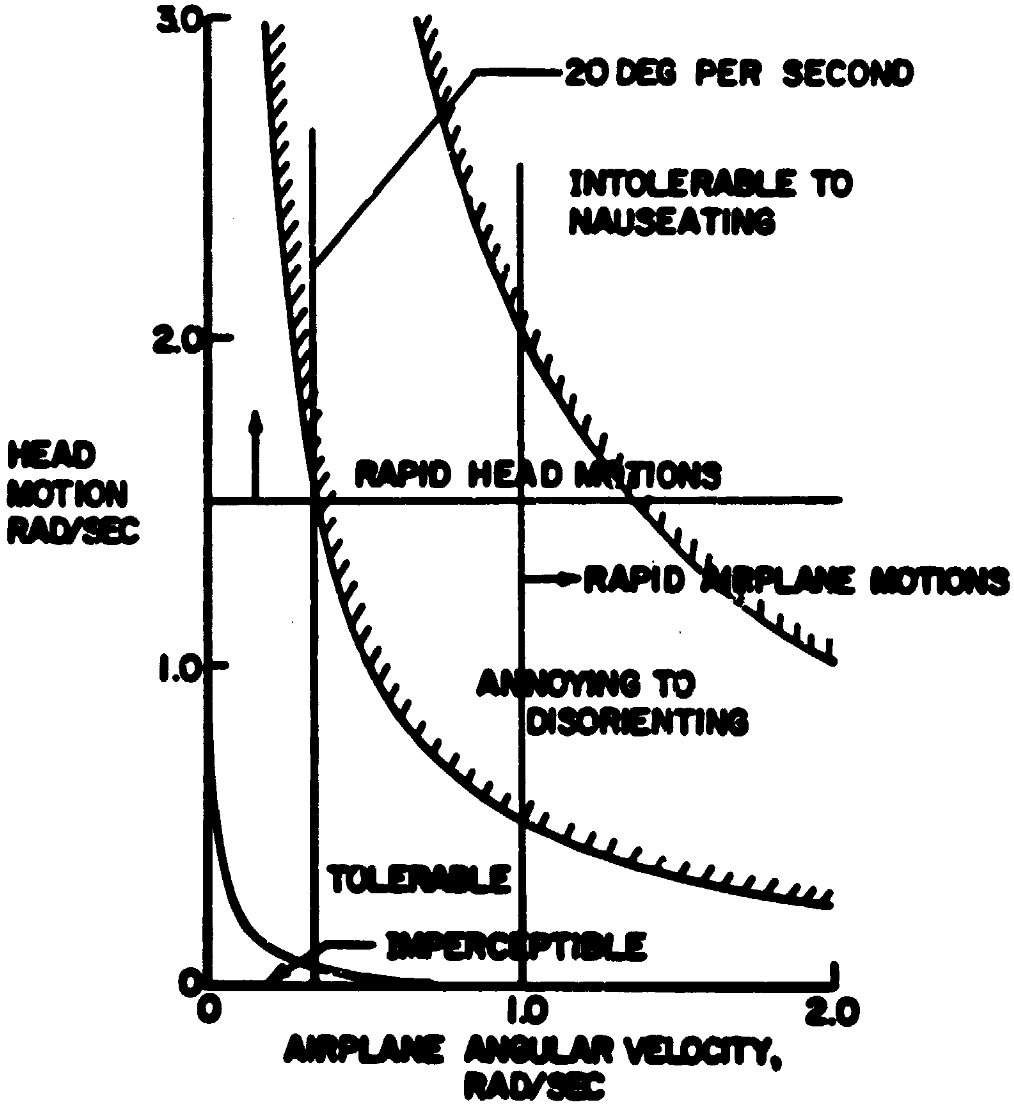


Figure 14.- Possible criteria for cross coupled angular accelerations.

AN AIRCRAFT MANUFACTURER'S APPROACH TO RIDEABILITY CRITERIA

2

By R. C. O'Massey, H. Leve,
and J. G. Gaume

Douglas Aircraft Company
McDonnell Douglas Corporation
Long Beach, California

SUMMARY

This paper describes an overview of an aircraft manufacturer's approach to Rideability. The paper is organized as follows:

The Current Ride Environment section describes the external and internal environment in terms of vibration and acoustic sources and general response.

Rideability Design/Evaluation describes guide lines and criteria reflecting current practice at Douglas.

Example Rideability Studies are presented representing an Analytical Study (STOL Buffet), a Design Analysis Study (the rebounding airplane), and Aeromedical Evaluation.

The last section describes the Douglas Aircraft Company ride research plan showing present and future efforts to develop Rideability Criteria.

A Summary of Needs is presented listing identified needs for data, criteria, and research in the various rideability areas.

INTRODUCTION

Airlines spend millions of dollars annually in advertising campaigns, personnel training, and in airport facilities to create an atmosphere of travel luxury. Wide-bodied jets were introduced as a means of expanding this luxury concept while capitalizing on advanced technologies in other areas. The aircraft manufacturer has always had to maximize comfort in air travel as a recognized part of building a quality product and as a requisite to expanding air travel. With the advent of the wide-bodied jets, and the need to offer an improved psychological setting in terms of greater space and more freedom of movement for the passengers during flight, came the requirement for a commensurate improvement in vehicle ride quality. The need to achieve improvements in rideability was clear, but the means to measure this quality for design and evaluation purposes was not and is still not clear.

One approach that was taken to meet the improvement in rideability was to conduct an analytical review of the systems that dominated ride quality (i.e., the landing-gear system as an example) and derive the parameters and parameter values most contributory to ride response. These parameters and their values were then compared to a contemporary aircraft baseline and selected parameters were optimized in the design process. At times the optimization included compromising one parameter value to achieve another. For these cases design alternatives were developed so that the basic design would not be "locked-in" during the evaluation phase. The effect of following this approach was to upgrade the rideability system design over contemporary jet transport aircraft, but obviously could not account, in a measurable sense, for the effect on the pilot, cabin attendants, and passengers.

In an effort to account for the human "factor" during design and flight test evaluation, the approach which had been used for many years was formalized into a set of qualitative guidelines, a ride evaluation baseline, and ride design/evaluation criteria based upon available published human factor data. This more formal approach was supplemented by experience gained from previous aircraft developments, and in the flight development phase by an executive review consisting of VIP flight evaluations.

The manufacturers have provided an improved ride comfort level, but at rather high development cost. This is compared to what it could have been had an effective rideability criteria been available to guide the many design tradeoffs that have to be made during the initial design when the basic system design configurations are "frozen."

RIDEABILITY OBJECTIVES

One of the guideline listings that was formalized for rideability design and evaluation efforts is listed below. Although the listing is entirely qualitative, it did set the stage for a large number of analytical and design studies.

Rideability Objectives

- Smooth transition of rigid body motions during all operational phases. Minimization of detracting motion (overshoots, rebounds, etc.).
- Minimization of rigid body acceleration levels during all operational phases.
- Minimization of sustained and transient vibration in primary and secondary vehicle structure. (Inputs to floors, seat tracks, etc.).
- Minimization of "jolts," vibration, etc., due to normal operation of aircraft systems.
- Noise in the cabin should be low enough to permit conversation in a normal voice.

An example of the scope and depth of the studies generated by this simple listing is shown in Figure 1. This chart for landing gear systems also shows the heavy reliance that is placed upon having a contemporary baseline of both cabin responses and airplane and landing gear/system parameter values in lieu of effective rideability criteria.

CURRENT RIDE ENVIRONMENT

External Environment - General

Transport aircraft are subjected to a multitude of environments which individually and collectively can have significant effects upon the aircraft's rideability. One major class of environments is that which causes vibrations in the airplane. Table I provides a list of the most important vibration producing environmental sources pertinent to rideability. Some features of these sources are also given.

TABLE I

VIBRATION PRODUCING SOURCES

Source	Character	Frequency Range, Hz	Most Significant Frequencies, Hz
Landing Impact	Pulse	-	-
Runway Roughness	Random	0.5 to 30	0.5 to 5
Atmospheric Turbulence	Random	0 to 20	0 to 10
Buffeting and Oscillating Shocks	Random	1 to 50	1 to 20

With regards to the sources in Table I, it is to be expected that the airplane ride will have a certain amount of discomfort if

1. the landing impact is the result of an airplane sink rate greater than 1.8 m/sec at ground contact,

2. the taxi of the airplane is done on a runway or taxiway with RMS (root-mean-square) roughness greater than 3.8 cm,

3. gusts (atmospheric turbulence) are flown through that have velocities greater than 10.7 m/sec and,

4. buffet conditions are produced in which lift surface pressures in excess of 0.138 N/cm^2 are developed.

The above stated levels are not usual and thus are not the major concern when the degree of rideability of an airplane is to be ascertained. It is the typical environmental levels that must be considered for rideability determinations. Thus, for the purpose of evaluating rideability, attention should be given to

1. landing impacts occurring below 1.2 m/sec,

2. taxi over surfaces with RMS roughness less than 1.5 cm,

3. gust levels less than 6.1 m/sec and

4. buffet pressures of 0.069 N/cm^2 or less.

The random sources listed in Table I can be classified as being in the low frequency range. These sources can cause significant motions of the airplane but will not produce any acoustical effects within the airplane. Some vibratory sources that are important to rideability for their possible acoustical consequences are given in Table II.

TABLE II

ACOUSTICAL PRODUCING SOURCES

Source	Character	Frequency Range, Hz	Most Significant Frequencies, Hz
Jet Exhaust	Random	50 to 10,000	100 to 1000
Engine fan blades	Traveling shocks	$n \cdot f_s$ ($n=1, 2, 3 .. B, 2B ..$) f_s=fan shaft speed B=no. of fan blades	Multiples of fan shaft speed equal to and below $B \cdot f_s$
Engine rotor speeds	Sinusoidal	-	N_1 and N_2 (Low and high pressure turbine speeds, resp.)
Boundary-layer turbulence	Random	100 to 10,000	500 to 5000

It will be noticed that the sources in Table II produce vibration in a significantly higher frequency range than the sources in Table I. The specific frequencies associated with the engine rotor and fan blade sources are numerous even for a given engine. These frequencies depend upon the portion of the mission that the airplane is flying. Of the listed acoustical sources, the boundary-layer turbulence for subsonic transports is most important to in-flight rideability while the others usually have their most prominent effect on rideability during the takeoff and ground-related phases.

The vibrations from the engine rotor source travel along structural paths from the engine to the fuselage. Besides causing low-amplitude fuselage vibrations, under some conditions this source may cause noticeable sound levels to be produced within the fuselage. This may be the case especially when the engines are supported directly off of the fuselage.

The outer portions of the jet engine's bypass fan blades are moving at supersonic speeds. This condition sets up shock waves which are propagated through the air from the engine inlet duct to the fuselage. Due to irregularities in the blades, the shock wave produced at each blade may differ in strength. This causes the shock associated with each blade to propagate at a different speed. Thus the character of the train of shock pulses arriving at the fuselage wall will be dissimilar from the pulse train leaving the engine. The sound effect produced within the fuselage from these shock pulses is termed buzz saw noise.

The random sources listed in Table II contain a wide range of frequencies. The sound pressure levels (SPL's) produced by these sources vary with frequency. (The SPL for a particular frequency is the RMS value of the sound pressure that would be filtered out in a 1 Hz band centered at the frequency.) The sound pressure level as a function of frequency usually has a single, relatively flat peak within the frequency range. The overall sound pressure level (OASPL) produced on the fuselage wall from the jet exhaust depends upon the jet exhaust velocity, airplane speed and distance, and directional orientation of the engine exhaust from a location on the fuselage. (OASPL refers to the RMS value of the unfiltered sound pressure.)

The OASPL produced by the boundary-layer turbulence at the fuselage wall is relatively uniform along the length of the fuselage. The peak in the SPL-vs-frequency function will vary for the different locations along the fuselage due to a changing thickness in the boundary layer. Moving from the front to the rear portion of the fuselage, the frequency at which the SPL peaks will shift from a lower to a higher frequency.

In conjunction with the listed sources, an important environmental consideration is the amount of time that the aircraft is subjected to each source. A way to indicate this aspect is shown in Table III which gives a breakdown of an airplane mission. Specified in this table is a duration range for each phase of the mission and the most significant sources pertinent to the phases. (Because they are more specialized to particular situations, the engine rotor and fan blade sources are not considered in Table III. The information in Table III was taken from Reference 1.)

TABLE III

AIRPLANE MISSION DESCRIPTION AND PROMINENT VIBRATION SOURCES

Flight Phase	Approx. Time Duration	Vibration Sources
Warmup	1 to 15 min	Jet Exhaust
Taxi	5 to 15 min	Runway Roughness Jet Exhaust
Runup	2 to 20 min	Jet Exhaust
Takeoff	1 to 5 min	Runway Roughness Jet Exhaust Atmospheric Turbulence Buffet
Climb	3 to 30 min	Jet Exhaust Atmospheric Turbulence Boundary-layer Turbulence
Cruise, flight maneuvers, etc.	1 to 8 hr	Jet Exhaust Atmospheric Turbulence Boundary-layer Turbulence Buffet
Descent	5 to 15 min	Atmospheric Turbulence Boundary-layer Turbulence
Landing Gear down, Flaps down	1 to 15 min	Flap Buffet, gusts (atmospheric turbulence)
Landing	5 sec to 2 min	Landing Impact Runway Roughness

Internal Environment - General

A source's character within the fuselage will usually be quite different than its description outside the fuselage. The changes to the sources stem from a number of reasons some of which will be brought out in the subsequent discussion.

The landing impact appears inside the fuselage as a sequence of short duration vibrations. These vibrations are the result of the flexible airplane structure on its gears responding to the imposed pulses. The first in the sequence of vibrations is that due to the initial impact. This vibration has a duration of the order of 1 second and is composed of a number of frequencies, only a few of which are prominent. These frequencies will generally be below 20 Hz and are usually below 10 Hz.

After the initial impact, a bounce typically occurs causing a second pulse. The vibrations produced by this pulse are similar to those from the initial impact but usually with lower amplitudes. Following this pulse, nose gear contact occurs causing another pulse to be transmitted to the fuselage. Vibrations of a type similar to those produced by the initial impact can again be excited by this pulse. After this point in the landing, further vibrations may be caused by thrust reversing and braking.

The sources other than landing impact listed in Table I will produce vibrations of a random nature within the fuselage. These internal vibrations will be typically dominated by two or three frequencies. The magnitudes of these frequencies will be dependent upon the vibrational properties of the airplane and the frequency composition of the source. The most significant frequencies contained in the sources are given in Table I. The airplane natural frequencies to be considered for each of the sources will usually be different. This difference could stem, for instance, from dissimilarities in the airplane weight configurations involved with the sources. Further, the airplane supported on gears and tires, in the case of taxi, or the airplane supported by aerodynamic forces, in the case of atmospheric turbulence, will cause the lowest natural frequencies to be different for these two cases. Above these lowest values, the natural frequencies of interest for the three sources are related to the flexible properties of the airplane. The manner in which the source acts on the airplane will tend to emphasize one flexible airplane frequency as against another.

The effects of the environments shown in Table II on the sound levels inside the fuselage depend on the character of the source, the vibrational properties of the fuselage structure, and the acoustical treatment used to attenuate the sound levels. The description of the sources is given in Table II. The airplane vibrational properties to be considered for the acoustical-producing sources are completely different than those for the vibration-producing sources listed in Table I. The vibrational properties of the total airplane are of concern with regard to these latter sources. For the sources in Table II, the concern is with the vibrational properties of localized portions of the fuselage. The localized fuselage shell structure typically will have numerous natural frequencies above 50 Hz. Due to this vibrational character, the fuselage will tend to admit the external sound pressures with little attenuation.

A reduction of the sound pressures entering the fuselage cabin can be accomplished at the source or within the fuselage. Acoustic material lining the walls of the fuselage will absorb a significant portion of the sound that is transmitted through the fuselage shell. This acoustic material will be most effective in attenuating the higher frequency portions of the sound. Acoustic sandwich linings can be used to absorb some of the sound energy emitted by jet engines. The inlet cowl, bypass exit, and primary exhaust exit are some of the locations at which lining material can be placed for sound-reduction purposes. The acoustic sandwich lining material is also most effective in attenuating the higher frequency portions of the sound. Thus the acoustic-absorbing materials reshape the external acoustical environments such that the lower frequencies have increased prominence in the internal environment of the fuselage. It is not to be inferred that the acoustical effects of higher frequencies can be completely eliminated by acoustical treatment. Lower sound levels at higher frequencies may be more annoying to humans than somewhat higher sound levels at lower frequencies. Thus, even though attenuated, the higher frequency portions of cabin sound can still influence the riding comfort of fuselage occupants.

The People

The passengers; the cabin attendants; the flight crew; each of these groups of people are affected by rideability in different ways. These differences arise from different flight orientations, seating, and primarily changed internal environments due to varying locations in the aircraft. Table IV below presents a composite view of people in a ride quality setting.

TABLE IV

THE PEOPLE

People	Flight Orientation	Present Ride	Dominant Disturbances	Remarks
Passengers	Business Pleasure Anxious Curious	Excellent	Rise, Sink Bumpiness in gusts Landing Flex Mode responses	Excellent psychological and physiological environment, spaciousness and comfortable seating
Cabin Attendant	Gracious host Passenger safety Passenger comfort	Good to excellent	Rise, Sink Bumpiness Flex mode responses	As above
Flight Crew .	Safety Pilot technical functions Passenger comfort	Functionally adequate	Flex mode responses	Maximum comfort with functional constraints

From the standpoint of aircraft safety and degraded flight crew performance resulting from poor rideability, it is necessary to relate the ability to function effectively to all plausible states of vehicle ride. An example of this is the ability of the pilot to see the instruments clearly during takeoff on a rough runway. Other types of ride disturbance may be less dramatic but very real in terms of creating unnecessary fatigue and annoyance for the flight crew.

RIDEABILITY DESIGN/EVALUATION

For the aircraft manufacturer, the need for a usable "ride" criteria stems from the requirement to design, to analyze, and to evaluate the end product in a realistic setting. For Douglas' purposes, the design and the analyses are so highly integrated that one criterion covers both of these functions. Because the final evaluation function is concerned with the end product and therefore includes the total reality of the ride environment, the evaluation criteria is quite different from the criteria used for design. This variance in criteria is a major problem because costly redesign results. The essential differences between the design and the evaluation criteria are primarily due to the following:

The effects of interaction of sound, motion-time, and operational phase (i.e., taxi, cruise flight, etc.).

The difference between design conditions and test conditions (for example, the ride is rough - but how rough is the runway?).

The specific nature of rideability problems, most of which require exhaustive studies to identify the cause and resolve the problem.

Current Douglas Practice

Until the Ride Criteria Research Program described later in this paper matures, an interim criteria is currently being used.

Because of the interaction and other effects noted previously, only the baseline criteria are presented here. These baseline criteria are modified in two ways in practice: (1) As a result of specific human factor/flight test correlation, and (2) by subjective modification where actual data are lacking. Acoustic guidelines are included in this section because of the noted interaction with rideability; however the inclusion of acoustic criteria is considered beyond the scope of this paper. Because pavement unevenness plays a prominent role in "on the ground" rideability, a brief table of pavement unevenness criteria is provided.

Current Douglas Practice

Acoustic Guidelines

Speech interference level should be better than that existing in present airplanes.

Equipment noise should not be audible in fuselage cabin.

High frequency portions of the scunds produced in the fuselage cabin should not be annoying.

Vibration Criteria Baseline (Figure 2)

1. Short duration criteria is Parks Human Factor Criteria (Reference 2) using the mildly annoying curve as an acceptable comfort limit.

2. Long duration criteria is from the Air Force Design Handbook (Reference 3), and presents comfort boundaries as a function of RMS acceleration, frequency, and time.

3. Multimode vibration interaction is treated as the vector sum of the applied to the allowable ratio, evaluated for each frequency, the vector sum being less than unity. Figure 2 shows this as a circular interaction for a bimodal vibration.

4. For criteria lacking, such as "jerk," shock, motion, and interaction of noise and vibration, etc., a subjective alternative is used to minimize the effect as practical and evaluating the result in flight test.

Pavement Unevenness Criteria

Nai C. Yang of the Port of New York Authority employs vehicle response characteristics and NASA Ride Criteria studies as an integral part of his system of pavement design and construction specifications (Reference 4). Until this example is followed by the rest of the airport community, the pavement unevenness problem will remain as a significant contribution to ride discomfort.

With the expressed need by the Department of Transportation to double air transportation by 1980 (Reference 5) follows a requirement to increase airport capacity via increased off-runway taxi speeds. Thus a variety of unevenness as shown in Figure 3 must be considered for "on the pavement" rideability.

Executive Review

- Initial flight development: Subjective evaluation by select ride committees and engineering executives.

- Final evaluations: By top company executives.

EXAMPLE RIDEABILITY STUDIES

This section presents the approach to the rideability problem taken by three different departments within the Douglas Engineering Division. These approaches are representative of analytical, design/analysis, and aeromedical departments. The general approach that is taken is similar to that taken for most subsystem analyses for design efforts and consists briefly of

1. Defining a set of ride baseline conditions
2. Performing design and analytical studies on alternative design approaches
3. Selection of best design
4. Flight development test planning
5. Flight development evaluation
6. Executive evaluation

The last item is unique in that, in addition to evaluations by select engineering committees, an evaluation by top company executives is made for major programs. This is not only an indicator of the importance of ride quality but suggests the need to make ride comfort measurement more of an organized discipline.

The three sample rideability studies are:

1. The STOL buffet study - an analytical approach
2. The Rebounding Airplane - a Design/Analysis approach
3. An Aeromedical Evaluation.

STOL Buffet

Ride comfort or rideability is a major factor in the feasibility of STOL aircraft. There are a number of sources that have a contributing influence on STOL rideability. A source which is distinctive to STOL operations will be the concern of the following discussion.

One way of obtaining increased lift for STOL operations is through use of externally blown flaps (see Figure 4). With a high-power setting on the engine and the large flaps fully deployed, as is the case during landing approach, significant buffeting of the airplane can result from the engine exhaust impinging on the flaps and wing. The produced buffeting has its source in the nonsteady pressures contained in the engine exhaust flow. Inflight, when the flaps are retracted, buffeting will be caused by the nonsteady exhaust pressures acting on the wing. This buffeting will be of lesser severity than during landing approach and takeoff but will be of longer duration.

An analytical study in which the effects of engine exhaust buffeting on STOL rideability are assessed will now be described. The analyzed vehicle was a small size STOL airplane using externally blown flaps. Although non-existent, this airplane was considered representative of its category. The natural frequencies and natural vibration modes were established for the airplane. A spanwise buffet pressure distribution over the wing and flaps was prescribed. The data upon which the buffet pressures were based were obtained from a wind-tunnel test on a small scale model of the airplane. The RMS net buffet pressures (RMS of the difference of the upper and lower surface pressures) on the wing and flaps were found to have their largest values at locations along the engine centerlines. From an analysis using the airplane vibration and buffet pressure data, RMS accelerations were found at a number of locations along the fuselage. The contributions to one of these RMS accelerations from the airplane vibration modes are displayed in Figure 5 by the heights of vertical bars erected at the natural frequencies of the modes. The specific results presented in Figure 5 pertain to a location at the cg of the fuselage for a landing approach condition using maximum thrust (flaps deployed). (Not shown in the figure are modal contributions less than 0.001 g. Thus all modes are not represented in the figure.) Also shown in Figure 5 are curves giving human comfort criteria. These curves were obtained from Reference 3.

The modes contributing the greatest amount to the total RMS acceleration at the considered cg location are seen in Figure 5 to have frequencies of approximately 3, 9, and 11 Hz. Taking the contributions individually, Figure 5 indicates that the maximum duration at which no discomfort will occur is 4 hours for the 3-Hz vibration mode, 1.6 hours for the 9-Hz mode, and 5 hours for the 11-Hz mode. On the basis of individual contributions, approximately 1.6 hours would be taken as the time duration for which the occupants near the cg of the airplane would have no discomfort. (The landing approach will be typically performed with less than maximum thrust, thus significantly increasing the obtained comfort duration. The time actually spent by the airplane in this phase, in accordance with Table III, will be considerably less than the obtained result.)

The influence of the combined effects of the various frequencies is unknown since the curves in Figure 5 do not account for contributions from more than one frequency. This aspect makes it difficult to interpret vibration data in terms of human comfort criteria. Further, the rideability result established above only accounts for buffet vibrations and does not include the effects of other simultaneously occurring environments. Atmospheric turbulence and sounds introduced into the fuselage cabin from external acoustic sources, for example, can modify the calculated comfort duration. These additional factors make it even more difficult to assess rideability.

It is an eventual goal that a proper determination can be made for comfort durations. When this is done for a particular airplane, these durations can be considered in relation to the mission requirements of the airplane. For the above study, this requires comparison of the obtained maximum duration of comfort with the amount of time to be spent in the landing approach phase of the mission. Comparisons must also be made for portions of the fuselage other than the considered cg location. In addition, other phases must be studied. A satisfactory STOL airplane ride requires that all portions of the fuselage have comfort durations in each mission phase greater than the time duration to be spent in the phase.

The Rebounding Airplane

This section is concerned with those ride qualities that are used to discriminate between a "harsh" and a "soft" landing airplane.

The landing phase is over in less than 5 to 7 seconds after touchdown. The initial landing impact is over in less than 1/2 second, with the final settling out of the aircraft making up the noted total time. It is therefore surprising that so short a time of moderate discomfort for a harsh landing should rank on a par with ride quality areas of considerably longer duration.

The Rebounding Airplane Example

During the initial shock strut design, a critical decision was made to favor the taxi ride over the landing. This had the effect of producing a particularly soft taxi spring which is important for runway unevenness for taxi, takeoff roll, and rollout after landing. However, in achieving a soft taxi spring, the physics of shock struts required that the load factor at landing impact would be compromised. With these facts as background the following will be reviewed: (1) The sequence of events that occurred during flight testing, and (2) a comparison of time response plots of selected parameters obtained during four landings of a "harsh" landing airplane and five landings of a "soft" landing airplane. The lessons learned from this study are then summarized.

Phase I Initial Aircraft Flight Testing

Initial landings conducted during the flight development phase indicated that the aircraft indeed had a harsh landing characteristic. A plot of vertical-acceleration versus time revealed a second bump 2 seconds after impact due to poor spoiler "wing lift reduction" phasing (i.e., to settle the aircraft rapidly after impact the aircraft lift must be destroyed by deployment of wing spoilers).

The spoiler deployment schedule was revised to reduce the second (spoiler) bump to less than the first (impact) bump. Even with this reduction, the landings were still rated as harsh and unacceptable.

Phase II Revised Gear Design

The landing gear design was revised to reduce initial impact loads and flight tests were performed at the target sink speeds of 2/3 to 1 meter per second. The low (approximately 1 Hz) and high frequency (approximately 5 Hz) g's were compared to short duration criteria and found to be within the acceptable region. The evaluation of the landing was noted as considerably improved with no noticeable degradation in the taxi ride; however, the landings were still typical of contemporary airplanes and improvement was needed.

Phase III Revised Gear Design

For this gear design a departure was made from the functional restrictions of a conventional gear design and it was possible to maintain a soft taxi spring while reducing the impact bump substantially. The flight test evaluators were particularly enthusiastic in that the airplane landings were consistently soft over a much wider band of attitudes and sink speeds. Of course, the reduction in the first impact bump was a contributor to the improvement; however, it was found that the whole "quality" of the landing was changed and contributed greatly to the landing improvement. The landing impact load factor (first bump) as a function of aircraft sink speed at landing is shown in Figure 6, for the three development phases.

Time Response of Selected Parameters - The Quality of a Landing

Figure 7 shows the landing gear strut stroke (compression) as a percent of maximum versus time for firm landings (discomfort expected) for the three development phases described above.

Figure 7 also shows how the airplane lands with the struts fully extended and compresses them to absorb the shock of landing impact; also that the rebound that occurs after about 0.75 second degrades the landing in terms of undesirable motion and widely varying landing gear loads and shocks transmitted to the flexible airframe.

Figures 8 through 10 are the results of overlaying the individual parameter time histories during landing (for four landings) of the Phase II strut design to compare with (five landings of) the Phase III design. The first impression one obtains in looking at the ensemble is the chaotic behavior of the Phase II responses in comparison with the Phase III regularity of response.

Figure 8 shows the Phase II struts fully rebounding for the low sink landing, and a number of oscillations before nominally settling for the other higher sink rate landings. This is in comparison with the Phase III struts which settle rapidly with appreciably reduced rebound and oscillation.

Figure 9 shows the extreme variation of strut load for the Phase II versus the Phase III design. Although the strut load is substantially a function of strut position for low sink landings, the nonlinear strut characteristics greatly magnify the strut stroke variations on a load basis.

Figure 10 shows the elevator position time history comparison. This parameter is interpreted as one of the pilot activity indices during landing. The pilot is evidently sensing the quality of the landing and automatically responding in an effort to compensate for the load and motion variations.

From this brief study of the landing process and other studies for ride improvement it is urged that ride quality research programs be given the following considerations:

1. Ride criteria and evaluations should take more than G's versus frequency into account when describing vehicle ride quality. What the vehicle is doing in terms of attitude and motion time response is an important ride quality factor for flight crew and passengers.

2. What the pilot is required to do to execute smooth transitions in ground maneuvering, ground to air, in flight, and flight to ground bears heavily on the achievement of consistent vehicle ride quality and calls for more complete criteria and improved system design.

3. Even mild "surprises" to the passenger should be minimized; for example, "jerky" high speed turns off runways can be very discomforting primarily because they come as a surprise.

Aeromedical Evaluation

Figure 11 illustrates the portions of the vibrational spectrum where the general state of knowledge is reasonably good, although perhaps far from adequate (Reference 11). Our best data are shown in the left portion of the figure; some preliminary data in the ultrasound range are shown at the extreme right (Reference 12). The latter is representative of vibrations produced by ultrasound therapy units used in medicine, for periods of time up to 15-20 minutes. The former is related to vibration imposed primarily on the seated operator (pilots, etc.) and the responses of the whole body or of organs within the body. Again, these data relate for the most part to time periods of a few minutes to an hour. Man's approximate natural frequency is indicated by the vertical arrow at the left. Also obvious, is the great section of the spectrum which is labeled "Area of Insufficient Exploration."

In the lower frequencies (10^{-1} - 10^{2} Hz) the discomfort pain or other effects are produced by resonance of body parts - limbs, organs, etc. - or of the whole body. In the ultrasound range at 3-MHz resonance is produced in flowing blood columns when the vibration is applied in the direction of the long axis of the blood vessel. Standing waves can be produced in the blood columns, resulting in inhibited blood flow and tissue hypoxia in the part of the body supplied by the affected vessel(s). This situation may exist as long as the ultrasound vibration continues.

It is thus apparent that resonance vibrations can be set up in any part of the body, by some frequency and some amplitude and that resonance of the part is likely to continue as long as the stimulus is being applied. It is also apparent, therefore, that vibrational effects for the frequencies of more than 10^2 Hz, at various amplitudes and times of exposure, have not been adequately explored, and that this must be done to understand the subtle effects of vibration on parts of the body which constitute less than whole organs or organ systems. Most of the evaluation scales criteria for vibration effects are too gross to be of value in assessing the mechanisms of damage at the subsystem, component, or subcomponent levels in the body (Reference 13).

Effects produced at these levels also appear to be related to long-term exposures - in terms of hours, days, weeks, or months. Sensitivity thresholds are beginning to be investigated and so far appear to be very low, probably less than 1 cm/sec^2 (about 1/1000g (Reference 13)). Long-term effects may be caused by vibrations below conscious levels. The sensitivity thresholds are known to vary for gross body parts, and it should also vary in microscopic parts - probably throughout the "insufficiently explored" region.

Recent investigations of vascular disorders found among industrial workers (Reference 14) exposed to long-term vibrations of 20-1000 Hz have shown that these frequencies and exposure times need to be more thoroughly investigated, initially as basic, generalized research. The problem has been recognized by occupational physicians for over 50 years (Reference 13). Portions of this unexplored vibrational spectrum are involved in the problem of aircraft rideability.

AN APPROACH TO RIDEABILITY CRITERIA

The three primary elements of present and planned ride research at the Douglas Aircraft Company are:

1. The use of portable onboard recorders to measure ride quality parameter values on contemporary aircraft in commercial use.

2. Available recorded data on Douglas Aircraft products.

3. Near future use of a full motion simulator for ride research and generation of rideability criteria obtained under realistic conditions.

The first two elements are operational and have been used but not fully exploited. Element 2 is particularly comprehensive but lacks the interiors and people which provide the necessary setting for realistic data. The test aircraft are usually bare of seating and contain much instrumentation, recorders, etc. Element 1 lacks the more controlled test conditions of Element 2 but has people in a realistic setting. Hopefully Douglas will be able to combine Elements of 1 and 2 and create a realistic total environment in a simulator in which ride criteria cannot only be developed but also solve potential ride problems on future aircraft developments.

The elements of the plan are then to

1. Continue the accumulation of acceleration data to provide an acceleration response statistical baseline for contemporary aircraft. These data would be obtained in a realistic setting.

2. Compare existing measured responses of Douglas flight test aircraft to those obtained under Step 1 above to measure improvement, change, problems, and to fill in the picture with system responses and pilot activities with data not obtainable under the service conditions of Step 1.

By providing a cabin section with actual interior furnishings, visual cues, an appropriate acoustic environment, thermal/air-conditioning, etc., controlled tests could be performed using as inputs to a full base motion, recordings obtained under Steps 1 or 2 above. The inputs could be varied by filtering or by mode enhancement techniques.

This procedure would be used to define more precisely the disagreeable elements in a given phase.

Figure 12 shows in block diagram form the major elements that contribute to the plan.

Modifying Flight Ride Quality

Although modifying flight ride quality is not a part of Rideability Criteria research at Douglas, it is an area of ride research that should be pursued and accordingly is treated in this section.

The ground environment, as represented by surface unevenness, can be affected by airport paving and maintenance criteria such that the ground ride quality of most airplanes will be acceptable to the airplane's occupants. A similar consideration will not apply to atmospheric turbulence and other means must be employed to obtain the maximum in inflight ride quality. A large amount of data is available on the intensities and spectral content of atmospheric turbulence from near ground to high altitudes. These data, however, will not satisfy the airplane occupant who is flying along a specific route on a particular day. The collected atmospheric turbulence data will only tell what might be expected on a probability basis. What will be actually encountered is the prime concern of the airplane occupant.

Atmospheric turbulence (gust) intensity descriptions over a route are typically obtained from communications of flight crews whose airplanes have just previously flown the route. This communication is generally qualitative and the discomfort experienced depends to a considerable extent upon the particular airplane being flown and its weight configuration. This type of report can be expected to vary for different individuals.

Although not a Douglas approach, an attempt is now being sponsored by the FAA to replace the qualitative communications on gust intensities with quantitative information. Simple gust measuring devices will be installed on airplanes and the gust intensity measurements will be converted to a 10-point rating scale. Only the external environment, however, is being rated by this approach. Each airplane must be calibrated so that this measurement can be interpreted in terms of vibration responses within the airplane. This calibration can be established from experience and aided by analysis. With more reliable information about gusts along a route, airplanes can be flown such as to diminish the possibility of uncomfortable rides.

SUMMARY OF NEEDS

The summary of needs presented below is based upon needs defined in this paper, and others which although not discussed, are a part of an aircraft manufacturers' needs for rideability design and evaluation.

Pavement Unevenness

Because of its importance to ground rideability, an extension and completion of the table shown in Figure 3 is needed to intelligently design for pavement unevenness. Among the most urgent needs are these listed below:

Typical and Maximum Grade Changes (Overcrossings, Etc.)

Typical and Maximum Crowns and Transitions

Typical and Maximum Slab Settling, Faulting, Spalling, Etc.

Typical and Maximum Washboarding, Rutting, Etc.

Percent Distributions of Runway Roughness Power Spectra

Airport Operations

Because crossing velocity is one of the primary factors in determining response to pavement unevenness, and because future trends to increase airport capacity will demand increases in off-runway taxi speeds, the present and future taxi speed typical and maximum values need be studied to provide improved design criteria.

Present and Increased Capacity, Off Runway Taxi and Maneuver Speeds

Human Discomfort

The most basic need is for an updating, using a representative class of nonmilitary personnel, of data similar to Parks (Reference 2) and the AFSC Data (Reference 3). This would take care of immediate needs for short and long-duration general human factor criteria. Next, or in parallel, an effort would be required to define a ride quality baseline for contemporary aircraft by type of aircraft and for the various flight and ground phases of operation. Finally, the generation of human factor criteria must be obtained in the most realistic setting practical (real or simulated total environments) that could be used to study necessary design tradeoffs including interactions of vibration, sound, motion, etc.

General Human Factor Criteria - Civilian Basis

Contemporary Aircraft Ride Quality Baseline

Human Factor Criteria, Total Environments

The following listing is provided for completeness and to typify the kinds of other needs not covered in this paper.

Testing Guidelines

Laboratory

On Ground, Full-Scale Airplane Tests (to simulate response to pavement unevenness.)

In Air, Full-Scale Airplane Tests

Research

Analytical Methodology

Seat and Human Dynamic Response

Improved Interior Sound Prediction Techniques

Development of Ride Quality Indices

Physiological

Explore Critical Frequencies of Vibration Spectrum

Design

Automated Braking and Ground Maneuvering Guidelines for Ride Comfort

Takeoff and Landing Trajectory Comfort Guideline for STOL, Etc., Aircraft Developments

REFERENCES

1. Houbolt, J. C., R. Steiner and K. G. Pratt, "Dynamic Response of Airplanes to Atmospheric Turbulence Including Flight Data on Input and Response," NASA TR R-199, June 1964.

2. Parks, D. L., "Defining Human Reaction to Whole-Body Vibration," Human Factors Vol. 4, No. 5, October 1962, pp. 305-314.

3. AFSC DH 1-3, Personnel Subsystems, First Edition, Revision No. 4, 1 January 1971.

4. Yang, N. C., "Interaction of Aircraft and Ground Structure," Journal of the Structural Division, ASCE, June 1970.

   See also

   "Systems of Pavement Design and Analysis," Highway Research Record No. 239, 1968.

5. The Airport and Airway Development Act of 1970 (Public Law 91-258).

6. Wignot, J. E., et al., "The Development of Dynamic Taxi Design Procedures," FAA DS-68-11 Department of Transportation, Federal Aviation Administration, June 1968.

7. RTD-TDR-63-4139, Vol. I, "Design Criteria for Ground-Induced Dynamic Loads," November 1963.

8. WADD-TR-60-470, Part III, "Automatic Runway Profile Measuring Instrumentation and Runway Properties - Base Surveys," July 1963.

9. Houbolt, John C., "Runway Roughness Studies in the Aeronautical Field," Journal of the Air Transport Division, Proceedings of the American Society of Civil Engineers, Vol. 87, No. AT1, March 1961.

10. Hall, Albert W., Paul G. Hunter, and Garland I. Morris, "Some Loading Conditions Imposed during Ground Operations of Present-Day Transport Airplanes," Presented at the FAUSST VIII Meeting, Washington, D.C., January 25-29, 1971.

11. Bioastronautics Data Book, NASA SP-3006, p. 78.

12. Dyson, M., B. Woodward, J. B. Pond, "Flow of Red Blood Cells Stopped by Ultrasound," Nature, Vol. 232, August 20, 1971, pp. 572-573.

13. Guignard, J. C., "Human Sensitivity to Vibration," J. Sound Vibr. (1971) 15(1), p. 11-16.

14. Teisinger, J., "Vascular Disease Resulting from Vibrating Tools," J. Occupat. Med. Vol. 14:2 Feb 1972, p. 129-133.

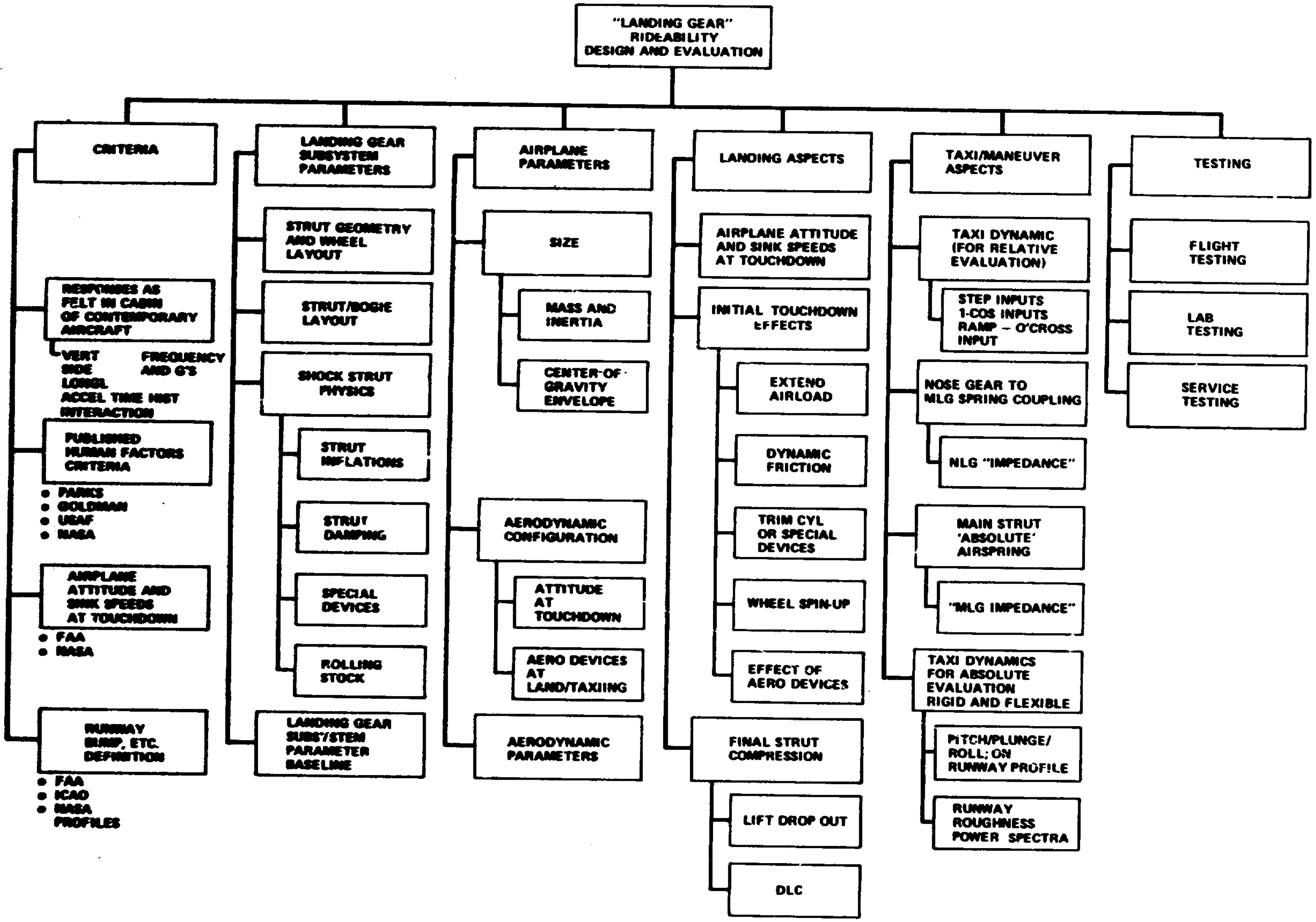


Figure 1.- Douglas approach to rideability.

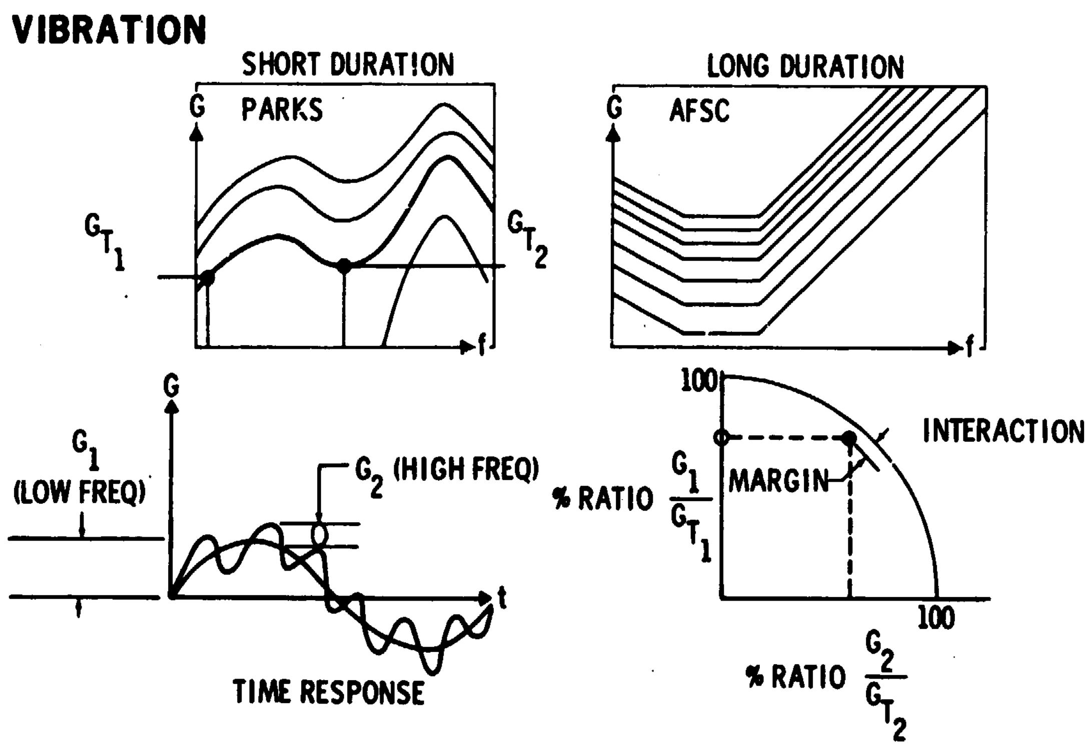


Figure 2.- Rideability design/evaluation criteria (current Douglas practice).

TYPE	ESTIMATED PERCENT OF AIRPORTS	NUMBER OR DURATION	MAGNITUDE	DOMINANT RESPONSE
DESIGN GRADE RUNWAY OVERCROSSINGS	100	2-5/FLIGHT	FAA ICAO CONSTRUCTION STANDARDS	RIGID BODY MODES
SLAB FAULTING AND SPALLING	5-10		1.27 cm (1/2 IN.)	FLEXURAL MODES NOISE
SETTLING OF SLAB CENTERS, ETC.	5-10	LENGTH OF RUNWAY TAXIWAY	* RUNWAYS 0.6 cm TAXIWAY 1.27 cm	RIGID BODY MODES FLEXURAL MODES NOISE
WASHBOARDING			VARIED	RIGID BODY MODES FLEXURAL MODES NOISE
RUNWAY ROUGHNESS SPECTRA PSD f	50-70-90	-	FAA NASA NATO AIR FORCE STUDIES AND REPORTS	RIGID AND FLEXURAL MODES AND NOISE

* ON 6 TO 8m SPACING

Figure 3.- Pavement unevenness for design, analysis, and evaluation efforts.

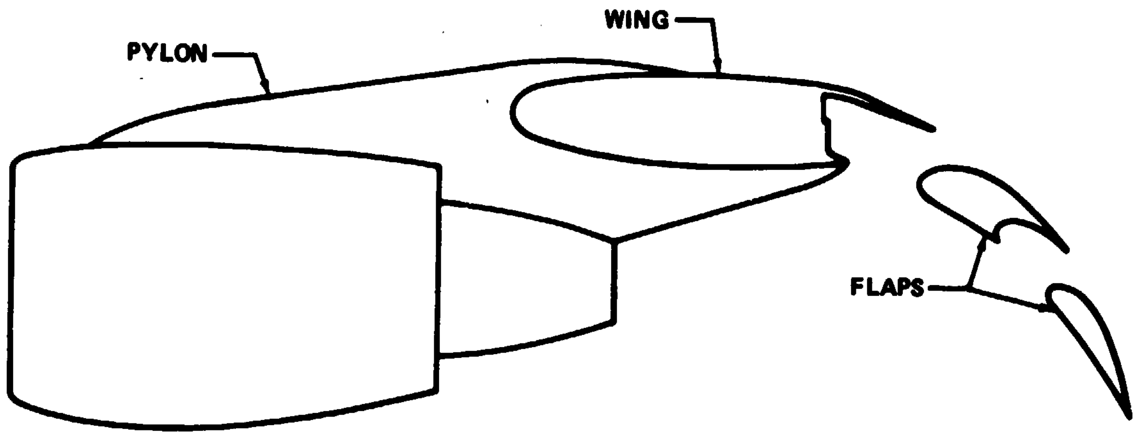


Figure 4.- Externally blown flaps.

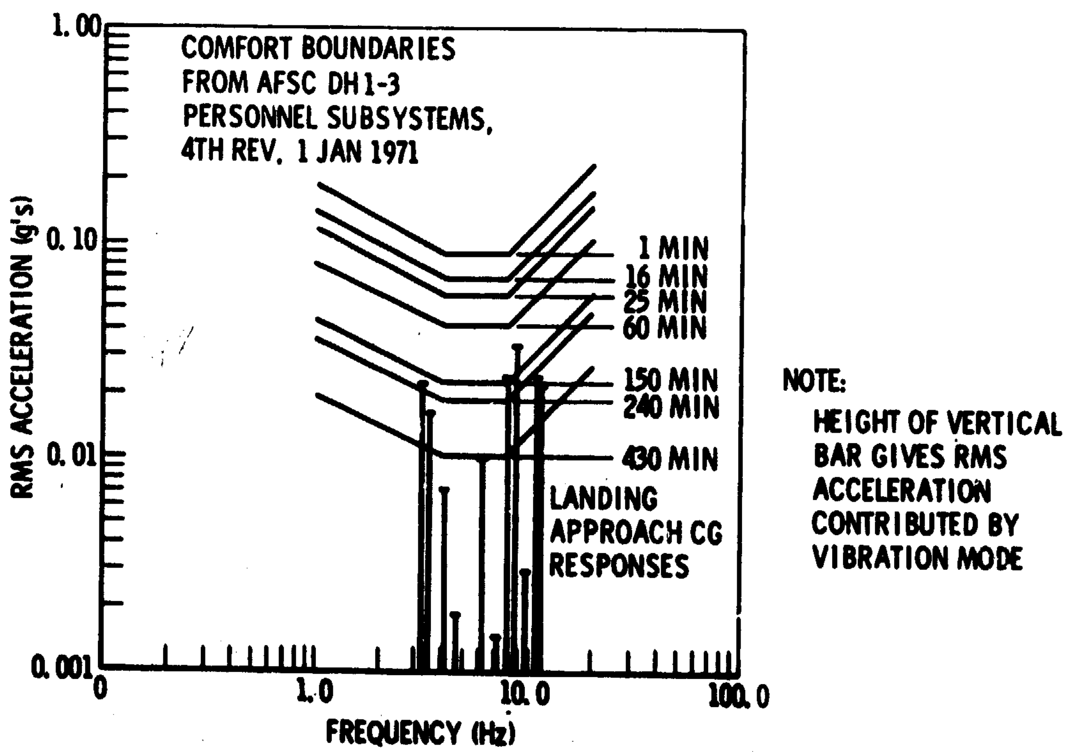


Figure 5.- Engine-induced buffet responses.

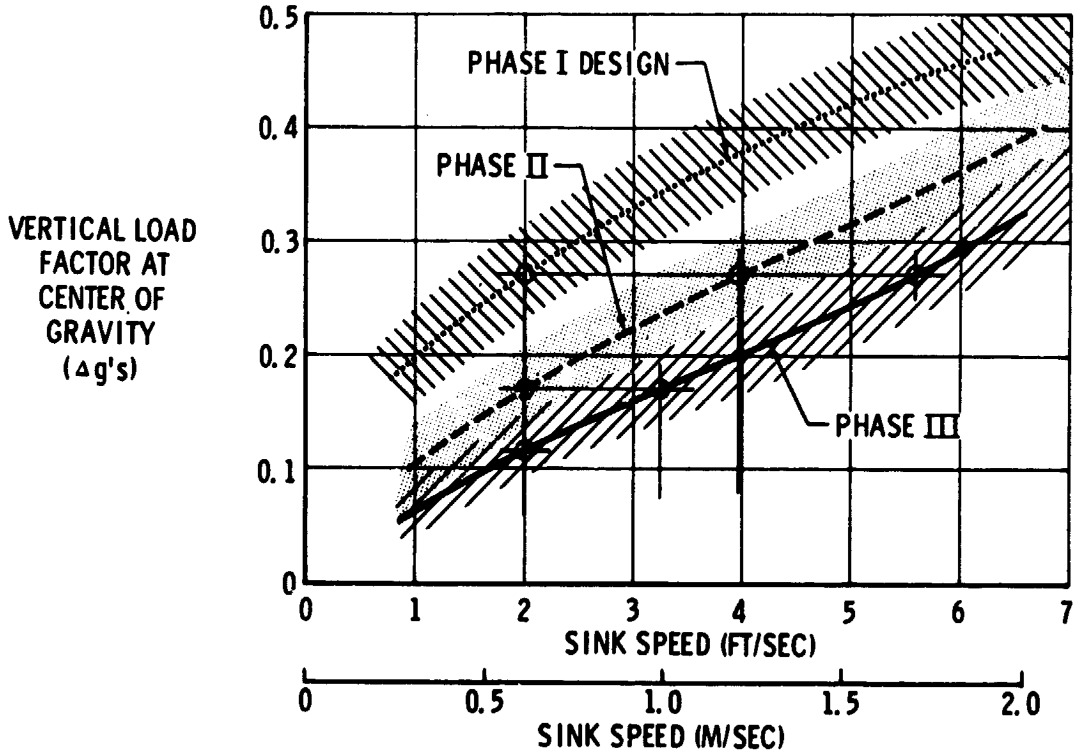


Figure 6.- Effect on impact load factor (main landing gear shock struts).

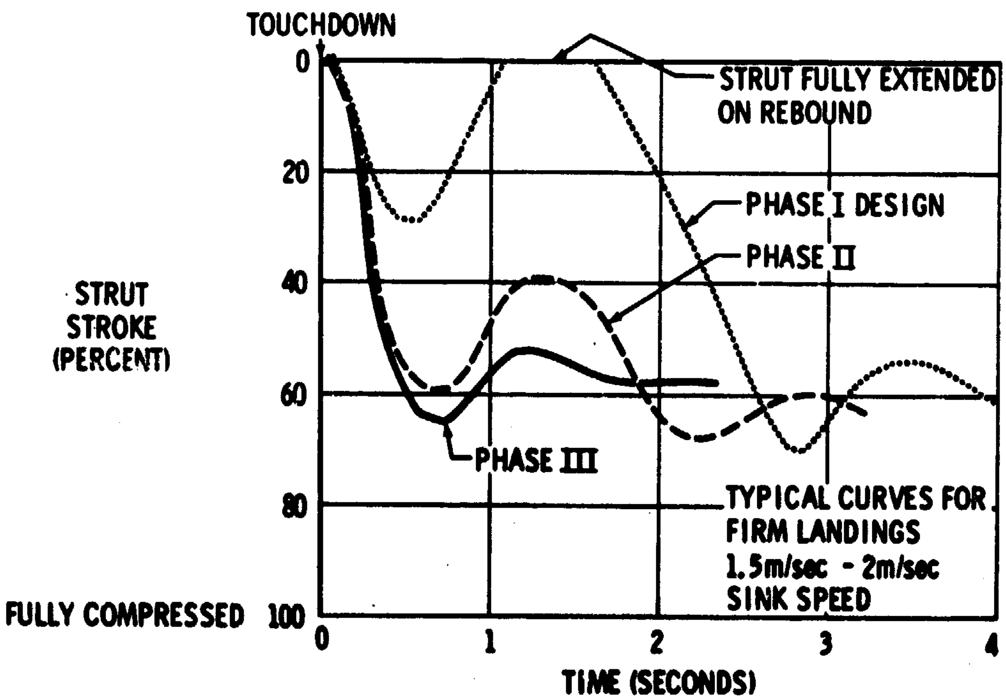


Figure 7.- Variation of strut stroke with time from touchdown (main landing gear shock struts).

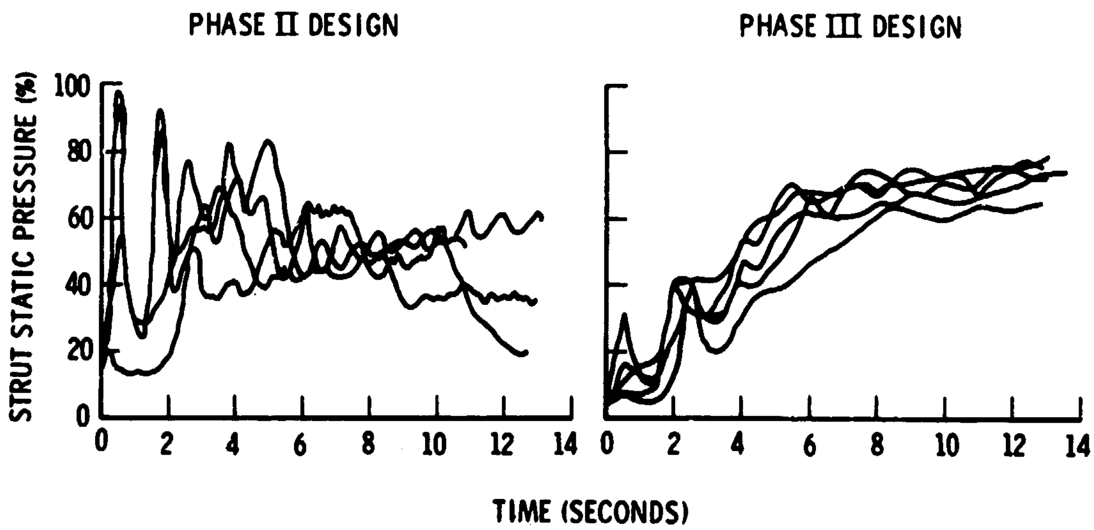


Figure 8.- Right wing main landing gear strut stroke.

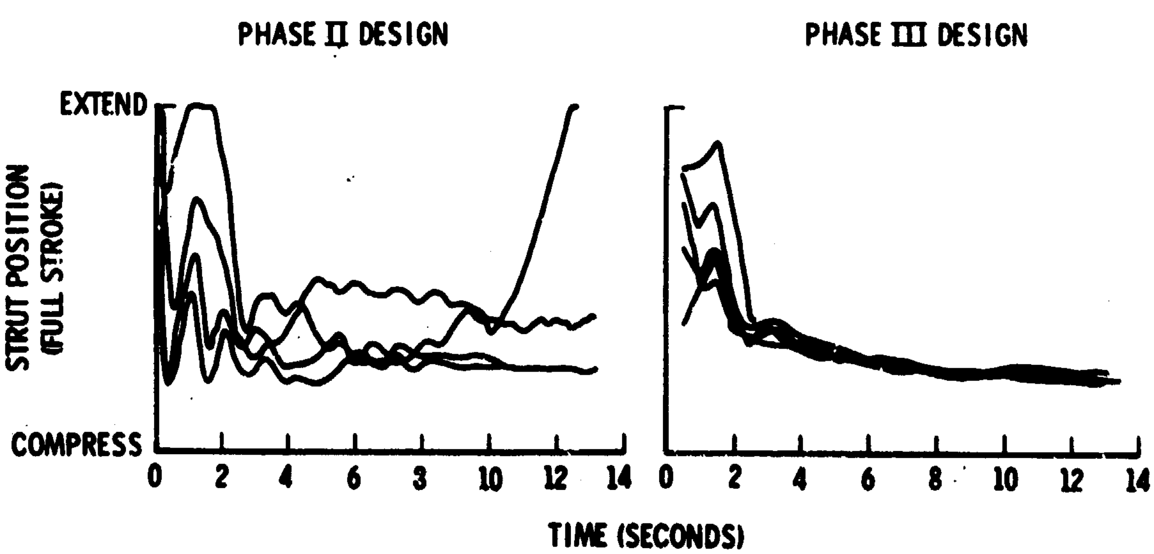


Figure 9.- Right wing main landing gear air pressure.

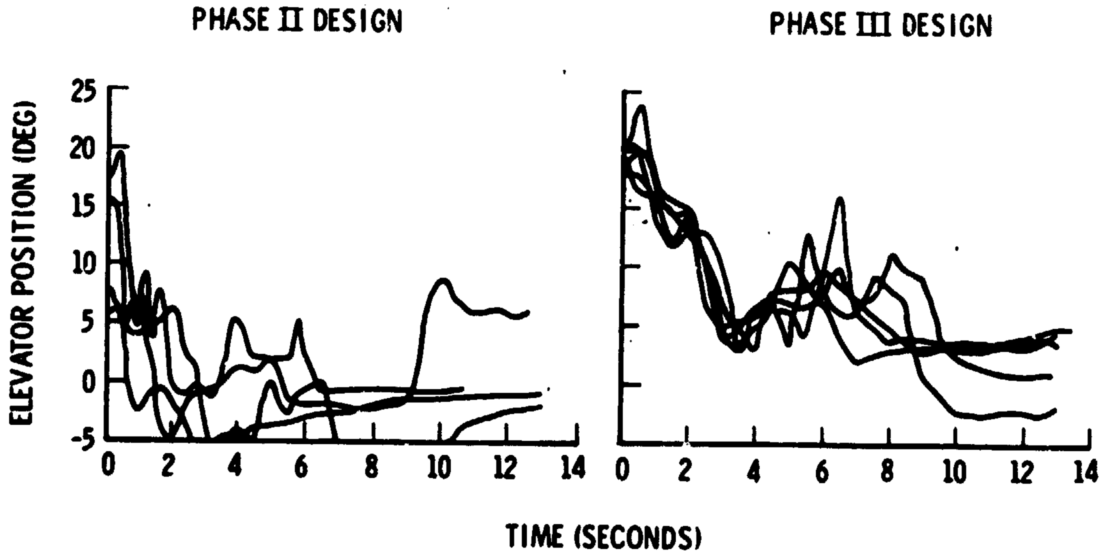


Figure 10.- Elevator position.

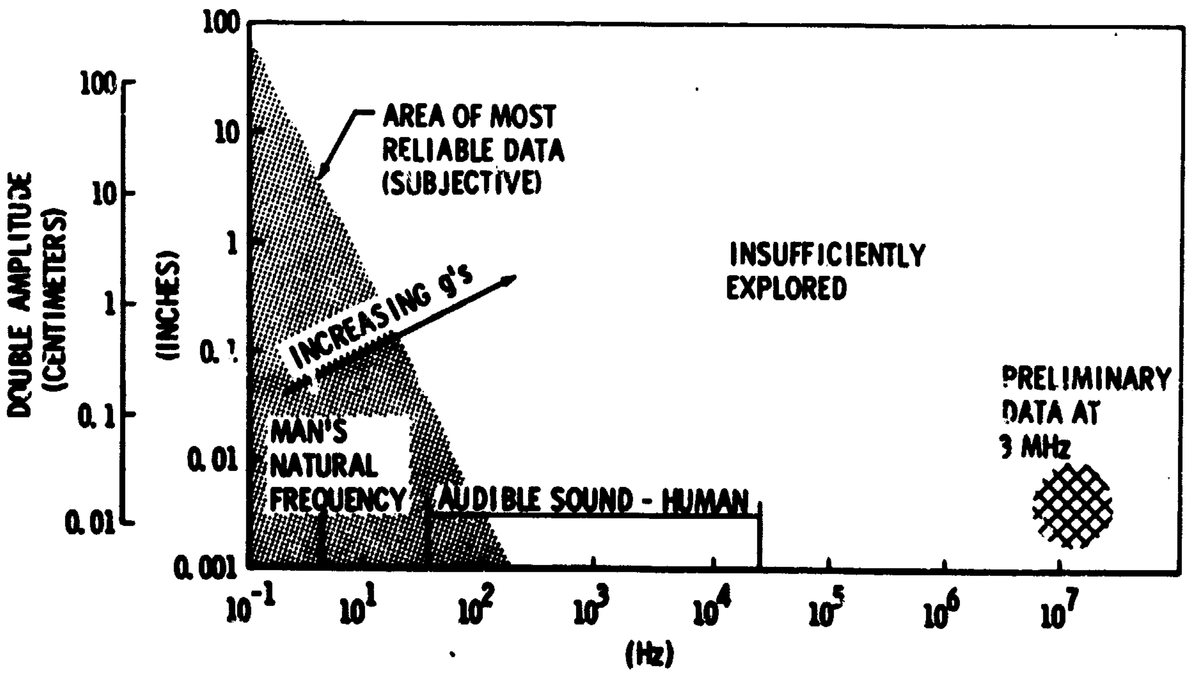


Figure 11.- Spectrum of known vibrational effects.

RIDEABILITY PROBLEMS ARE SPECIFIC AND CRITERIA SHOULD BE OBTAINED WITH MAXIMUM PRACTICAL REALISM

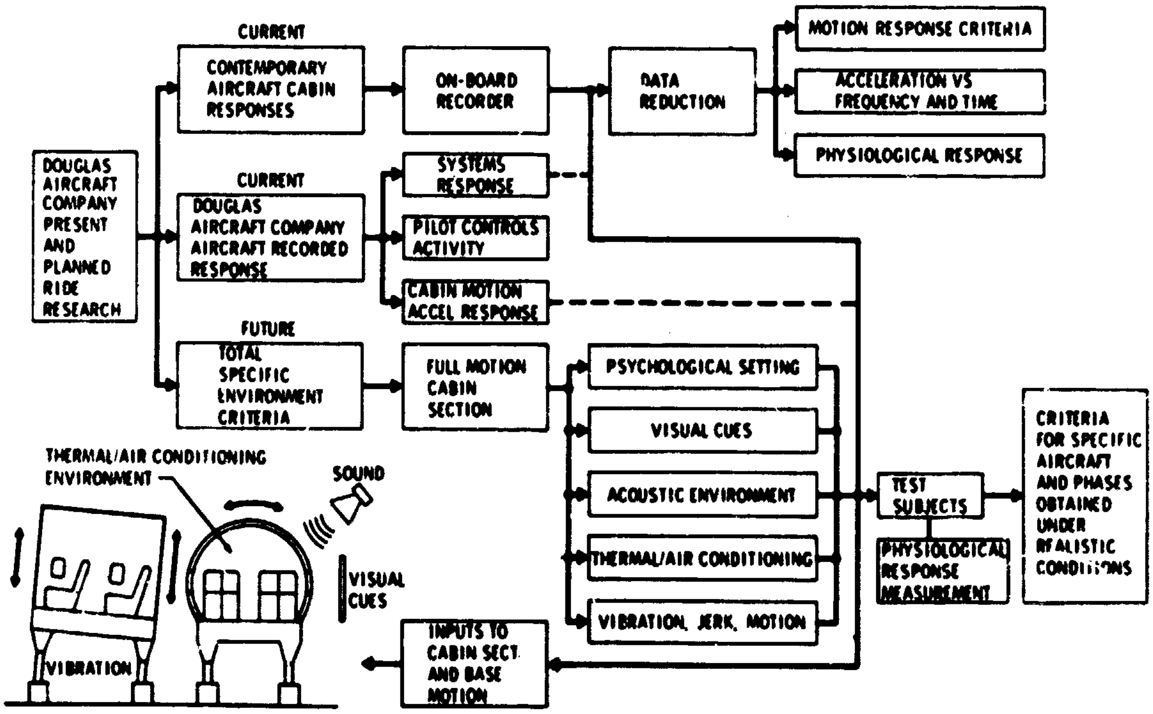


Figure 12.- Planned douglas aircraft company approach to rideability.

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RIDE-QUALITY CRITERIA FOR LARGE COMMERCIAL HELICOPTERS

By Ronald G. Schlegel, Allen M. Stave, and Alfred A. Wolf

Sikorsky Aircraft Division
United Aircraft Corporation
Stratford, Connecticut

SUMMARY

N73-10015

This paper presents a review of major ride-quality criteria used by Sikorsky Aircraft in the design of commercial helicopters, some of the limitations of these criteria, research programs conducted to better define these criteria, and some recommended research programs. Primary emphasis is given to the question of noise and vibration criteria for passenger acceptance and comfort.

INTRODUCTION

Figure 1 gives a list of ride comfort factors which should be considered in determining the passenger acceptability of a large commercial helicopter. Of the factors listed, noise and vibration are those receiving primary emphasis for improvement in commercial helicopters. Preliminary results of an ongoing survey of helicopter commercial customer reactions show noise to be the most significant single complaint of the passengers. Criteria for the selection of goal levels are difficult to define. The problem is not one of lack of criteria but rather one of overabundance of sometimes conflicting opinions. Noise and vibration levels can be made low enough to satisfy even the most conservative of criteria but not without weight and performance penalties.

In the area of noise, the parameter of speech interference level (SIL) has been used historically as a measure of comfort. Experience indicates that this may not be the best measure. But then which one is? There are several to choose from, some of which have been evaluated on the basis of human reaction, but none have been universally accepted. Sikorsky currently uses criteria which are similar to many existing CTOL aircraft. The rationale behind this criteria selection will be discussed.

The criteria available for vibration are voluminous. Many studies have been performed to establish comfort criteria with varying ground rules and correspondingly varying results. The combination of these criteria with results of Sikorsky studies on seating vibration transmissibility has served to collapse some of the criteria and to clarify the situation. In addition to the seat itself there are the armrests and floor to consider because these can provide uncomfortable vibratory inputs under certain circumstances. Results of seat vibratory transmissibility studies, application to criteria, criteria selection, and some of Sikorsky's application experience in this area will be discussed.

Historically, many commercial helicopters have been the offspring of vehicles developed for the military. Because, for the most part, these vehicles were designed for peak performance in moving troops or equipment from point A to point B, noise and vibration levels were not matters of primary concern. Speech interference levels of 85 to 95 dB in the passenger compartments of these aircraft were not uncommon. Vertical vibration levels at blade passage frequencies as high as ±0.25g existed. As the result, the environment of the commercial offsprings was largely that which could be economically achieved by converting the military vehicle at a minimum weight and performance penalty.

The recent world-wide emphasis on man's environment has served to make the helicopter industry more conscious of providing vehicles with improved environments for commercial passengers. This consciousness on the part of Government and industry has stimulated a fair amount of research activity in recent years toward improving ride quality of commercial helicopters. The question which faces the designer today is what criteria (or combinations thereof) to apply to provide passenger comfort in an economically viable manner.

INTERNAL NOISE CRITERIA

In the area of noise level there is a great deal of question not only as to the allowable level but also the criteria to select to best define passenger comfort. Figure 2 shows some of the criteria which can be used to define internal noise levels. A typical Sikorsky S-61 commercial cabin noise signature is shown on the right side of this figure along with the respective overall sound pressure level, "A" weighted sound pressure level, speech interference level (old octaves), speech interference level (preferred octaves), perceived noise level, and noise criteria curve number.

In terms of any of the human factors criteria for the evaluation of speech interference, loudness or annoyance, the overall sound pressure level has very little meaning and is, therefore, not recommended as a criteria to be used for ride comfort.

The "A" weighted sound pressure level, like the overall sound pressure level, gives an indication of the total energy summation of the acoustic octaves. The difference between the two being that the "A" weighted octaves are weighted (ie, shaped) to simulate the response characteristics of the human ear. The dBA level has been shown to give a reasonable approximation for annoyance and, in certain conditions, to speech interference, but does not seem to have gained popular acceptance as a criteria number.

Speech interference level seems to have historically gained most popular acceptance as an internal noise specification criteria. Speech interference level (SIL) is defined as the arithmetic average of the 600-1200, 1200-2400 and 2400-4800 Hertz octaves. These octaves have center frequencies of 850, 1700, and 3400 Hertz, respectively. Speech interference level is used as a handy guide to the interfering effect of the noise on speech. Because of its historical acceptance by industry and customers, this is the criterion which has been used for years for internal noise specifications. The introduction of "preferred" octaves to replace the "old" octaves, however, has created a new speech interference level, PSIL, based on the arithmetic average of the 500, 1,000 and 2,000 Hertz center frequency octaves. This is the criterion currently used by Sikorsky Aircraft in its internal noise specifications.

Using SIL or PSIL by itself as the criteria has some definite limitations. First, one must be careful whether SIL or PSIL is being specified because, as shown in the case of the S-61 in figure 2, the two levels can be significantly different due to the increased importance given the lower frequencies in the PSIL rating scheme. In addition, there are limited data available to evaluate the speech interference effects of spectrum which contain discrete frequency tones, multiple discrete frequency tones, amplitude modulated noise, or beat frequencies between adjacent tones. Data are also not generally available to evaluate the speech interference of spectra whose octaves in the speech interference frequency range may vary from each other by as much as 20 dB. Finally, speech interference level does not appear adequate, by itself, to evaluate the annoyance of a signal.

Noise criteria (NC) curves are an improvement to the speech interference criteria, as they give empirically derived octave band levels to accompany the speech interference levels for equal loudness levels. The speech interference level is the level of the noise criteria curve. The NCA (Noise Criteria Alternate) number allows higher low frequency levels than the NC curves and are used where a "compromise due to economic factors" is necessary in the low frequency octaves. The NCA curve is designed such that substantial objections will not occur if the speech interference level is low enough for satisfactory speech communications.

An improvement over all of the above mentioned criteria is the PNdB, whose level for the S-61 helicopter is almost identical with the dBA. This rating scheme weights each of the octaves for its annoyance contribution and then adds the annoyances to result in a single number. Its limitations are like those mentioned earlier for the SIL and PSIL in that its adequacy has not been determined for the factors such as impulsivity or multiple tone combinations peculiar to classes of V/STOL aircraft. Two studies by Sikorsky Aircraft emphasizing the limitations of the PNdB rating system were conducted on United Aircraft's Turbotrain® in its early development as well as in the laboratory. In the former study, a "clickety-clack" noise resulting from a component resonance at the track joint frequency was modified to a "clunkety-clunk" noise through a car redesign. Although a significant reduction in the Perceived Noise Level resulted, no significant impact on passenger acceptance was realized. In a more controlled laboratory experiment, which will be better explained later in the paper, a study of noise with and without an impulsive modulation was conducted to determine the adequacy of PNdB for subjective annoyance in the presence of impulsive signals. Results showed as much as 5.5 PNdB error in the subjective evaluation of annoyance.

Data most readily available in the literature for internal noise comparison are speech interference levels. Figure 3 uses preferred speech interference level (PSIL) to compare the historical record of typical Sikorsky commercial helicopters with the internal levels of turboprop and jet aircraft. The commercial S-58 and S-61 aircraft, which were designed in the 1950's and 1960's, have speech interference levels of 85 PSIL. Although published literature relative to speech interference levels would not indicate such, these levels allow raised voice communication for distances up to 6 feet. The 1970 aircraft, the S-58T and the S-65-40 for which commercial interiors were designed, have been designed for 75 dB PSIL internal levels. The S-200, which is intended for use in the 1980's, has been designed for an internal level of 68 dB PSIL.

Some recent measurements in turboprop and jet aircraft are shown for comparison. Measurements in typical turboprop aircraft show a spread of levels from 64.5 to 84.5 dB PSIL. In like manner, measurements in typical jet aircraft show a spread of levels from 66 to 80 dB PSIL. The goal for Sikorsky's 1980 S-200 aircraft of 68 dB PSIL is, therefore, not inconsistent with today's CTOL aircraft. Source noise reduction research is currently in progress which holds promise of reducing these levels (and particularly discrete frequency noise) even further. We feel that our goal of 65-70 dB PSIL is one which is practically achievable and which should evoke universal passenger acceptance.

VIBRATION

In the area of vibration criteria, there is an abundance of data from which to choose. Shown on figure 4 are vertical vibration criteria for acceleration in ± g's, versus frequency, in Hertz, for a frequency range of about 0.5 to 50 Hertz. The data selected for this chart are the ISO proposed recommendation, as shown in reference 1, a recommended comfort limit for high speed ground transports from reference 2, another ground transport recommended level from reference 3, and a recommended 2-3 hour exposure level curve from the reference 4 study. The intent of showing these curves, which have over a 2 to 1 spread in recommended levels, is not to select one which is better than the others but to indicate the spread in data of some of the more recent studies. Had the volume of data available on recommended criteria been plotted, the spread of data would have been significantly greater.

In looking at the studies, some of the apparent reasons for the spread in data are differences in test equipment and techniques, guidelines and remarks, body types, age, sex, seat types, exposure times, restraint mechanisms, physical conditions (fat, weak kidney, etc.), anticipation of excitation, degree of control of test environment, type of performing task (if any), type and response of seat (including modal coupling factors), position of subject and points of contact with seat, visual effect coupling, noise level, and many more.

Also shown in the figure, for comparison, are measured vertical vibration levels of the Sikorsky S-61 Mark II commercial helicopter at the spine of the passenger. At floor level, the vertical vibration level throughout the cabin at its primary vertical excitation frequency of 18 Hertz at the blade passage frequency ranges from ±0.05g to a maximum over a small portion of the cabin of up to ±0.15g. Most of the cabin is below ±0.01g. The vertical transmission ratio of seat vibration (as used herein, defined as the ratio of passenger rump to floor vibration) at this frequency has been measured at 0.4, resulting in the vibration levels to which the passenger's rump is being subjected from ±0.02 to 0.06. These levels appear to be within and below the ranges suggested by most studies as recommended acceptable levels for vertical vibration and are corroborated by a lack of passenger and customer complaints of vertical vibration.

Figure 5 shows the effect of seat transmission ratio on vertical vibration acceptability criteria. The data shown are from a recent study which utilizes recommendations from reference 5 to establish the threshold of unpleasantness. With measured seat transmission ratio used to establish maximum floor vibration levels, the upper curves result. The "x's" and "o's" shown are from helicopters which had received favorable pilot reaction and seem to corroborate the approximate accuracy of the criteria. A major point to be made from this figure is that the establishment of aircraft criteria must take into account the transmissibility characteristics of the passenger seat.

There appears to be less data available on human comfort to lateral vibration than there is on vertical vibration. Presented in figure 6 are the results of two of the recommended criteria from studies previously mentioned, references 2 and 3. Lateral vibrations in Sikorsky helicopters occur at two primary frequencies, the blade passage frequency (shown here at 18 Hertz for the Sikorsky S-61 Mark II helicopter) and the rotor rotational frequency (shown here at 3.6 Hertz for the S-61 Mark II). The levels shown for the S-61 are ±0.015 to ±0.075 g's at blade passage frequency. Here, a conservative estimate for passenger seat lateral transmission ratio of 0.75 was assumed to arrive at the levels shown from those measured on the floor of ±0.02g to ±0.1g. There are data available which show lateral transmission ratios for pilot type seats at this frequency of 0.15. Since most passenger seats are attached to the side wall, this ratio, however, would appear to be too low for use here. It is believed by the authors that this ratio is something greater than 0.15 but less than 0.75.

In the case of the lateral once per revolution vibration of the Mark II, a transmission ratio of 0.75 was assumed, although pilot seats exhibit a transmission ratio of approximately 0.5. Even without this small amount of assumed seat attenuation, measured floor vibration levels of ±0.005g (not shown on the curve) to ±0.015g at this frequency appear to be well below the acceptable limits. Some recent studies have created a concern for potential vertigo at this frequency. Recent operator experience has shown that careful rigging of the main rotor brings cabin floor lateral vibration levels at this 3.6 Hz frequency down to a level of ±0.005g or lower. Even were there to be pilot or passenger discomfort at the upper end of this data spread, the level of ±0.005g appears from this experience to be quite satisfactory, even for extended periods of instrument flight.

OTHER COMFORT CRITERIA

Some of the other comfort factors which will not be addressed to any significant extend are also listed in figure 7. On seat configuration, the criterion used by Sikorsky Aircraft in pitch is 32-34 inches and in width 20 inches. Commercial seats should also be selected which isolate the passenger from vertical and lateral vibrations as much as is practically possible. Studies conducted by Sikorsky Aircraft have also shown that vibration flanking paths, through items such as the floor, head rests, and arm rests, should also be eliminated as much as practically possible. In the case of the arm and floor, padding for the arm and foot rests is an effective solution. In the event that head rests are used, it is important to select a seat which does not exhibit fore and aft back coupling to the vertical floor vibration.

When air-conditioning systems are available, helicopters are designed to maintain cabin temperatures of 72 to 75°F. Maximum values of relative humidity of 35 to 50% are desirable for passenger comfort. Sikorsky commercial helicopters of the S-65-40 and S-200 size require around 18-20 cubic feet per minute (CFM) of fresh air to remove odors and maintain relatively uniform cabin temperatures. Air velocities of 40-60 feet per minute appear to be maximum values for passenger comfort.

Human factors studies have shown that recommended limits for rate of pressure change for passengers is 0.1 psi per minute. This may be practical for pressurized aircraft; however, unpressurized aircraft can experience somewhat higher pressure changes. Unpressurized commercial helicopters can experience up to 0.8 psi per minute pressure change. This has not appeared to be a factor affecting passenger acceptance of commercial helicopter service. Rates of 1.0 psi per minute are also common in high speed elevators. It seems that the 0.1 criteria is extremely conservative in light of this experience and there is therefore a wide band of uncertainty as to what the acceptable criteria is.

The floor attitude has been shown to be one which produces anxiety in the passengers. Angles of bank for low attitude turns of over 5° are not recommended and a sustained floor attitude of over ±5° should be avoided for climb and descent. Recent experience with STOL aircraft operations has emphasized the significance of this recommendation. For 6 to 8° glide slopes, floor attitudes of 15 to 20° were experienced, with reported passenger discomfort. From this experience floor attitude appears to be a factor in determining overall ride comfort. Sikorsky's large helicopter can maintain approach and take-off path angles of 10° while maintaining an almost level floor.

Experience has shown that window size should be as large and as low as convenient and practical. The Sikorsky S-200 vehicle uses 15 x 20 inch windows with a sill height of 27 inches.

Among the factors not listed in this figure are visual effects and coupling of all the factors. More needs to be known about both of these two factors, although they have been shown to be occasionally significant in influencing passenger acceptance. Visual effects in a helicopter can include empennage and window vibration as well as a phenomena known as rotor blade flicker, the periodic change in light level created by the rotor blade passage. Aircraft have been made subjectively smoother by reducing the vibration of items such as valences, instrument panels, and windows. Coupling of all the factors listed on figures 1 and 7 is an area which needs more attention to better understand because very little has apparently been done in this area to date.

SIKORSKY'S RIDE COMFORT RESEARCH PROGRAM

The Ride Comfort Program at Sikorsky is guided by the following theoretical conception of passenger comfort:

Comfort is the resultant of several forces acting on the individual through several dimensions. It is not known exactly how many factors enter into the situation but the items discussed previously provide at least a partial list. A feel for the complexity of a scientific investigation into comfort can be obtained by considering the interactions between temperature, humidity, and air flow which must be taken into account when designing an air-conditioning system. Our assessment of the total situation indicates that probably all of the comfort parameters interact with each other in an extremely complex manner. For example, a higher level of noise is probably allowable if the passenger is on a short pleasure trip. On a business trip of the same duration but which will be repeated on a periodic basis the passenger will desire a lower noise level.

One approach to the evaluation of comfort is to break down the various variables into classes and study each class individually as though the others do not vary. To this end four basic types of parameter have been extracted from the mass of variables: physiologically based variables, motivation variables, duration variables, and ride cost.

Physiologically Based Variables

Physiologically based variables generally involve variables, such as temperature humidity, vibrations, and noise, that have a comfort zone around some central value with either extreme being considered unpleasant. Much research is needed to determine the limits of each parameter's comfort zone and to determine how the parameters interact with each other.

Motivation

The passenger does not come to the situation in an unbiased state He has some reason for traveling and brings with him attitudes toward the vehicle in which he is riding as well as his attitude toward his destination and toward life in general. All of these attitudes bias his judgement of the travel situation. For example, a traveler who is on his way to an interesting vacation and has promised his family a sight-seeing trip on a helicopter will tend to ignore any annoying aspects of the environment and focus on positive aspects. On the other hand a passenger who is on an unpleasant business trip and has just had an unpleasant argument will tend to focus on any annoying aspect of the environment and complain.

Exposure

Passenger reactions to vehicle environment is also colored by the length of exposure and exposure just prior to boarding the vehicle. For example, consider a traveler who uses a particular mode of transportation on a daily basis to and from work. His reaction to vibration will depend on the length of the trip. A trip of 5 minutes may not cause discomfort whereas a trip of over an hour would. Another example concerns a man who has completed a 20 hour business trip and must make a connecting helicopter flight to get to his home. His reactions differ from a man who is just starting a trip of 20 hours.

Cost

On a qualitative basis we can say that passengers will tolerate environments for an inexpensive mode of transportation that they will not for a more expensive mode.

Research Techniques

Literature review.- Once the need for new criteria is established, one is faced with the task of finding ways to develop information that can be used to generate the needed criteria. Perhaps the easiest way of obtaining data for new criteria is through existing literature or customer's records of passenger complaints.

Surveys.- If existing information is inadequate new data must be obtained. This can be done through surveys of passenger and/or crew opinion. Asking crew members to provide data on passenger complaints is a more efficient way of getting data since a few crew members come in contact with a large number of passengers and can quickly provide a summary of passenger complaints. Survey forms have a low rate of return and there is no way of determining the seriousness with which they are filled out. Also people with the most complaints have probably stopped using the service. Obtaining data through interviews provides more control on the type and content of the responses but is a very time-consuming, expensive way of obtaining data.

Current helicopter transportation is very short in duration (5-15 minutes). It is, therefore, difficult to find a time when passengers are willing to devote time to the interviewer. Current method is to talk to them in the waiting room before they leave on a flight. Another problem with interviews and surveys is the difficulty of getting opinions on various aspects without suggesting answers to passengers. For example, simply asking if flicker bothers passengers may cause them to look for flicker and then comment on it when, in fact, without pointing it out they might not have noticed it.

Simulation.- Another method of obtaining information of the limits of comfort is through laboratory-type experiments. There are a great many ways of looking at individual parameters such as temperature tolerance, vibration tolerance, and noise annoyance. These methods, however, give no information on the interaction of these parameters. For example, one might expend a great deal of energy in reducing the noise level in a vehicle by an extreme amount only to find that passengers then complain about the vibration being intolerable. It might be possible to reduce the noise by only a small amount while also reducing the vibration a similar small amount. The result might be an acceptable environment for passengers. The major point to be made here is that we know practically nothing about parameter interaction.

One way of efficiently studying parameter interaction is to have some type of controllable simulator (an environmentally controlled room or a flight vehicle with modifiable environments). With a device such as a room or an aircarft, the environment could be degraded or improved along various dimensions, to determine subject reactions. The problem in such research would be, however, to obtain subjects that yield data similar to that from passengers.

Variability in Results

Motivation.- Subjects in an experiment probably do not react in the same way passengers do. Consider the differences in motivation. The subject is taking part in an interesting scientific study which has a definite start and end point. He may be getting paid for his effort as well. Passengers on the other hand are paying for the privilege of riding and could very well be forced to take the trip by the company for which they work.

Environmental exposure. - In addition to motivational differences, exposure to the environment must also be considered. For instance, how does one simulate daily exposure to a helicopter environment for a year's period? It isn't known if passengers grow tired of an environment gradually or if it annoys them immediately. The data collected to date seem to indicate that the list of annoyances increases in length with flight experience.

Another exposure aspect which is difficult to simulate with subjects involves people who travel for 20 or so hours prior to boarding your aircraft.

Sikorsky Research Activity

Motion sickness. - In the past four years a number of studies have been accomplished in various areas. The first study involved a literature review in the area of motion sickness. The study was accomplished to provide criteria for a gust alleviation program. In the study, literature on motion sickness was reviewed and the conditions under which sickness has been induced were plotted (in terms of vertical acceleration and frequency). As can be seen in figure 8, they all occurred below 1 Hertz and above about ±0.07g. The worst frequency of vibration appeared to be between 0.2 and 0.4 Hertz.

Annoyance of impulsive noise.- The second study involved a controlled laboratory experiment on the annoyance of impulse noise. This study was undertaken to investigate some observed deficiencies in PNdB calculations of helicopter annoyance. In the study, subjects were asked to compare the annoyance of impulse noise with bands of white noise. The results (shown in figure 9) showed that the PNdB method underpredicted the annoyance of impulse noise by at least 5.5 PNdB. For passenger comfort criteria, this finding may prove to be significant in vehicles whose passenger compartments experience a high degree of impulsive noise.

Seat transmissibility.- Another study involved resolving the apparent discrepancy between laboratory studies of the tolerance to vertical vibration levels and the levels in cockpits of existing aircraft. Aircraft with much higher levels than laboratory experiments would indicate are judged satisfactory. A review of the literature quickly showed that aircraft vibration is generally measured at the floor of the vehicles whereas laboratory studies generally measure vibration levels at the spine of the subject. A seat shake study measuring the difference between floor level and spine level was carried out and transmissibility data obtained. When a series of operational vehicle floor levels were attenuated to determine the vibration level at the pilot's spine, the resultant points fell remarkably close to the threshold of unpleasantness curve as reported in reference 5. These data were previously shown in figure 5. The findings of this study explain the discrepancy and permit effective use of the large numbers of laboratory studies on vibration tolerance for design of passenger seating.

Passenger survey.- At the present time Sikorsky is actively designing new passenger aircraft. Because of Sikorsky Aircraft's interest in designing vehicles with good ride comfort characteristics and because of NASA's interest in developing ride comfort criteria, Sikorsky and NASA have recently completed a survey program to determine passenger reaction to the environment of presently used commercial helicopters. A typical passenger survey form is shown in figure 10. To date three major complaints have emerged: noise, seat comfort (too crowded) and, to a lesser extent, vibration. The results of surveys such as these serve to emphasize the areas which need attention in future vehicle designs. The question that remains, however, involves passenger reactions to the environment of the new vehicle. Will some other parameter then emerge which has previously been masked by now reduced factors such as noise and vibration? Another factor to be considered is the increase in flight time. New vehicles will be cruising for periods of 45 minutes to 1.5 hours whereas existing helicopter transports have current flight times of 5 to 30 minutes.

CONCLUDING REMARKS

The NASA Langley Research Center should be commended for its forward looking view toward the development of passenger ride comfort criteria as well as its interest in defining the ride comfort factors in current vehicles. We in the helicopter industry are pleased to see NASA undertake a systems approach to ride comfort. We at Sikorsky are convinced that, with careful attention to each of the potential ride comfort criterion, the helicopter can give a top quality ride in all of its flight conditions. We are addressing our attentions to conducting the research which will enable us to obtain this goal over the next several years.

REFERENCES

1. Calcaterra, Peter C., Active Vibration Isolation for Aircraft Seating, Sound and Vibration, March, 1972.

2. Carstens, J. P. and Kresge, D., M.D., Literature Survey of Passenger Comfort Limitations of High-Speed Ground Transports, United Aircraft Corporation Research Report D-910353-1 July 26, 1965 (prepared for the Department of Commerce under Purchase Order P-7995-5).

3. Batchelor, G.H.: Determination of Vehicle Riding Properties, Four part article published in Railway Gazette; Part I -pp. 69-72, July 20; Part II -pp. 97-100, July 27; Part III -pp. 129-131, Aug. 3; Part IV -pp. 158-160 and 164, Aug 10, 1962.

4. Gabel, R., Henderson, B.O., and Reed, D.A., Pilot and Passenger Vibration Environment Sensitivity, Presented at the Symposium on Environmental Effects on VTOL Designs, November, 1970. Sponsored by the AHS, AIAA, and the University of Texas at Arlington.

5. Gillies, J.A., A Textbook of Aviation Physiology, Pergamon Press, 1965.

• NOISE
• VIBRATION
• MOTION SICKNESS

OTHER FACTORS

• SEAT CONFIGURATION
  (PITCH, SIZE, SOFTNESS, ARM RESTS, FOOT CUSHIONS, ETC)
• TEMPERATURE
• HUMIDITY
• VENTILATION
• AIR VELOCITY
• CABIN ALTITUDE
• RATE OF PRESSURE CHANGE
• WINDOW SIZE & LOCATION
• TIME IN AIR
• ROTOR BLADE FLICKER
• ANGLE OF BANK
• ANGULAR ACCELERATION
• COUPLING OF ABOVE FACTORS

Figure 1.- Ride comfort factors.

CRITERIA	S-61 LEVELS
OVERALL SPL	105
"A" WEIGHTED SPL (dBA)	93
SPEECH INT. LEVEL (SIL)	80.3
SPEECH INT. LEVEL (PSIL)	86.3
PERCEIVED NOISE LEVEL (PNdB)	93.3
NOISE CRITERIA CURVES (NCA)	85 ?

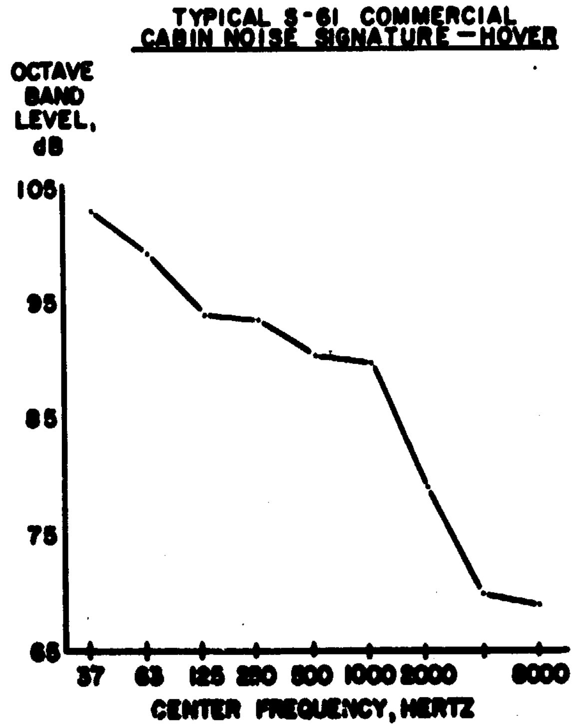


Figure 2.- Criteria for internal noise specification.

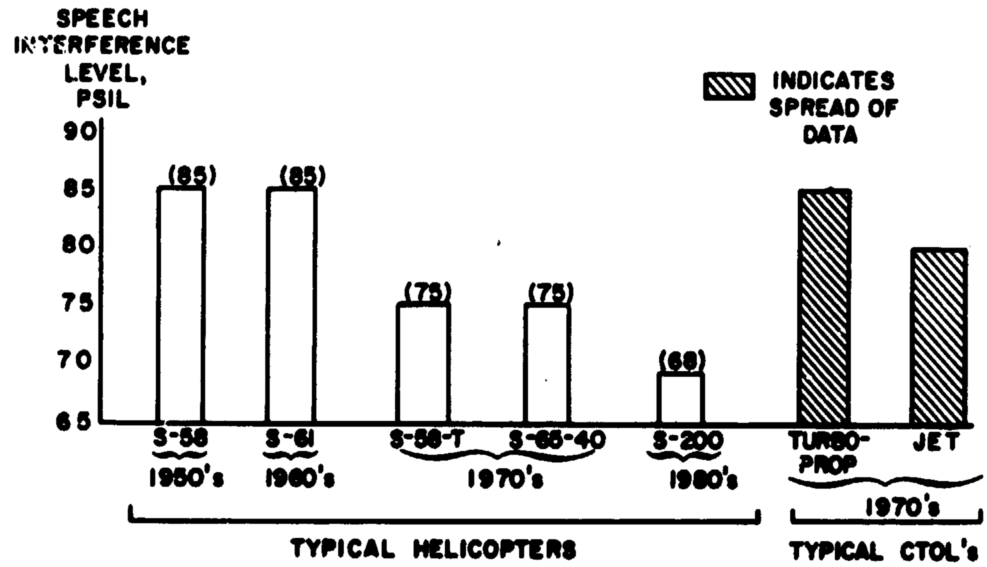


Figure 3.- Internal noise level comparison.

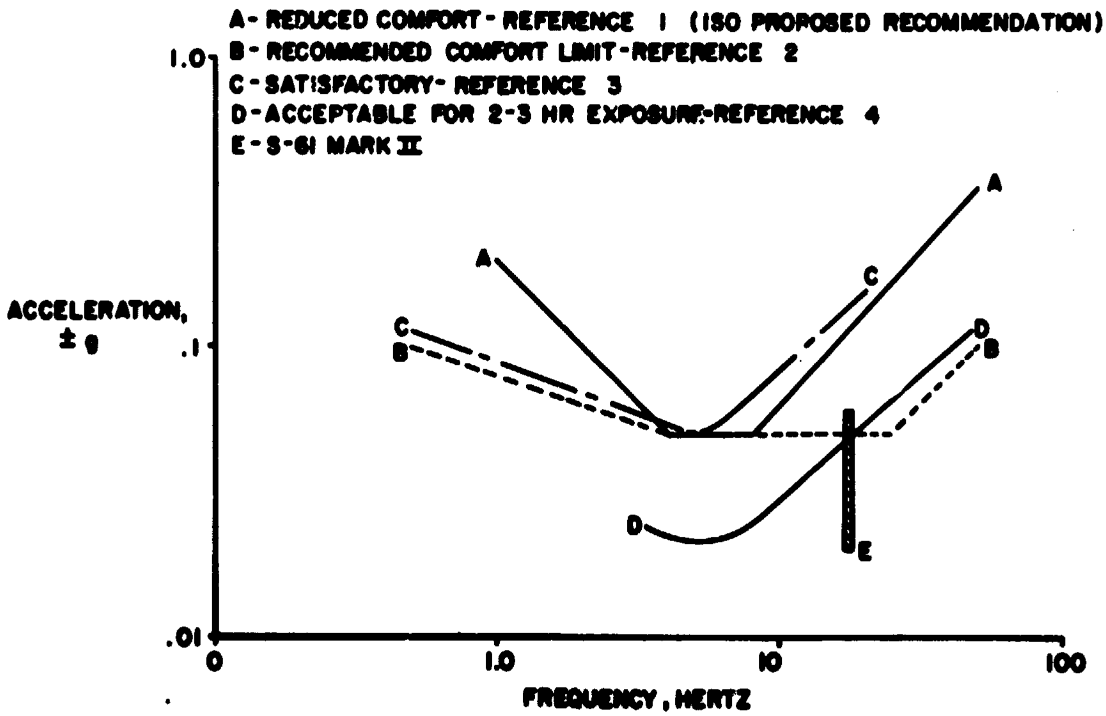


Figure 4.- Vertical vibration comfort criteria.

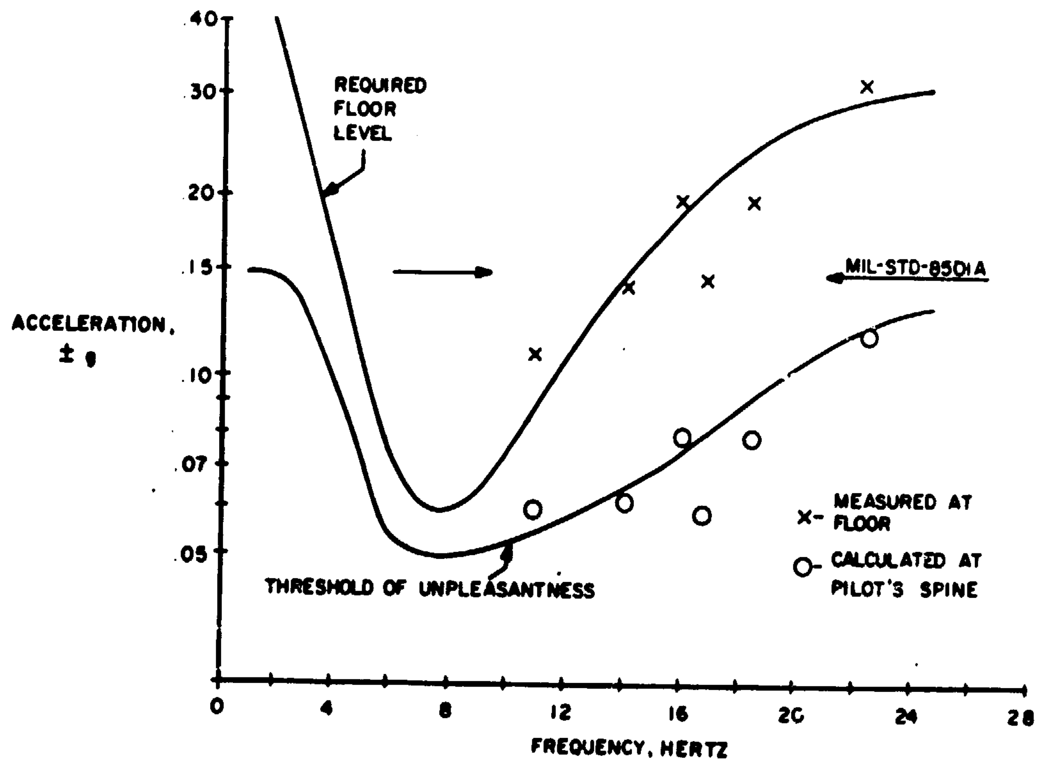


Figure 5.- Seat transmissibility.

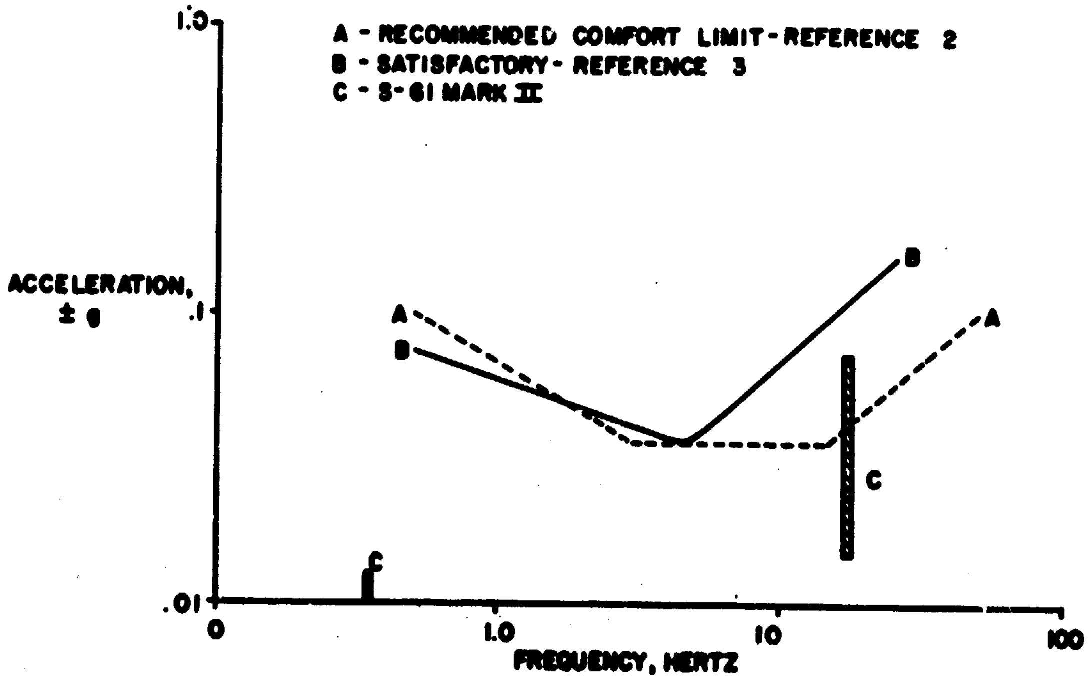


Figure 6.- Lateral vibration comfort criteria.

FACTOR	CRITERIA
• SEAT CONFIGURATION	
PITCH	32-34"
WIDTH	20"
SOFTNESS	ISOLATE FROM MAJOR FREQUENCIES
ARM RESTS, FOOT CUSHIONS	ISOLATE FROM MAJOR FREQUENCIES
• TEMPERATURE	72 - 75° F
• HUMIDITY	35 - 50 % RELATIVE HUMIDITY MAX.
• AIR VELOCITY/FLOW	18- 20 CFM FRESH AIR
• RATE OF PRESSURE CHANGE	0.1 PSI/MIN
• ANGLE OF BANK	5° FOR LOW ALTITUDE TURNS
• WINDOW SIZE	LARGE AS CONVENIENT 15 x 20"
SILL HEIGHT	LOW AS CONVENIENT 27"
• SUSTAINED FLOOR ATTITUDE IN CLIMB & DESCENT	± 5°

Figure 7.- Other comfort criteria.

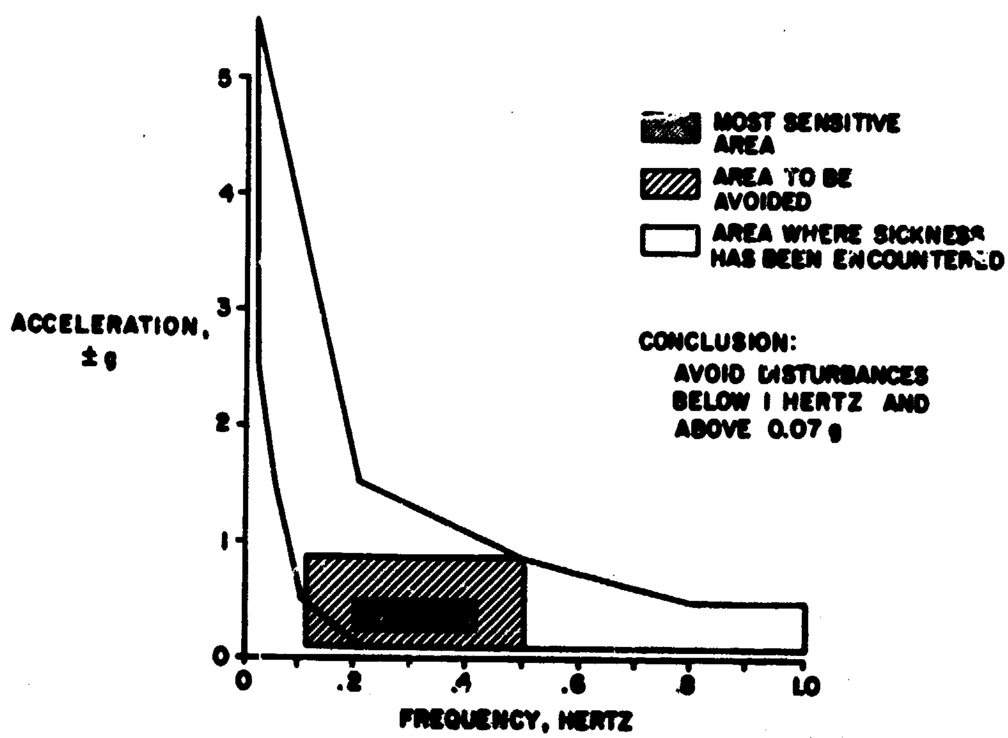


Figure 8.- Motion sickness study.

IMPULSE NOISE VS. WHITE NOISE

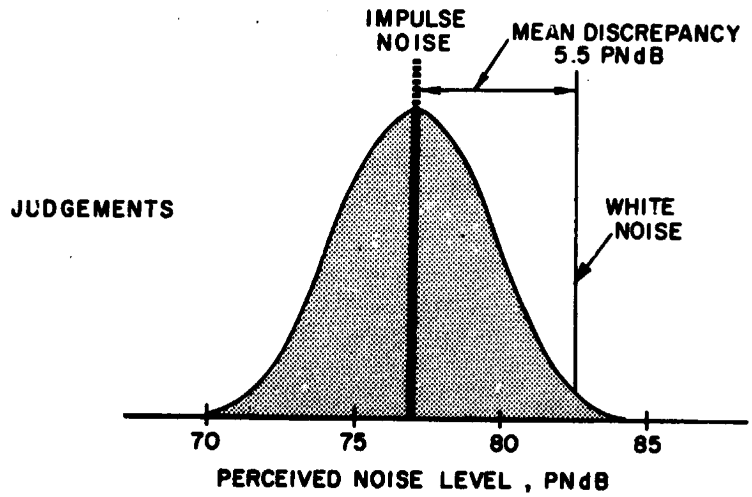


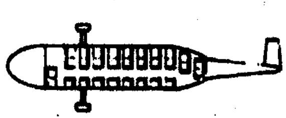
Figure 9.- Annoyance study results.

1. HOW OFTEN HAVE YOU FLOWN ABOARD A HELICOPTER?
   FIRST FLIGHT_____; LESS THAN FIVE TIMES_____; LESS THAN TEN TIMES______; MORE THAN TEN TIMES_________.

2. DO YOU USE HELICOPTERS FOR BUSINESS TRIPS______, PLEASURE TRIPS________, BOTH_______.

3. PLEASE RANK THE FOLLOWING THREE FACTORS 1st, 2nd, and 3rd IN ORDER OF THEIR IMPORTANCE TO YOU.
   GOOD VIEW______; SMOOTH RIDE______; QUIET RIDE _____.

4.a. DO YOU HAVE A FAVORITE PLACE IN WHICH TO SIT? YES______ NO_______
   WHERE? PLEASE MARK SEAT OR CIRCLE AREA ON DIAGRAM.



4.b. WHY DO YOU LIKE THIS SEAT LOCATION?
   ____
   ____
   ____
   ____

5. WHAT ASPECTS OF THIS HELICOPTER ANNOY YOU MOST?______________________
   ____
   ____
   ____

6. IF YOU WERE DESIGNING THE NEW HELICOPTER, WHAT FEATURES - IF ANY - WOULD YOU ADD?
   ____
   ____
   ____
   ____

DATE:___________
FLIGHT NO. ______

Figure 10.- Passenger survey.

EXPLORATORY FLIGHT INVESTIGATION OF RIDE QUALITY IN SIMULATED STOL ENVIRONMENT

By Edward Seckel and George E. Miller

Princeton University

N73-10016

SUMMARY

A flight test experiment is described, in which various aspects of ride qualities were explored. Situations included simulated cruise and terminal area maneuvers, as might be typical of STOL transport operations. Various motion components were studied in isolation and in many combinations.

The experiment included runs with and without turbulence, variations in airplane stability and handling qualities, and differences of pilot technique. The experimental facility was the Princeton Variable Stability Navion.

The ride quality was strongly affected by roll, yaw, and heave motions; but very little by pitching. It was strongly affected by airplane stability and handling qualities - and, in some cases, by piloting technique.

Recommendations are made for further exploration of the subject.

INTRODUCTION

A program to define quantitatively the factors that influence ride qualities and passenger acceptance of the motion associated with maneuvering and with turbulence must ultimately involve a large experiment. The whole system is large and complicated, the number of factors and influences must be considerable, and eventually, for statistical significance, various kinds of subjects must be tested in significant numbers. The experiment reported here was meant to explore widely and qualitatively various factors of possible importance, in order to identify and focus on them more effectively in a larger program.

An actual airplane in real flight was used to produce the motion to be evaluated. It was the Princeton Variable Stability Navion, with automatic controls being used in four axes to produce the desired motions. Within its limits of authority, arbitrary motions in pitch, roll, yaw, and heave could be produced. The rides that were evaluated simulated three kinds of STOL transport ride situations:

1) Cruise. Basically, a five-minute run of essentially straight-and-level flight in turbulence. Disturbances simulating turbulence were applied through the automatic controls of the airplane so as to produce motion in one axis at a time and then in all various combinations. It was expected that in this way the various components of motion could be ranked for significance, and various associated effects could be studied.

The automatic controls of the Navion were adjusted so that the airplane handling qualities and response simulated a range of STOL-type characteristics. The turbulence disturbances were random in character, of natural spectral distribution, and of sizes judged by the subjects to be "moderate" and "heavy." The details of these aspects of the experiment will not be given here, since they are, in a way, peripheral. The actual motions of the airplane were sensed and recorded, and they are the variables determining the ride quality. Details of the simulation and the turbulence signals will be included in the later full report.

At any rate, in the "cruise" runs, the pilot maintained only "loose" control so that the actual motions were essentially those of the airplane in response to the disturbances. The pilot, in pilot-vehicle-system lingo, maintained only very loose, low gain altitude and heading control.

Runs were five minutes in duration, separated by short intervals of rating and commentary by both pilot and passenger. As many as eight runs per hour were made, and flights went up to two hours in length. Ordering and conditioning effects were sometimes present, and were often checked by repetition of runs in opposite order, back-to-back comparisons, and plain subjective comments. Sometimes, when the subjects tired quickly or felt ill, flights were terminated and substantial rest periods were allowed (usually only one flight per day).

2) "s" turn maneuvers. These maneuvers were intended to relate to possible terminal area vectoring or delaying procedures. They consisted of constant bank angle and turning rate for twenty seconds; first right, then left, etc., for five-minute runs. The bank reversal was done without pausing at a wings-level attitude, using roll rate that might be encountered in a terminal-area-control situation. Runs were done with and without turbulence, and with several variations of STOL-type handling qualities. Some runs were done with variations of pilot technique.

The five-minute runs were done as many as eight per hour for as long as two hours. Again, pilot and passenger ratings and commentary were obtained between runs and recorded. Difficulties with ordering and conditioning effects were dealt with as before.

3) ILS approaches. Simulated ILS approaches were made, including a missed-approach wave-off and climbing turn at the end. Typical ILS pilot technique was applied in runs with and without turbulence, and with variations of handling qualities. These runs, in a race-track-like pattern, took about two minutes on the approach. They went at the rate of about eight to ten per hour, with ratings and commentary on the downwind leg. The details of all these runs, including maneuver patterns, turbulence simulation, etc., will be given in the later full report.

The Subjects

The subjects for the experiment were selected for expediency in perception, analysis, and reporting of their feelings and symptoms. They are both expert pilots, widely experienced in the use of rating scales - and above all, experienced in evaluating their own performance, feelings, and difficulties. They alternated between pilot and passenger in the experiment, and lent a professional level of perception and sophistication that allowed the whole affair to go at a reasonable pace with a minimum of repeats and hesitations.

Both subjects were considered to be about average in proneness to motion sickness. In the course of the experiment, they both reported sickness symptoms in relatively equivalent situations. It is assumed that whereas the two subjects might be either more or less prone to motion sickness than the general population, they are probably not "far out"; and the same motion features that affect them, probably also are significant in general.

The Rating Scale and Passenger Activity

A rating scale was devised for a numerical measure of ride quality. Shown in Figure 1, it was deliberately designed to emulate the Cooper-Harper scale for handling qualities. The long and constant success of the latter sets an excellent precedent, for one thing; and for another, the intimate familiarity and experience with it by the subjects would surely transfer to the new context.

The scale seems to have been used carefully, thoughtfully, and repeatably by the subjects. They report "zeroing in" on ratings easily and consistently; and the repeatability and scatter of rating data suggests qualities that are roughly similar to those of the Cooper-Harper parent.

The emphasis in this paper is on the passenger subject, who during each run divided his time between attempting to read with concentration from a journal, writing a few intelligible sentences, and trying to sort out the causes of his discomfort. His forward view was blocked by the pilot seated ahead of him, and although side windows were available, the evaluation was conducted with head down, concentrating on the materials in his lap. This activity was considered to be typical for a businessman passenger who would be trying to use his travel time in a profitable way.

SYMBOLS

φ bank angle, deg

p roll rate, deg/sec

r yaw rate, deg/sec

q pitch rate, deg/sec

n_z normal acceleration, g's

$(\bar{\ })$ root-mean-square value: $\bar{p}$, $\bar{r}$, etc.

In Figures 2 and 3, the symbols $\bar{p}$, $\bar{r}$, $\bar{q}$, $\overline{pr}$, $\overline{prqn_z}$, etc. are used to identify components of turbulence disturbances represented.

M, H In the figures, the abbreviations for "moderate" and "heavy" levels of turbulence disturbances

R numerical rating of ride quality - see Figure 1

RESULTS AND DISCUSSION

The various parts of the experiments are presented below. Data are analyzed, discussed, and conclusions drawn.

The "Cruise" Experiment

The "cruise" situation consisted of approximately straight-and-level flight with disturbance accelerations about various axes. The latter, simulating the effects of turbulence, were random appearing, with spectral characteristics like those of natural turbulence. The two levels were considered by the pilots to be representative of "moderate" and "heavy" turbulence, and they are labeled such in the figures. "Runs" were about five minutes long, followed by periods of smooth flight where evaluation ratings and commentary were recorded.

The passengers' evaluation ratings are presented in Figure 3, a and b, for the various kinds and combinations of disturbances. A number of interesting details can be noted:

a) Although one subject was somewhat more critical than the other, generally giving somewhat higher ratings, they usually agreed about relative effects and differences between situations and parameters. Their comments and ratings were quite consistent and repeatable, in spite of awkward ordering and conditioning effects which must have been present to some extent. Comments on these aspects were occasionally made by the subjects, who clearly estimated the effects and attempted to allow for them.

b) The range of ride quality was from roughly one to seven on the rating scale. The passenger ranges from almost perfect comfort to complete misery, being quite close to vomiting in the extreme case.

c) Figure 3, a and b, seem to indicate that the disturbances in pitch, q, are quite innocuous. By themselves, even at a heavy level which was unrealistically large, they present no problem to the subjects, who report that they experience "not unpleasant, rocking-chair motions." When added to heave (n_z) disturbances they produce hardly any additional degradation; and when they are removed from the combination of all disturbances, there is no improvement.

d) The remaining components, in roll (p), yaw (r), and heave (n_z), all appear to be significant contributors to the passengers' discomfort. Isolated, and in all the various combinations, they lead to high ratings as levels and number of components are increased.

In heave (n_z), the subjects report uneasy, annoying feelings, and a need to tense diaphragm and neck muscles because of the bobbing (vertical) accelerations. By itself, at heavy level, it leads to ratings of about 4½, where the discomfort is plain, and the head-down position for reading or writing causes stress and eventual queasiness.

The roll and yaw components are clearly, in commentary as well as ratings, responsible for considerable discomfort. The subjects speak of the ill feeling and disorientation due to head wagging and the side acceleration. Individually, the yaw and heave disturbances are somewhat worse than roll, but roll produces the largest improvement when removed from the combination of all.

With all four components of disturbances present at heavy level, the ride is very objectionable and alarming. The subjects become queasy very quickly and can probably not maintain equilibrium. The rating reaches the six to seven category, with the passenger feeling very poorly, indeed.

Analytical Fit of the Rating Function

There are various reasons against literal or quantitative interpretation of the ratings of Figure 3. Perhaps first is the obvious unevenness, or non-linearity, of the subjective rating scale. An increment of one unit of rating has a greatly different meaning at different positions along the scale, particularly at the poor rating end. Second is the fact that all the various combinations of disturbances shown in the Figure 3 exhibit some of all the components of motion. A pure yaw disturbance (r), for example, produces mostly yawing motion, but smaller residual ones for the other components as well. The actual motions of the aircraft, however, were continuously measured in the evaluation runs, and they have been analyzed and reduced to root-mean-square values. Various ways have been tried to construct an analytical fit to the numerical rating as a function of the rms values of the four motion components: $\overline{p}$, $\overline{r}$, $\overline{q}$, $\overline{n_z}$. The most successful of these is

$$\frac{R-1}{10-R} = .018\,\overline{r}^2 + .0024\,\overline{p}^2 + 8.0\,\overline{n_z}$$

The left-hand side has the feature of correct asymptotic behavior; that is, for zero motion, $R \equiv 1$; and for infinite motion, $R \equiv 10$. The right-hand side, entirely empirical, simply fits the data very well. The correlation between the formula and the actual ratings is shown in Figure 4b. The formula corresponds to the map of Figure 4a for the rating function of the motion.

First of all, pitch motion ($\overline{q}$) is conspicuous by its absence. This confirms the unimportance of $\overline{q}$ noted in the previous section. This has been consistent in all our attempts to fit the data to a formula, some even producing negative coefficients of $\overline{q}$. Taking $R = 3.5$ as a boundary of acceptability, the following conditions are necessary (but not sufficient) for passenger satisfaction:

roll,	$\overline{p}$	< 13 deg/sec
yaw,	$\overline{r}$	< 5 deg/sec
heave,	$\overline{n_z}$	$< .05$ "g"

The bounds cited are for individual, isolated components. In combinations, the allowable values would be smaller, as the figure indicates.

The "Turns" Maneuver and Handling Qualities

A second part of the experiment involved sets of "s" turns, in which a turn of 20 degrees bank was maintained for 20 seconds, then reversed to the opposite 20^{o} bank and maintained for 20 seconds, and so on. This maneuver was supposed to represent a possible terminal area vectoring or delaying action. Most of the runs of this kind were done without turbulence, in order to see the separate effects of the maneuver.

The turns maneuver was performed without rudder-aileron coordination, at a rate that might be considered to be near the upper limit of commercial practice, with a maximum roll rate of about 20 deg/sec from one bank angle to the other. The heading changes in the turn were about 90^{o}. They were done with a wide range of airplane stability and handling-qualities parameters. They range from a basic STOL type with a poor Dutch-roll mode and low roll-damping to a near-optimum, artifically stabilized characteristic.

The effects of the changes in stability parameters on the passenger ride rating are shown in Figure 5a, b, c. It is quickly seen that Dutch roll frequency (ω_d), damping (ζ_d), and roll-mode time constant (τ_{rm}) are important. For the good airplane, the passenger rating is only slightly above two, whereas for the bad airplane it is almost a five. For the former, the rolls are smooth with little sideslip; whereas for the latter, they are rough and sloppy, with sideslipping, overshooting bank angle, overcontrolling. These anomalies in the motion were apparently quite noticeable to the passenger subjects. Their comments and ratings agreed that in the poor cases, the motions were more noticeable, disconcerting, and disorienting on account of the poorer controlling.

A few of the turn maneuvers were done with moderate simulated turbulence for both good and intermediate handling-quality characteristics. The superposition of turbulence on the turns maneuvers produced a large degradation in ride quality and a corresponding large increase in subject rating. As shown in the summary Figure 2, for the good airplane the rating went from slightly over two to between four and five with the addition of turbulence; and for the intermediate airplane it went from about three to almost six. The subjects speak of the annoyance and jostling due to turbulence, and the sudden disorientation with a sweeping, catalysing effect of the rapid roll in the maneuver. It all adds up to a very disagreeable situation - one which the subjects were not anxious to repeat.

The summary Figure 2 also shows that the airplane stability characteristics were a factor in the "cruise" situation. This had little to do with handling qualities, since there the pilot was exercising, at most, "loose" control, with the airplane responding "open-loop" to the turbulence. The less stable airplane, however, responds more to the disturbances and upsets the passenger more, as would be expected from the "cruise" results previously described.

The "Rolls" Maneuver

Because of the seeming significance of the "turns" of the previous section, and prompted by some commentary of the subjects, it was decided to vary the abruptness in the maneuver of the roll from bank to opposite bank. At the same time the bank angle was increased from 20° to 30°. The roll time history was thus changed from the one at the top of Figure 6a to the others of the figure. These variations were done with the "good" airplane, with results shown in Figure 6b.

All the data points of Figure 6b represent turns at the same bank angle (30°) and the same yaw (turning) rate. Clearly, neither bank angle nor yaw rate, per se, had much to do with the ride quality of the maneuver. The turns involving the lower roll rates were quite innocuous to the subjects, who rated them about <u>two</u>, and reported that they were detectable, but not much above "threshold." The turn reversals became increasingly upsetting as the abruptness was increased by increasing roll rate, until a passenger rating of nearly <u>five</u> was reached for roll rates about 35 deg/sec. Some of the commentary suggests that the rating might level off or even decrease for yet higher roll rates because of decreasing duration of exposure (keeping constant change of bank angle). The data seem to confirm the idea and to show that there may be a "worst" way to do the "s" turn maneuver!

A few of these bank reversals were done in which the steady, 20 sec period of turning was eliminated between reversals of bank angle. The solid points, labeled "continuous rolls" in the figure, show no significant change of rating. With the other data, this suggests that the excursion of the roll rate history is the feature of significance. This is still further confirmed by the tagged points, showing that turbulence disturbances in yaw (only) had no effect.

Of course this experiment, and the figure, do not identify clearly what features of the roll motion are responsible for the rating variations. The possible significance of roll-rate magnitude, roll acceleration, duration of exposure, lateral acceleration, station in the aircraft - remain to be explored with special experiments.

The ILS and Missed Approach

A number of ILS approaches were simulated, with a missed approach wave-off and climbing turn at the end. The purpose was to see whether the maneuvers involved in acquiring the glide slope and localizer, keeping on the beams, and finally in the wave-off and turn, would be uncomfortable or disorienting for the passenger.

The general result was negative, as shown in the summary Figure 2. Without turbulence, both good and intermediate airplanes were rated between one and two by the passengers. The motions were barely noticeable, and even the wave-off and turn were in no way troublesome. With moderate turbulence, ratings degraded to the three level, but this was due to the turbulence disturbances, not the maneuvers. The subjects felt that the situation was equivalent to the "cruise" experiment, where the ride and the rating were functions of the kind and size of turbulence-induced motions.

The ILS (with moderate turbulence) runs were rated somewhat better than the "cruise" (with moderate turbulence) runs. The turbulence disturbances were the same in both cases. Commentary of the subjects reveals two factors for the difference. First, the duration of exposure was quite different, with five-minute runs for "cruise" and less than two minutes for an ILS run. Second, the piloting technique was different, which resulted in smaller airplane motion for the same turbulence, for the ILS situation. The differences of rating can be seen in the summary figure, with similar results for both airplane types.

Effects of Piloting Technique

It is amply evident that piloting technique is an important factor for the ride quality in any given situation. In this experiment, no attempt was made to define pilot technique quantitatively, but some variations of it were made and the subjects (who were pilots) frequently commented about the effects.

In the "cruise" experiment, pilot technique was "loose" with hardly any control being applied. The motion resulting from turbulence was almost the pure airplane response. But in some special runs, the pilot was asked to do his utmost to suppress the airplane response to turbulence. Surprisingly, this produced a consistent degradation of one-half to one rating unit. In back-to-back comparisons, it was clear and conclusive to the subjects that very tight control technique produced a worse ride. Comments suggested that the tight control produced unpleasant accelerations which over-rode, in effect, the reduction of displacements.

In the "turns" and "rolls" experiment, the variations of roll rate represented differences of pilot technique in the maneuver. The effects, as explained previously, were profound, with some indication of a maximum, or "worst," technique for performing the bank reversals.

In the ILS experiment, it was noted that the airplane motions were less disconcerting, for the same turbulence, than for the "cruise" situation. The difference was clearly one of pilot technique, which both pilots and passengers thought was intermediate between the "loose" and "tight" cases for "cruise." There is clearly an optimum technique, neither too loose nor too tight. Not that this is surprising - a little reflection about the pilot-vehicle-passenger system would suggest that it must be so! But the experiment confirms it, and suggests that the matter should be explored more fully and more quantitatively.

Ratings by the Pilots

Throughout the experiments described above, ratings were given by the pilots as well as the passengers. The two subjects, in fact, served alternately as pilots and passengers by simply exchanging places and duties. In this short presentation, we have not attempted to give both sets of results. The findings are similar, with some interesting differences, but no great surprises. The complete results will be presented in a full project report in the near future.

The Need for Further Exploratory Experiments

The experiments and results presented in this paper are distinctly exploratory in nature. A number of important factors have been only loosely controlled, and only two rather specialized subjects have been tested. Some important effects have been identified, and some new questions have been raised. The most interesting and important of these are the following:

a) In the "rolls" maneuver, what are the features of the roll rate history that define the ride quality? The significance of the variables φ, p, $\dot{p}$ - their excursions, durations, spectra, size - are essentially unexplored. Special experiments need to be devised to clarify the matter, which may be important in choosing the best kinds of maneuvers for certain terminal area procedures and for optimizing pilot technique.

b) The parts played in ride quality by pitching motion and by lateral acceleration need to be explored in some detail. The small effect of pitch rate, q, may relate in some special way to correlation with normal acceleration, n_z, and passenger position in the airplane. There is even some reason to suggest that pitch rate, q, may relieve some of the effect of acceleration, n_z, if they are properly correlated; and hence, there may be a preferred set of stability derivatives and a best position in the airplane.

Similarly, the part played by lateral acceleration may be very significant and yet is largely unexplored. Subject commentary suggests that lateral head motions are a problem, and therefore passenger position must be important, and should be explored in this context as well.

It therefore seems probable that both fore-and-aft as well as vertical displacement from the CG may be important. A number of particular stability derivatives of the airplane will also prominently affect the relations between these motion variables in turbulence, and they should be accounted for. Special experiments need to be devised to explore this matter on a broad basis.

c) The pilot-vehicle-passenger system needs to be looked at in a rational and broad way. The separate parts played by the features of turbulence, the airplane's response, pilot technique, and passenger sensitivity all need to be explored further to clarify their interactions. A theoretical approach is necessary for orientation in the problem and for unification of results, but the results themselves must ultimately come from experiments. The large experiment with statistical validity has yet to be designed, and further exploration is needed to define crucial areas and parameters. The results of this paper suggest, in particular, that more consideration must be given to the effects of pilot technique and the detailed sensitivities of human subjects.

CONCLUSIONS AND RECOMMENDATIONS

Results of exploratory flight tests, to identify factors affecting ride quality, can be summarised as follows.

1) In the simulated cruise situation, turbulence-induced discomfort ranged - in the experiment - from practically nothing, up to just short of nausea, depending on the size and type of airplane motions. Pitch rate was found to be innocuous; but roll rate, yaw rate, and normal acceleration were important contributors to passenger discomfort.

2) Passengers were disoriented and uncomfortable in "s"-turn maneuvers depending on the pilot technique (roll rate history), handling qualities, and dynamic response characteristics of the airplane. Abrupt roll

reversal and large roll rate were unfavorable piloting technique. In the turns, yaw rate did not appear to be a factor. Ride quality was degraded for low Dutch-roll damping and frequency, and for low roll-damping.

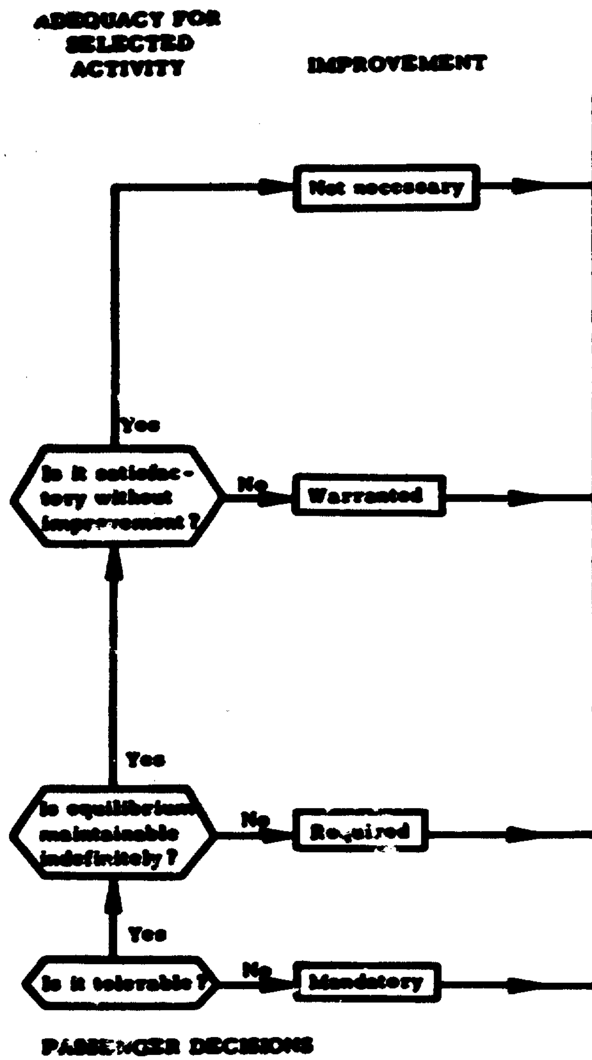
3) The motions involved in typical ILS approaches, including the wave-off and climbing turn following a missed approach, were relatively innocuous. In turbulence, the typical ILS control technique led to better ride quality than either the very loose or the very tight technique explored in connection with the "cruise" situation.

4) Further exploratory study and experiments, suggested by the results, are

   a) to identify the features of roll motion of significance to ride quality;

   b) to explore certain stability derivatives and passenger position in the airplane, with respect to the effects of pitch rate and lateral acceleration on ride quality; and

   c) to explore on a broad basis the pilot-vehicle-passenger system, emphasizing especially matters of pilot technique and the particular sensitivities of human subjects.



DEFICIENCIES	DEMANDS ON THE PASSENGER AND HIS COMFORT STATE	PASSENGER RATING
None	No significant unpleasant effects.	1
Negligible	Airplane motion noticeable but not an appreciable factor in comfort or activity.	2
Mild	Mildly unpleasant motion, but with minimal concentration, passenger can work mental problems, compose, read, and write.	3
Minor but annoying	With moderate concentration, passenger can do problems, read and think constructively, ignoring discomfort and mild symptoms like stomach awareness or burping. Writing may be difficult.	4
Moderately objectionable	Passenger definitely feels uncomfortable. May begin to feel queasy or dizzy, perspire lightly, loosen tie. Requires considerable concentration for reading.	5
Very objectionable	Passenger would rather not concentrate on problems. Reading or writing requires maximum determination. Barely able to maintain equilibrium indefinitely, due to ill feeling.	6
Major	Major discomfort. Passenger pale, simply rests in best position, unable to solve problems. Feels nauseous, dizzy, perspires; would eventually vomit.	7
Major	Passenger incapacitated by perspiration, dizziness or vomiting after about 15 minutes.	8
Major	Marginally tolerable for a short time at best. Passenger vomits after a few minutes exposure.	9
Major	Passenger dizzy, nauseous, vomits almost immediately.	10

Figure 1.- Ride qualities rating scale for passengers.

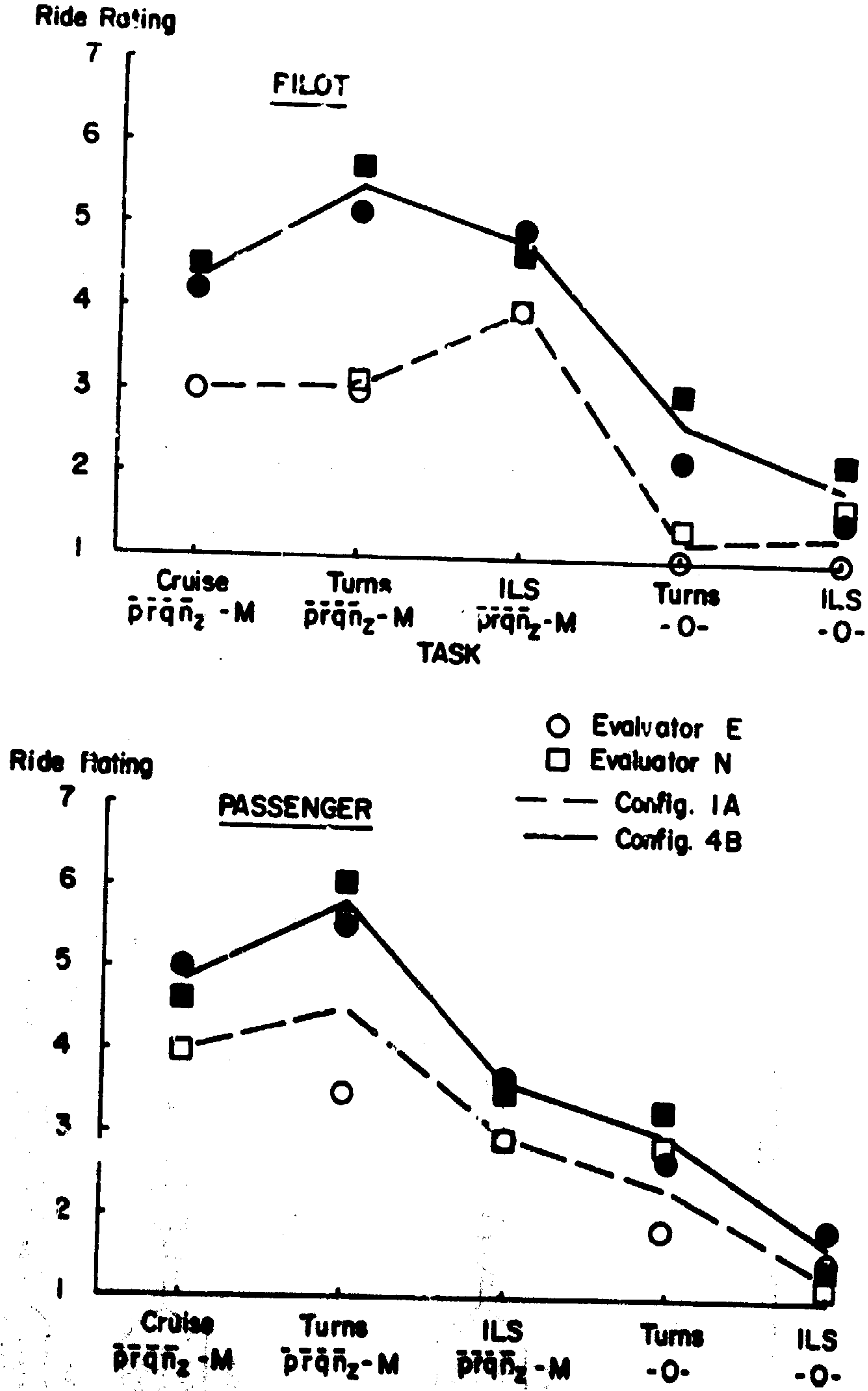
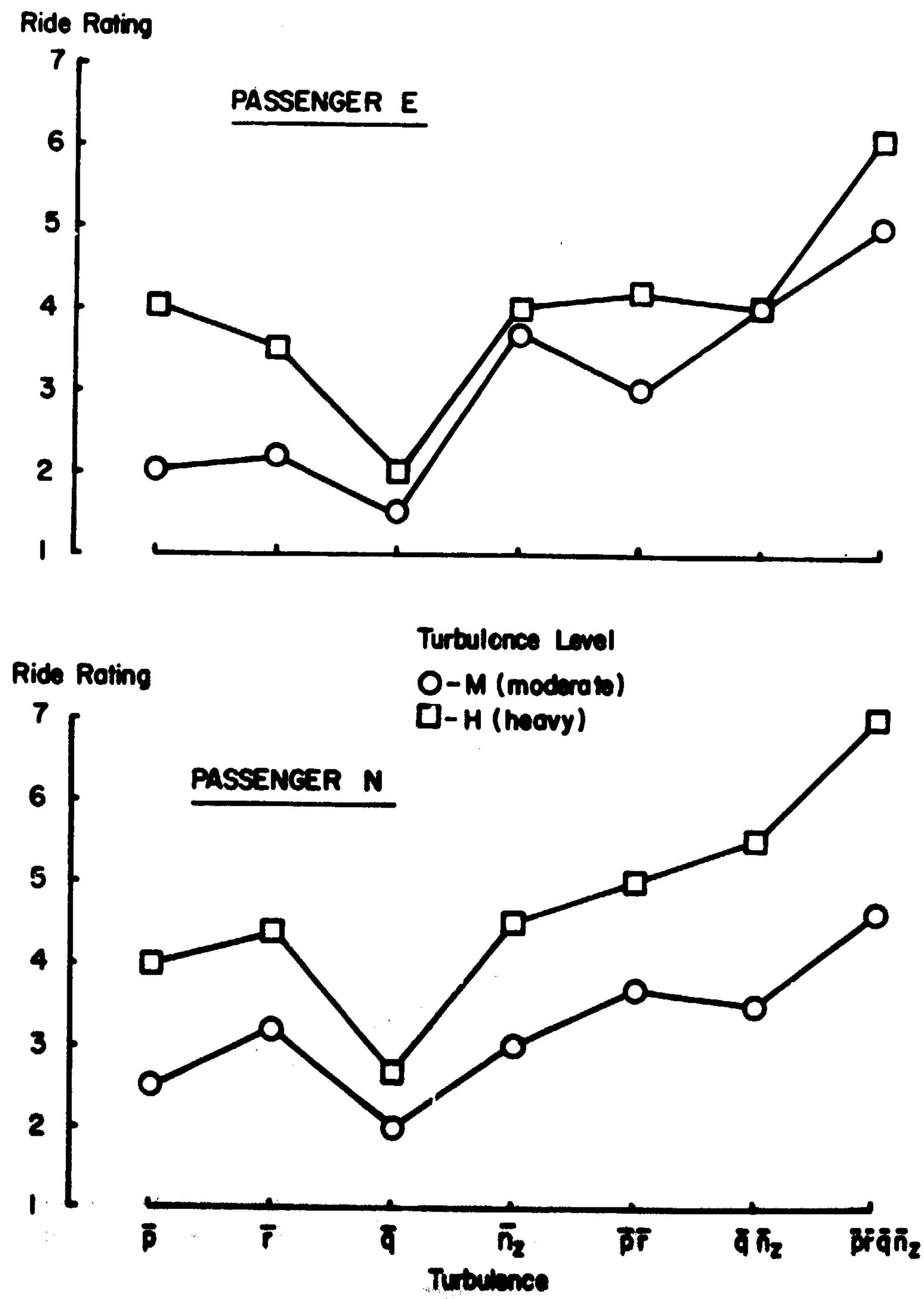
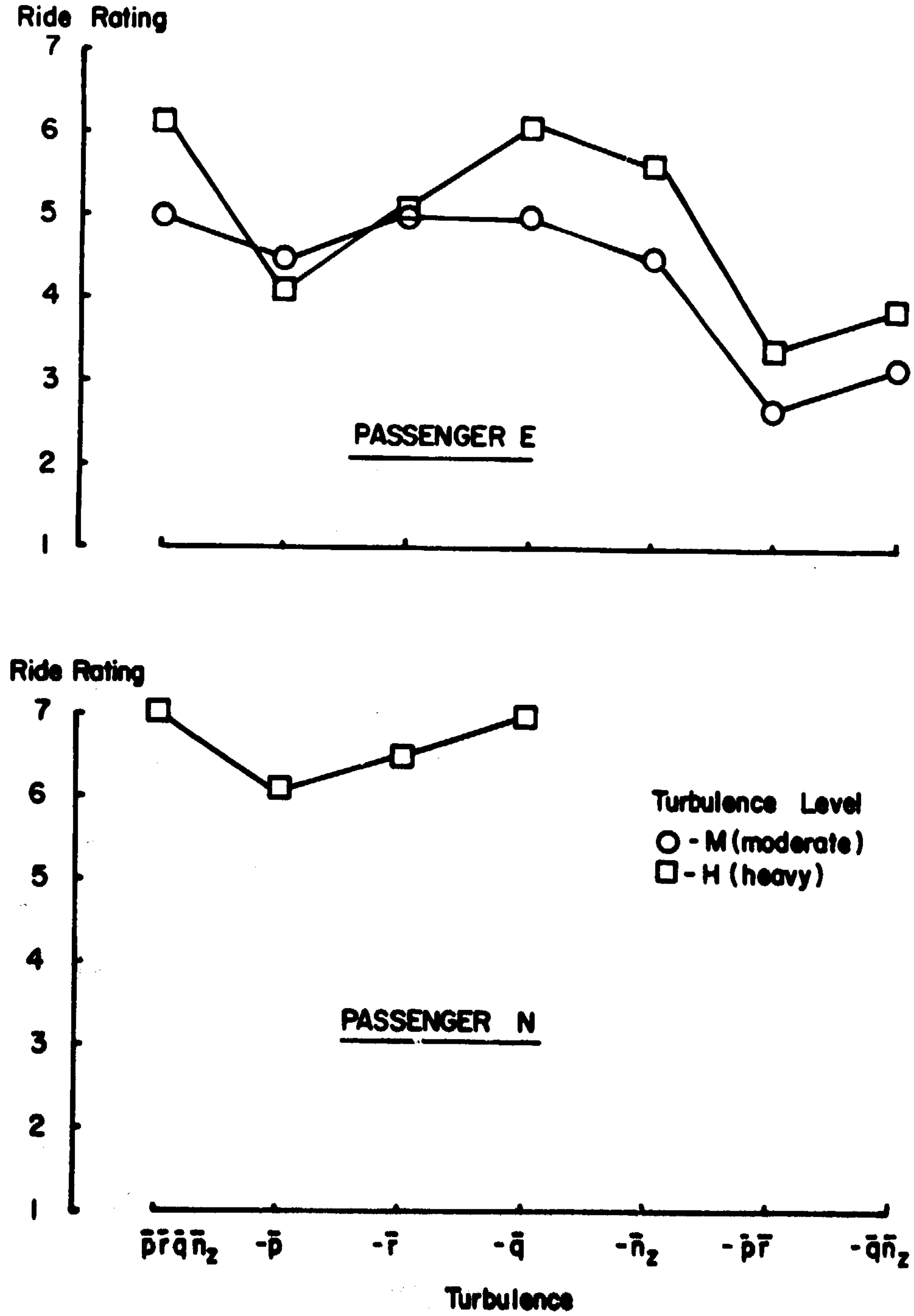


Figure 2.- Ride ratings for the various experiments, configurations, and subjects.



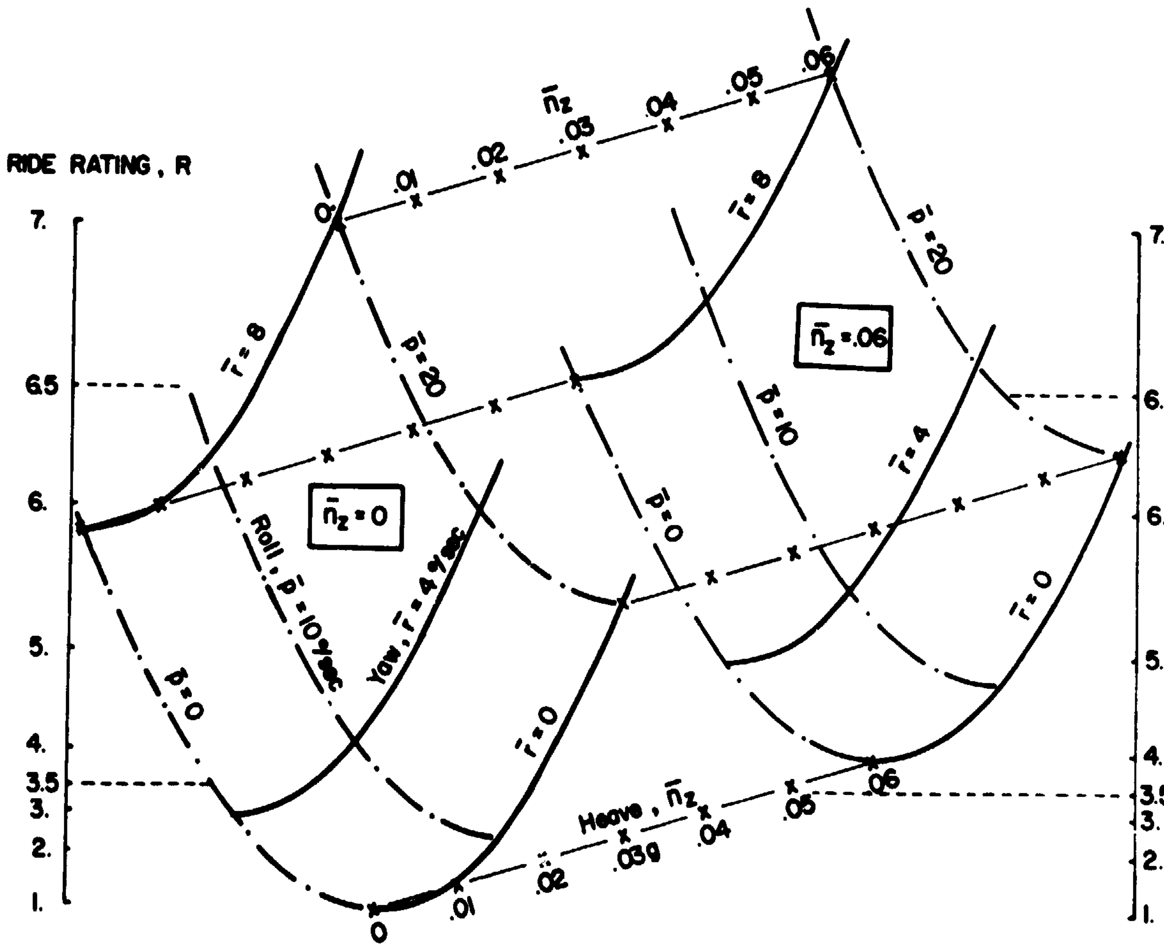
(a) Motion components added.

Figure 3.- Passenger ratings for the cruise experiment.



(b) Motion components removed.

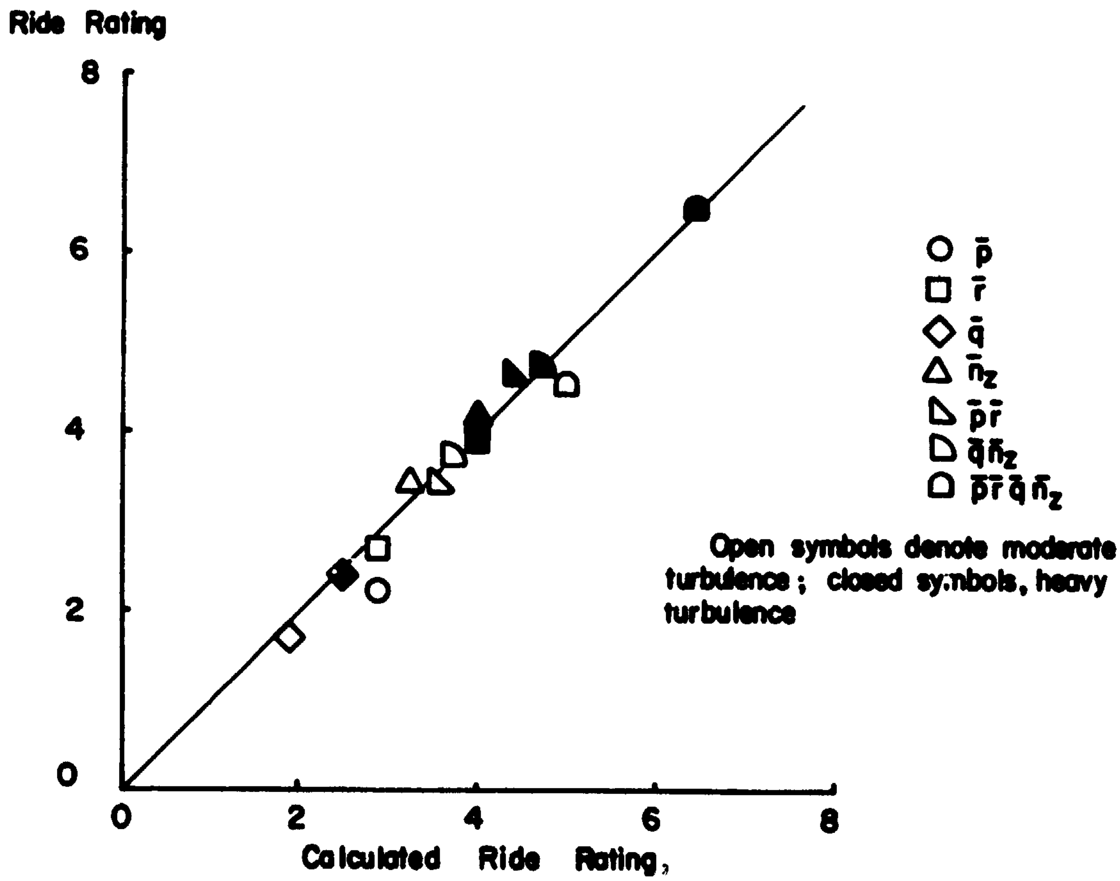
Figure 3.- Concluded.



$$\frac{R-1}{10-R} = .018\,\bar{r}^2 + .0024\,\bar{p}^2 + 8.0\,\bar{n}_z$$

(a) Carpet graph.

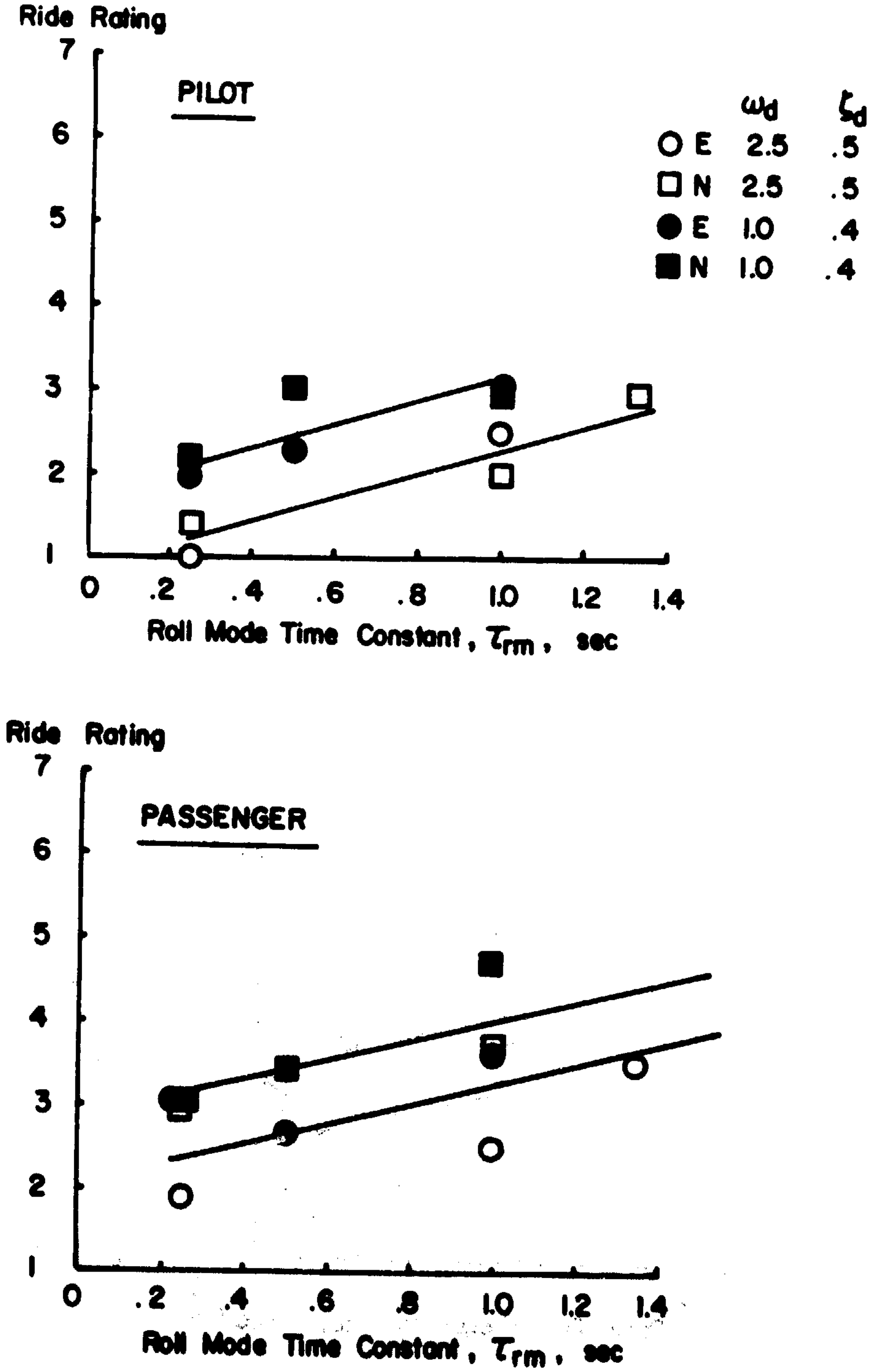
Figure 4.- Least-squares fit of ride rating for the cruise experiment.



$$\frac{R-1}{10-R} = .018\ \bar{r}^2 + .0024\ \bar{p}^2 + 8.0\ \bar{n}_z$$

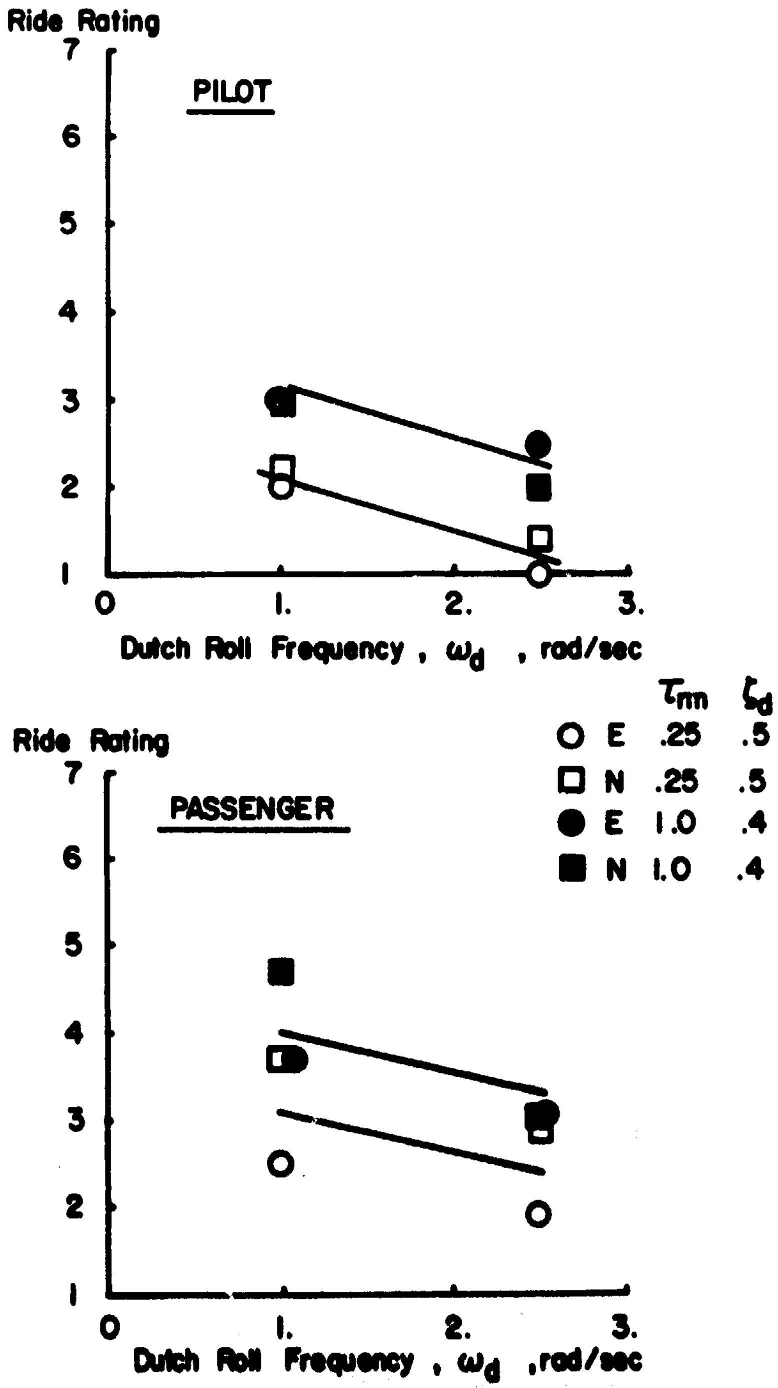
(b) Correlation with experimental ratings.

Figure 4.- Concluded.



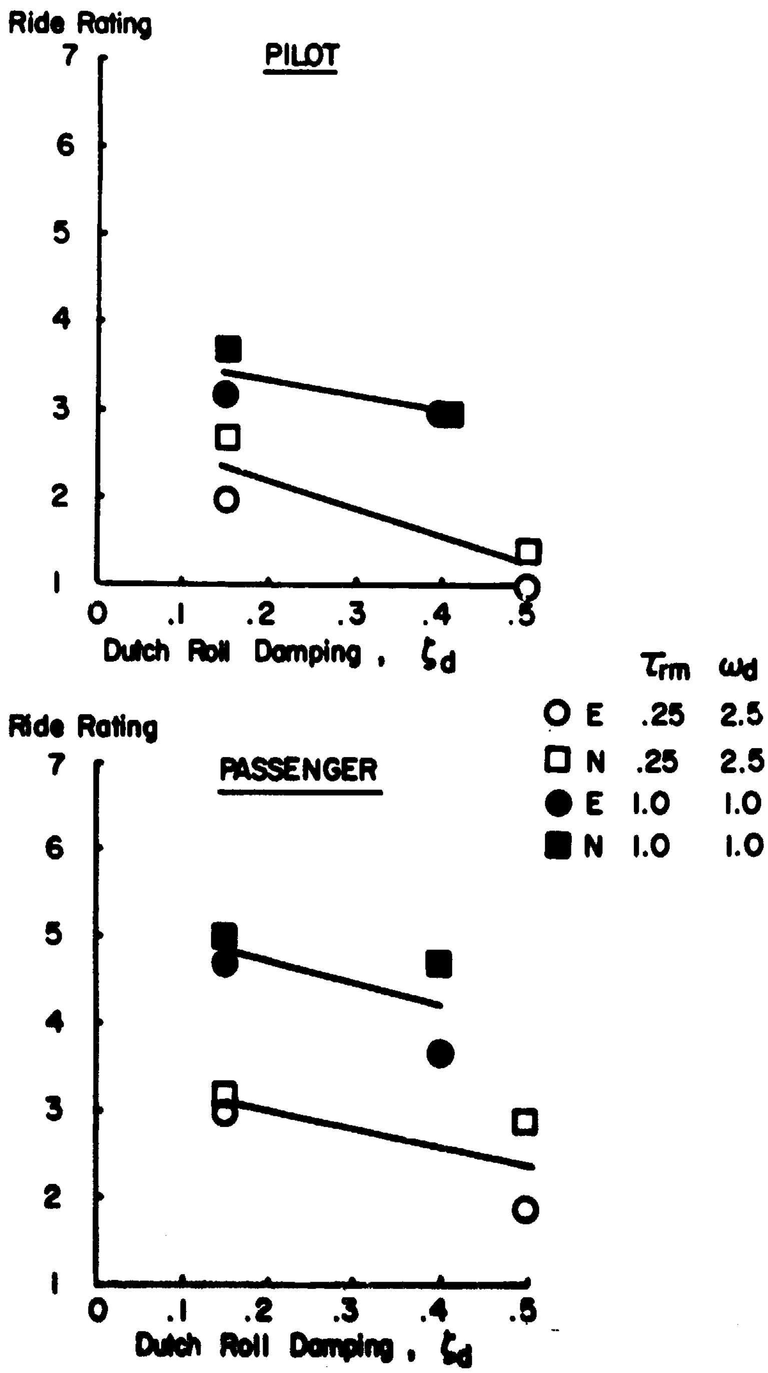
(a) Roll mode time constant.

Figure 5.- Effect of airplane stability and handling qualities in turns maneuver.



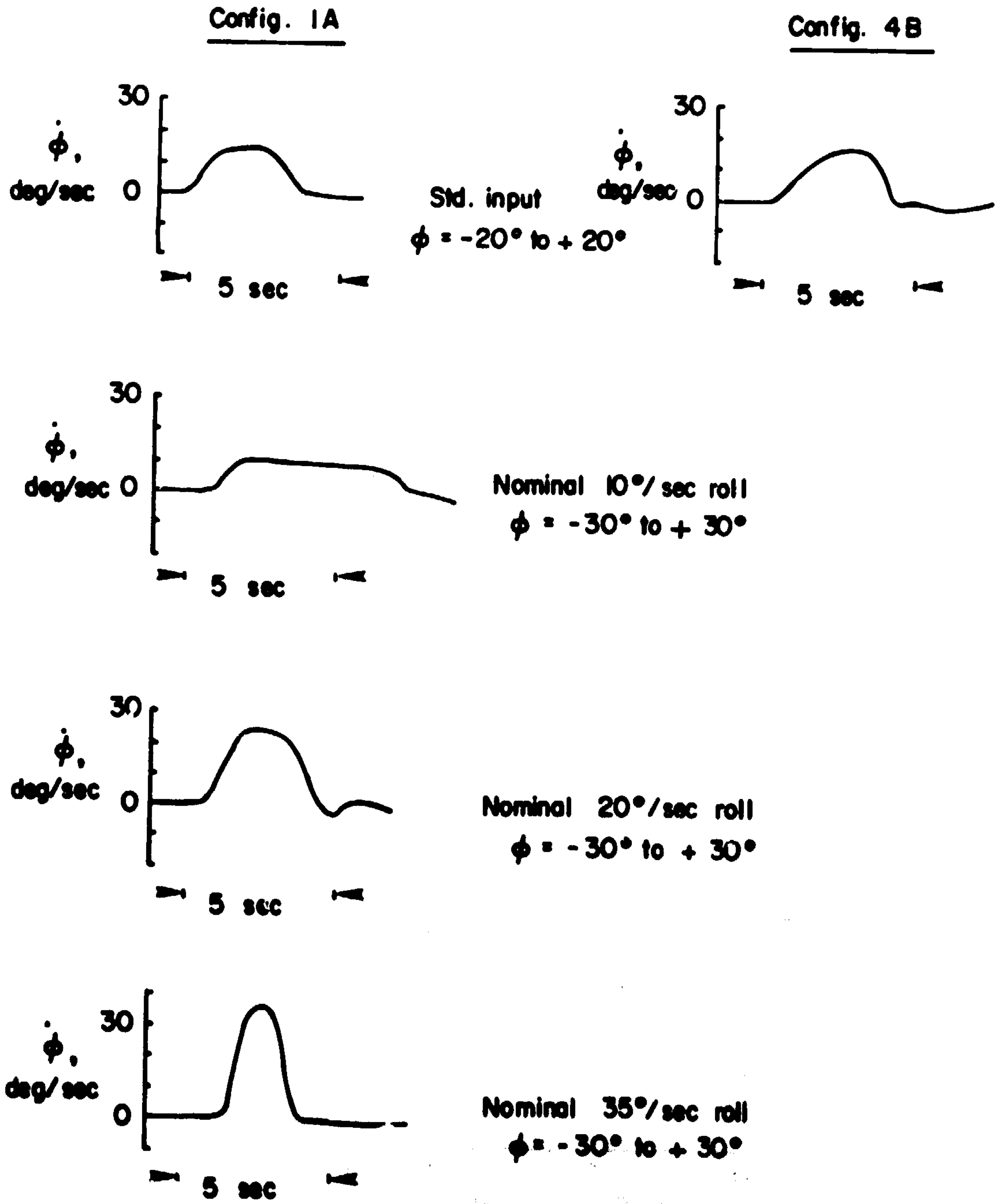
(b) Dutch roll frequency.

Figure 5.- Continued.



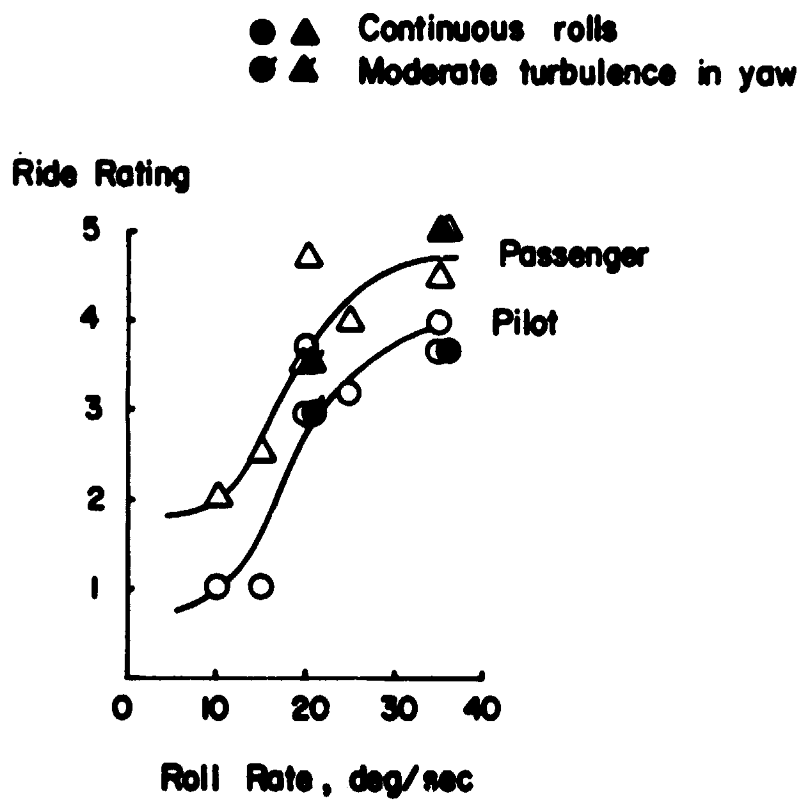
(c) Dutch roll damping.

Figure 5.- Concluded.



(a) Roll rate time histories.

Figure 6.- Effects of pilot technique in rolls maneuver.



(b) Passenger ratings.

Figure 6.- Concluded.

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TESTS AND ANALYSES APPLICABLE TO PASSENGER RIDE QUALITY OF LARGE TRANSPORT AIRCRAFT

By Richard B. Holloway and Stanley H. Brumaghim
The Boeing Company, Wichita Division

N73-10017

SUMMARY

A test program was undertaken to determine airline passenger reaction to vibration environments that might be encountered in a supersonic transport or other large commercial jet aircraft. The principal problem addressed was to determine accelerations of vertical and lateral vibration that people find objectionable. Further questions experimentally posed were: What is the relationship between human reactions to vertical and lateral vibration, to single- and combined-frequency vibration, and to single- and combined-axis vibration? Interest was confined to reactions to vibration in the frequency range of 0.20 to 7.0 Hz, a range typical of the vibration environment of a large airplane.

Results indicated an increasing sensitivity to vertical vibration as frequency was increased from 1.0 to 7.0 Hz. Subjects were found most sensitive to lateral vibration in the 1.0 to 3.0 Hz range. There was a nearly linear decrease in sensitivity as frequency of lateral vibration was increased from 3.0 to 7.0 Hz.

In addition, testing was conducted to determine perceptible accelerations for low-frequency cyclic oscillations representative of those associated with a "dead zone" in an airplane control system. It was concluded that cyclic incremental accelerations should not exceed 0.015g (zero to peak) in the vertical axis and 0.010g (zero to peak) in the lateral axis.

INTRODUCTION

Human vibration research, as related to both comfort of aircraft passengers and the ability of aircrew members to perform their duties, has been a subject of interest and concern almost since the beginning of flight. At Boeing-Wichita alone, many independent laboratory studies were conducted in the period 1957-67, including several under U.S. Air Force or Office of Naval Research sponsorship (fig. 1). Results of these studies are summarized in reference 1.

This paper describes briefly the results of passenger ride-quality studies conducted by Boeing in 1968-1969. Fifteen studies were conducted to test human reactions to single-axis, narrow band filtered white noise vibrations with center frequencies ranging from 0.10 to 7.0 Hz; to single-axis, combined-frequency vibrations; to combined-axis, combined-frequency vibrations; and to simulated commercial airplane rides. This paper will be limited to discussion of human response to vibration, and will not dwell on the ride qualities of specific aircraft.

TEST PLAN AND FACILITIES

Two major considerations guided development and conduct of the test program. To take advantage of previous Boeing-Wichita human vibration testing (reported in ref. 1), passenger ride-quality tests were scheduled so that new information obtained in any test could be added logically to existing data. This sequence led to an increasingly complex picture of passenger reactions to vibration. Tests were designed to answer several related questions: What is the relationship between human reactions to vertical and lateral vibration, to single- and combined-frequency vibration, and to single- and combined-axis vibration? Within the time constraints of the program, these relationships could be most effectively studied by using a small, and constant, subject sample.

Three test facilities were used during the program. The two Wichita human vibration facilities (vertical axis, fig. 2, and lateral axis, fig. 3) are each actuated by electrohydraulic rams. A standard airline passenger seat was located in the approximate center of each facility test room, resulting in movement of the vibration platforms relative to the room walls. The sole source of lighting in each facility was a standard overhead passenger reading lamp which was secured to the vibration platform. Room interiors were a dark matte green which, in addition to the lighting arrangement, helped to prevent subjects from obtaining visual cues from stationary room details. Test compartment temperature and humidity were controlled to provide a comfortable environment.

The experimenter and medical monitor viewed the subject through one-way vision windows and used an intercom for two-way voice communication with the subject and facility operator. A passenger seat back with pulldown tray was mounted on the vibration platform of the vertical-vibration facility. The seat back provided a support for passenger activity tests.

The Northrop Norair large-amplitude simulator, figure 4, also electrohydraulically actuated, was used for tests involving frequencies below 1 Hz and for tests requiring combined-axis vibration. A passenger seat was installed in a passenger compartment at the end of the simulator's 20-foot beam (fig. 5). Overhead lighting was provided by a standard passenger reading lamp mounted on the compartment ceiling. The experimenter had two-way voice communication with the subject and the medical monitor listened to subject comments over a one-way intercom.

Subjects were male company employees, from 24 to 39 years of age. Each of the 12 volunteers had commercial airplane flight experience, and 5 had military flight experience as either pilot or navigator. Each subject passed an extensive medical examination before being admitted to the vibration program. Brief medical tests were conducted for each subject prior and subsequent to each test session. Each vibration session was monitored by a medical doctor or a male nurse.

The tests reported here had several aspects in common. Subjects were seated in an airline passenger seat (including armrests) and restrained by a seat belt which each adjusted for personal comfort. The seat back was maintained in the forward position. No sitting posture was prescribed except that both feet were to be placed on the floor. Subjects wore street clothing during the tests except that ties and jackets were removed.

During tests, vibration on each trial was started at 0.015 RMSg acceleration and increased every 30 seconds in steps of 0.015 RMSg until the subject rated "annoying" and "objectionable" levels of vibration. The two levels were defined as:

Annoying - the point at which the vibration first begins to disturb you.

Objectionable - a level of vibration that would adversely affect you as an airline passenger, but not to the extent you would never fly on the airplane again. On future flights you would try to avoid flying on this airplane, however.

In this paper, only the "objectionable" levels of acceleration are shown.

Emphasis was placed on the need to assume the role of an airline passenger while making ratings. Instructions were read to each subject immediately before each test session.

Following a subject's "objectionable" rating, vibration was stopped and the next test condition was selected according to prearranged schedules. Appropriate counterbalancing randomization procedures were followed to preclude bias from potential extraneous influences and sequence effects. Vibration exposure on each trial averaged 3 to 5 minutes; vibration sessions lasted from 30 minutes to 1 hour per subject.

Tests involved single-frequency, single-axis vibration (vertical or lateral); combined-frequency, single-axis vibration (vertical or lateral); and combined-frequency, combined-axis vibration (vertical and lateral). Testing was restricted to the vertical and lateral axes and to frequencies of vibration from 0.20 to 7.0 Hz.

Vibration inputs were generated by recording narrow band filtered white noise on magnetic tapes. Output accelerations were recorded at the subject's passenger seat and power spectral density analyses were conducted to confirm input vibration conditions.

TEST RESULTS AND DISCUSSION

Single-Frequency Vertical-Vibration Tests

Objectionable accelerations of vertical vibration obtained in the tests are compared in figure 6. Vibration frequencies common to the tests were 1.5, 4, and 7 Hz. Subjects judged vertical vibration at 4 and 7 Hz to reach objectionable levels at comparable accelerations. Subjects accepted approximately

50 percent more acceleration at 1.5 Hz than at 4 or 7 Hz before calling it objectionable.

Subject comments indicated that the primary cause for objection to vertical vibration was the resulting vibration in abdominal, stomach, chest, and spinal areas. Reports of potential motion sickness, although infrequent, were most frequent during vertical vibration at 0.45 Hz.

Single-Frequency Lateral-Vibration Tests

Objectionable accelerations of lateral vibration obtained in the tests are shown in figure 7. Subjects were most sensitive to lateral vibration from 1 to 3 Hz. There was a nearly linear decrease in sensitivity as frequency of lateral vibration was increased from 3 to 7 Hz. On the average, subjects accepted about twice as much acceleration at 7 Hz before calling it objectionable as they did for vibration from 1 to 3 Hz.

A number of subjects were unable to reach objectionable accelerations at 0.20 Hz because of limited lateral travel of the simulator. These missing data points prevented definition of mean objectionable acceleration at 0.20 Hz.

Subjects reported the primary cause of objection to lateral vibration was body sway; that is, the head, shoulder, hips, knees, and feet of seated persons move out of phase with one another. More effort must be exerted to maintain a normal seated posture.

Comparison of Vertical- and Lateral-Vibration Test Results

Mean objectionable accelerations obtained for the vertical axis and the lateral axis are compared in figure 8. Subjects were approximately twice as sensitive to lateral as to vertical vibration at frequencies of 0.20 to 2 Hz. In general, sensitivity to vertical vibration increased and sensitivity to lateral vibration decreased as frequency was increased from 2 to 7 Hz. Objectionable acceleration thresholds for vertical and lateral vibration were nearly identical at 4 and 5 Hz. Objectionable thresholds for vertical vibration were slightly lower than those for lateral vibration at 6 and 7 Hz.

Subjects fell into three nearly equal groups on the basis of accelerations they considered annoying or objectionable. These individual differences were consistent and persisted regardless of axis of vibration. Subjects who judged vibration to become annoying or objectionable at relatively low accelerations were not influenced, in general, by frequency of vibration. Subjects who rated vibration annoying or objectionable at moderate or relatively high accelerations were differentially affected by frequency of vibration. The influence of vibration frequency on subjective reaction to vibration was more evident as the level of acceleration increased.

Combined-Frequency, Single-Axis Vibration Test

Combined-frequency, vertical- and lateral-vibration tests were conducted to determine whether reactions to multifrequency vibration can be predicted from knowledge of reactions to the component frequencies presented separately. Identical test designs and procedures were followed for the vertical and lateral tests.

Test conditions included both single-frequency and combined-frequency vibrations. Subjective reactions to single-frequency conditions were used as a basis for prediction of reactions to combined-frequency conditions. All conditions contained one or more narrow band filtered white noise inputs with center frequencies at 1.5, 4, and 7 Hz. Spectral shape was constant for each vibration condition and remained fixed for all trials involving that condition. Subjects rated annoying and objectionable accelerations of each vibration condition from the point of view of airline passengers.

Tables 1 and 2 present results of the vertical- and lateral-axis tests, respectively. The 10 test conditions are also indicated in these tables. Table entries showing the spectral composition of each condition indicate the percent of power contributed by vibration at each center frequency.

Combined-Frequency, Two-Axis Vibration Test

This test provided the first opportunity in the ride-quality program for study of persons' reactions to simultaneous vertical and lateral vibration. Two combined-frequency vibration spectra were selected for testing: 0.45, 1.5, 7 Hz and 0.45, 1.5, 4, 7 Hz. Relative power in each frequency band was equal for frequencies in each spectrum. For each test condition, the same spectrum defined both vertical and lateral vibration inputs.

Eight vibration conditions were presented for each frequency spectrum. Vibration in one axis was held at a fixed acceleration while vibration in the other axis was started at 0.015 RMSg and increased in steps of 0.015 RMSg every 30 seconds until the subject rated the combined-axis vibration. The eight vibration conditions were defined by two axes (vertical and lateral) × four levels of fixed acceleration (0, 0.015, 0.030, and 0.045 RMSg) for each axis.

Subjects were instructed to rate the total vibration environment and were cautioned that initial acceleration on a trial could already be beyond a level which they would define as annoying or even objectionable. If this were the case, they were to say so and not feel constrained to make both "annoying" and "objectionable" ratings. For some subjects the probability was high that this situation would occur on the initial vibration exposure in trials with fixed accelerations of 0.045 RMSg.

Results obtained when vertical acceleration was varied at fixed lateral background accelerations are presented in figure 9. In general, subjects required increasingly lower vertical accelerations to make the combined-axis vibration objectionable as lateral background acceleration increased.

2

Results obtained when lateral acceleration was varied at fixed vertical background accelerations to reach objectionable levels are shown in figure 10. There is no consistent trend evident, for either frequency spectrum, that increasing vertical accelerations had an effect on lateral acceleration required to make the combined-axis vibration objectionable.

PASSENGER RIDE COMFORT CRITERION

Based on analysis of the testing described above, a passenger ride comfort criterion was derived. Figure 11 shows the criterion compared with the results of the multiple-frequency, two-axis tests. The test data shown in figure 11 have been adjusted to reflect a structural frequency of 1.0 Hz and have been normalized to 2.0 Hz by application of frequency weighting factors.

LOW-FREQUENCY CYCLIC-OSCILLATION TESTING

Early in 1969 a limited test was conducted on the Northrop Norair moving base simulator to determine preliminary criteria for passenger acceptance of low-frequency cyclic accelerations. Such accelerations may occur continuously during flight as a result of tolerances (creating a dead zone) in the stabilizer position feedback mechanism.

The test was conducted in two phases. During Phase I subjects rated perceptible accelerations. During Phase II extended rides were conducted at a frequency of 0.20 Hz for several acceleration levels.

Phase I - Determination of Perceptible Accelerations

Perceptible ratings were made for vertical and lateral sinusoidal oscillations of 0.1, 0.2, 0.4, and 0.7 Hz. Perceptible accelerations were defined as "the point at which you first feel yourself beginning to oscillate."

The acceleration was slowly increased in each trial until the subject rated the oscillation perceptible. Acceleration was obtained from a strip chart that recorded output of a three-axis accelerometer, mounted on rigid structure in the passenger compartment.

Four subjects rated vertical and lateral perceptible accelerations three times for frequencies of 0.1, 0.2, and 0.4 Hz. One subject rated perceptible vertical and lateral oscillations twice at 0.7 Hz. The limited testing at 0.7 Hz was believed to be sufficient because of the low variability of previous ratings.

Median perceptible accelerations determined for the four frequencies are shown in figure 12. Median perceptible accelerations fell between 0.013g and 0.020g (zero to peak) across the frequency range tested.

Phase II - Effects of Extended-Duration Accelerations

Extended-duration rides of up to 40 minutes were conducted at a fixed frequency of 0.20 Hz for various vertical- and lateral-acceleration levels. A smooth flight (no turbulence) was simulated, since this is the most critical condition. Exposure times for each acceleration level are shown in table 3. Durations and peak accelerations varied among subjects, since the procedure followed was to determine, for each subject, the acceleration that would make the ride uncomfortable.

Based on subjects' comments, cyclic incremental accelerations should not exceed 0.015g (zero to peak) in the vertical axis and 0.010g (zero to peak) in the lateral axis. The majority of passengers will find these accelerations perceptible but not uncomfortable.

Because of the limited scope of this test, these criteria must be considered as preliminary upper bounds. Firm criteria can only be based on testing with a larger number of subjects, during several hours of exposure, with realistic airplane vibrations superimposed on the low-frequency oscillations.

Potential motion sickness was cited as the chief passenger ride problem arising from vertical 0.2 Hz vibration. There was considerable variability among subjects in vertical accelerations rated uncomfortable because of differences in susceptibility to motion sickness.

Subjects indicated that body sway was the primary disturbing factor during lateral oscillations. Selection of 0.010g (zero to peak) for the lateral limit was based on the statement of three of the four subjects that 0.010g was acceptable and 0.015g was unacceptable.

CONCLUDING REMARKS

Emphasis on study of relationships among human reactions to different vibration environments limits the generality of these test results. In particular, use of a small subject sample throughout the program affects the confidence with which absolute acceleration data may be said to reflect reactions of the airline passenger population. Further testing with a larger and more representative subject sample, including women and different age groups, is required to establish more firmly the percentages of passengers objecting as a function of increasing acceleration. Combined use of these percentile curves and information regarding the projected turbulence environment could then serve as a basis for design decisions concerning ride quality of future commercial airplanes.

Statements regarding relative sensitivity of humans to different vibration frequencies from 0.20 to 7 Hz can be made with more certainty. Test results indicating relative sensitivity of humans to vertical and lateral vibration appear to be consistent and repeatable.

The need for further combined-frequency and combined-axis testing is apparent, however. Test results to date afford a first look at problems met in predicting reaction to these more complex vibration environments.

REFERENCES

1. Beaupeurt, J. E.; Snyder, F. W.; Brumaghim, S. H.; and Knapp, R. K.: Ten Years of Human Vibration Research. Document D3-7888, The Boeing Company, Wichita Division, 1969.

2. Brumaghim, S. H.: Subjective Response to Commercial Aircraft Ride: Passenger Ride Quality Testing. Paper presented at the International Symposium on Man-Machine Systems, 8-12 September 1969, St. John's College, Cambridge, England.

TABLE 1 - OBJECTIONABLE ACCELERATIONS OF COMBINED-FREQUENCY VERTICAL VIBRATION

CONDITION NO.	PERCENT* 1.5 Hz	4 Hz	7 Hz	NO. OF FREQUENCIES	OBJECTIONABLE ACCELERATION (RMSg)
1	100	0	0	1	.105
2	0	100	0	1	.065
3	0	0	100	1	.064
4	50	50	0	2	.073
5	50	0	50	2	.065
6	0	50	50	2	.081
7	33	33	33	3	.070
8	50	25	25	3	.078
9	25	50	25	3	.092
10	25	25	50	3	.072

*TABLE ENTRIES INDICATE PERCENT OF TOTAL POWER CONTRIBUTED BY VIBRATION AT EACH CENTER FREQUENCY.

TABLE 2 - OBJECTIONABLE ACCELERATIONS OF COMBINED-FREQUENCY LATERAL VIBRATION

CONDITION NO.	PERCENT* 1.5 Hz	4 Hz	7 Hz	NO. OF FREQUENCIES	OBJECTIONABLE ACCELERATION (RMSg)
1	100	0	0	1	.053
2	0	100	0	1	.075
3	0	0	100	1	.092
4	50	50	0	2	.065
5	0	50	50	2	.082
6	50	0	50	2	.074
7	33	33	33	3	.068
8	50	25	25	3	.083
9	25	50	25	3	.068
10	25	25	50	3	.086

*TABLE ENTRIES INDICATE PERCENT OF TOTAL POWER CONTRIBUTED BY VIBRATION AT EACH CENTER FREQUENCY.

TABLE 3 - MINUTES OF EXPOSURE TO EXTENDED RIDE CONDITIONS

SUBJECT	MINUTES SPENT AT VERTICAL ACCELERATION (ZERO TO PEAK) OF -						
	0.010g	0.015g	0.020g	0.025g	0.030g	0.040g	0.045g
4			20		10	10	20
5	20		20		10	10	
9	20		15	8	8		
11	20	10/35*	20	10			

SUBJECT	MINUTES SPENT AT LATERAL ACCELERATION (ZERO TO PEAK) OF -						
	0.010g	0.015g	0.020g	0.025g	0.030g	0.040g	0.050g
4	10	15	25				
5	40	15	20				
9	15	10	20				
11	15	10	20				

*SUBJECT 11 EXPERIENCED TWO INDEPENDENT RIDES

BOEING-WICHITA HUMAN VIBRATION STUDIES

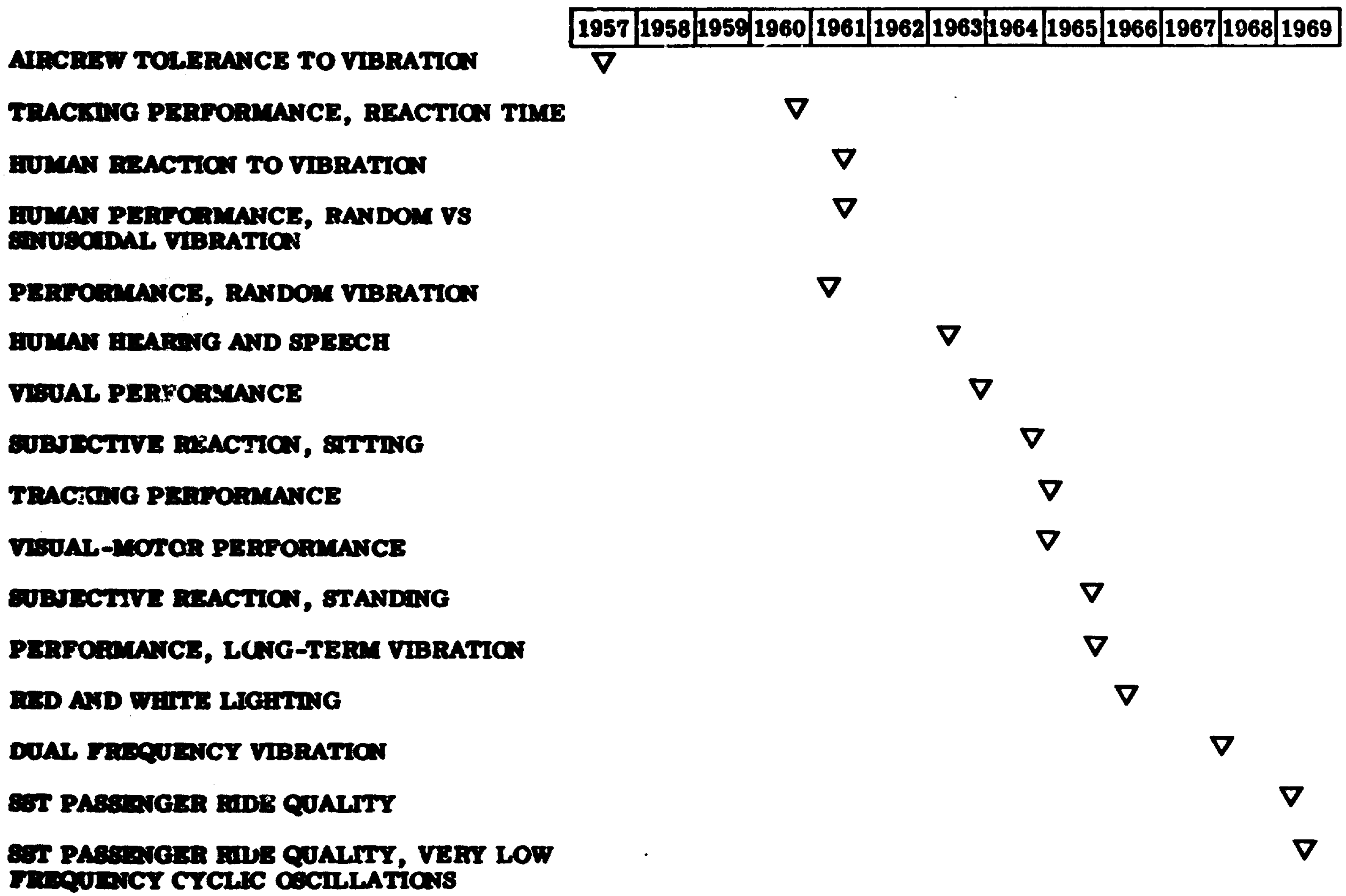

Figure 1

BOEING-WICHITA VERTICAL-VIBRATION FACILITY

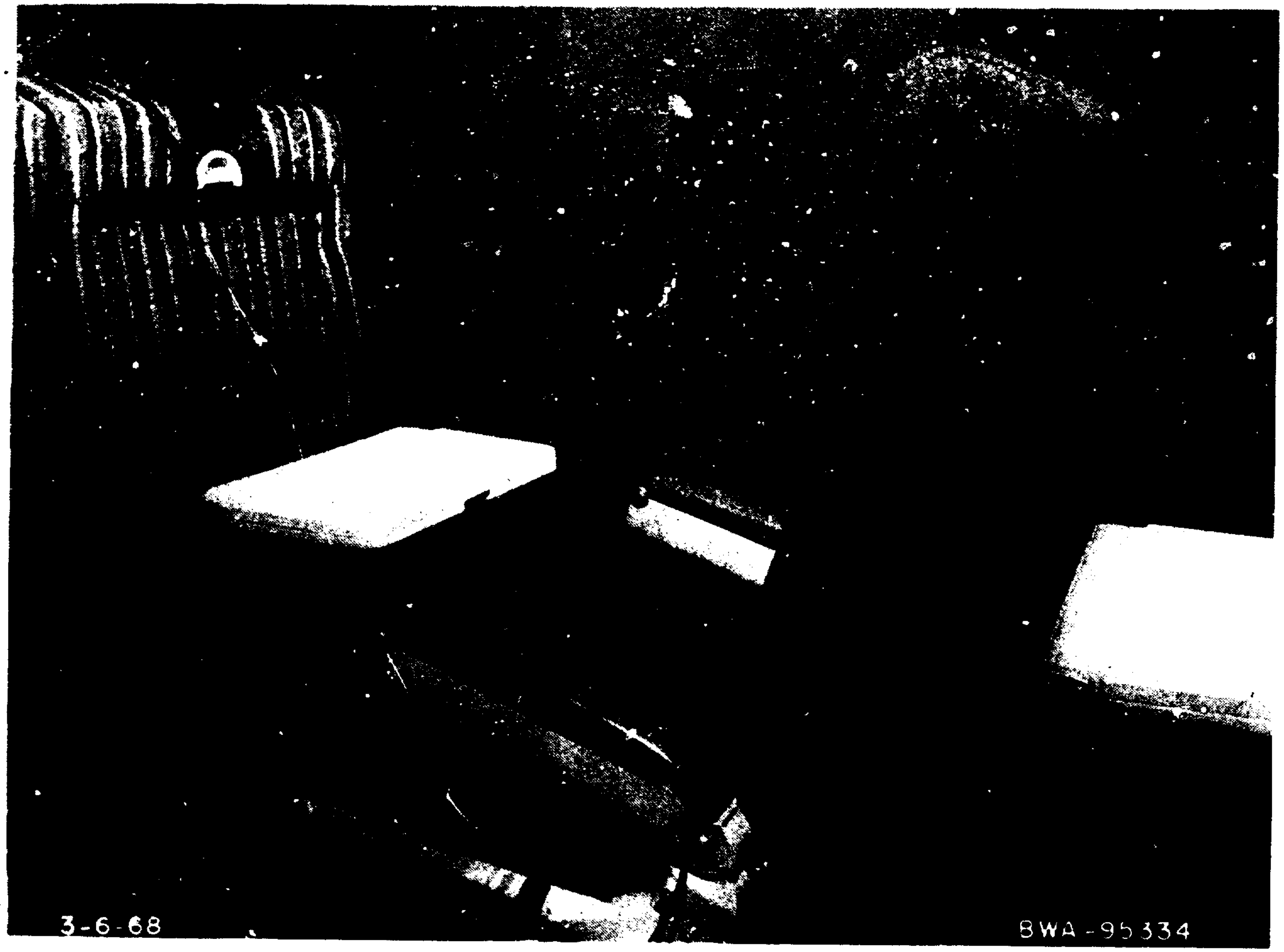

Figure 2

BOEING-WICHITA LATERAL-VIBRATION FACILITY

Figure 3

NORAIR LARGE-AMPLITUDE SIMULATOR

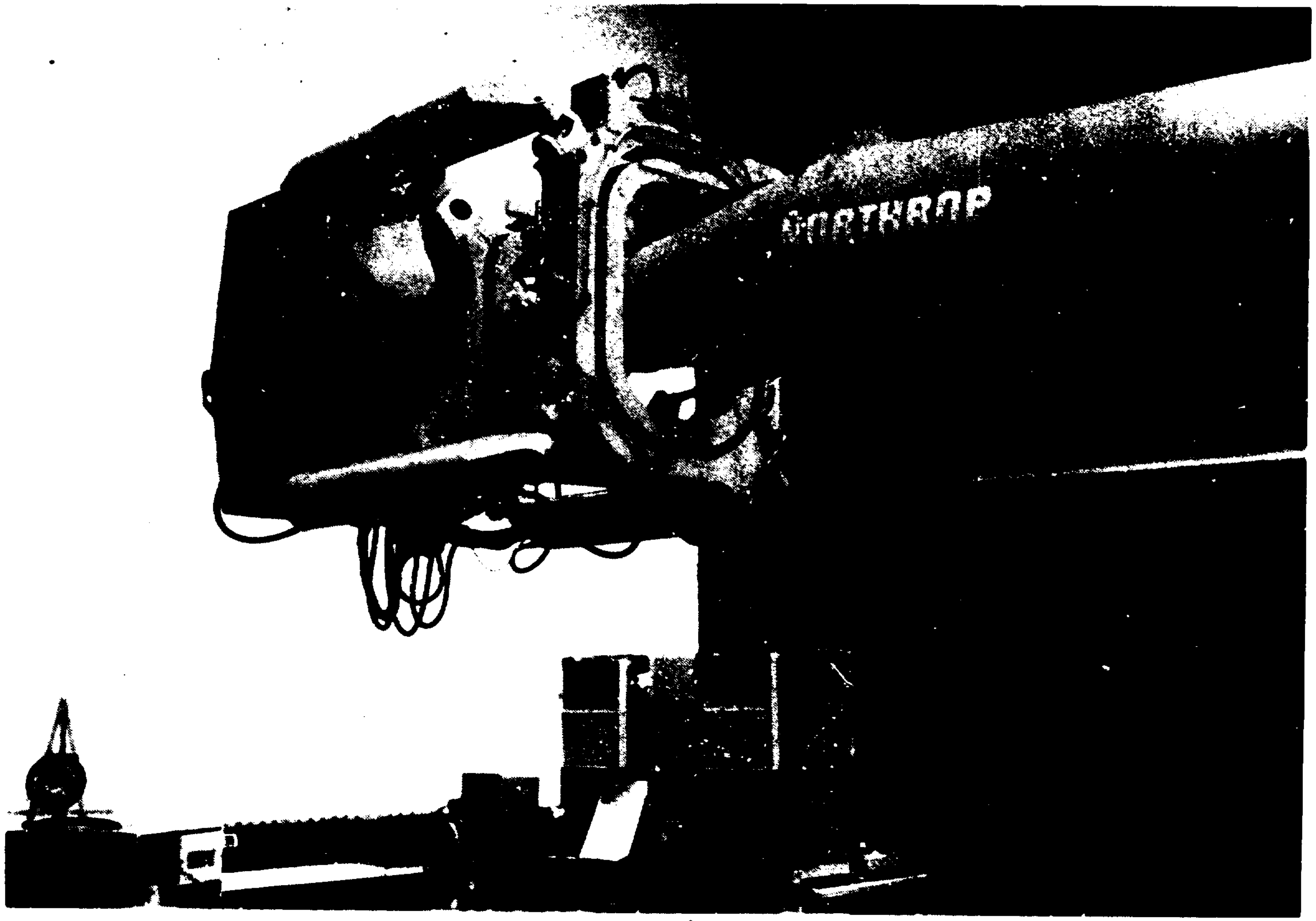

Figure 4

NORAIR PASSENGER COMPARTMENT

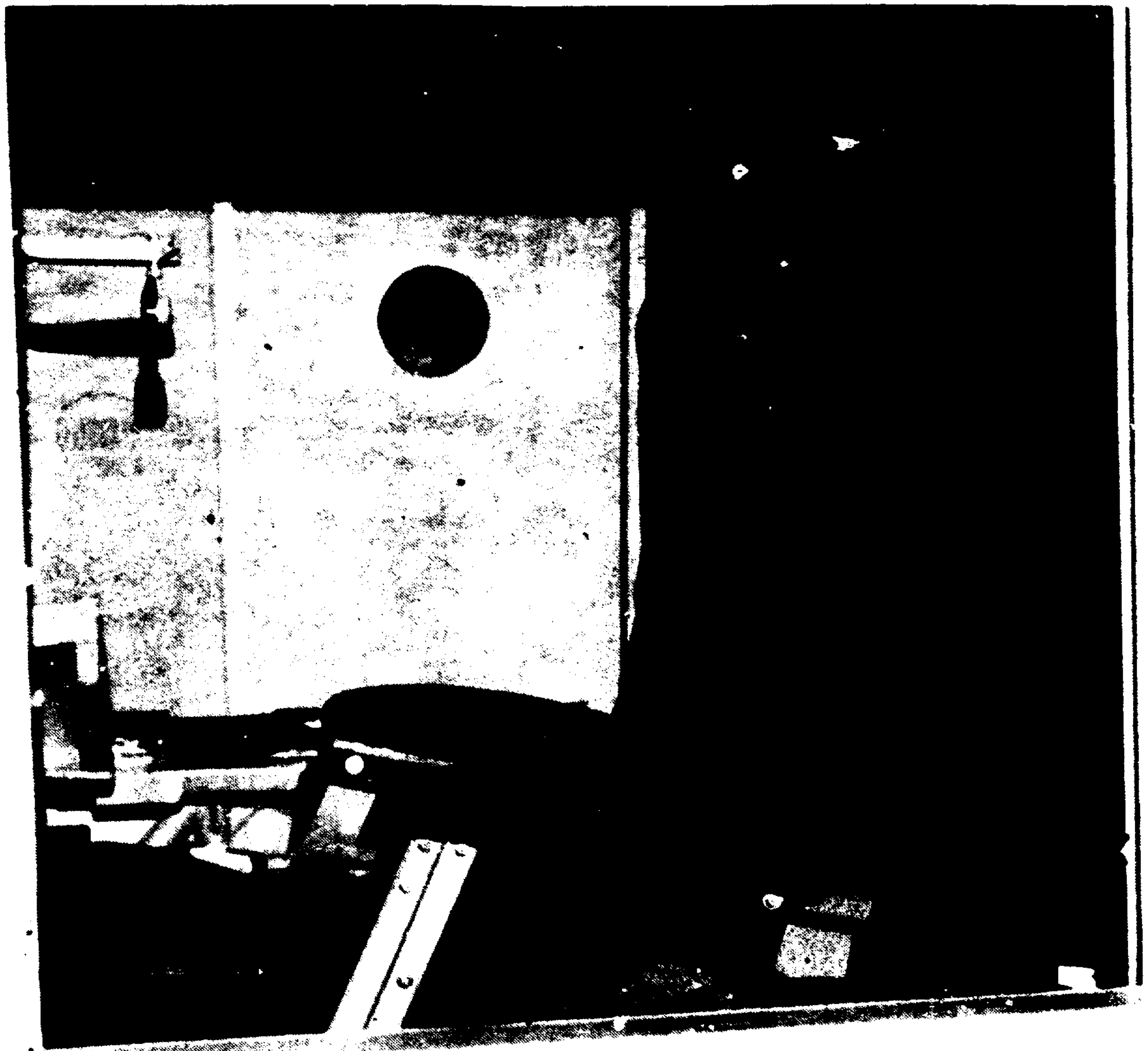

Figure 5

VERTICAL-ACCELERATION OBJECTIONABLE THRESHOLDS FOR PASSENGER RIDE

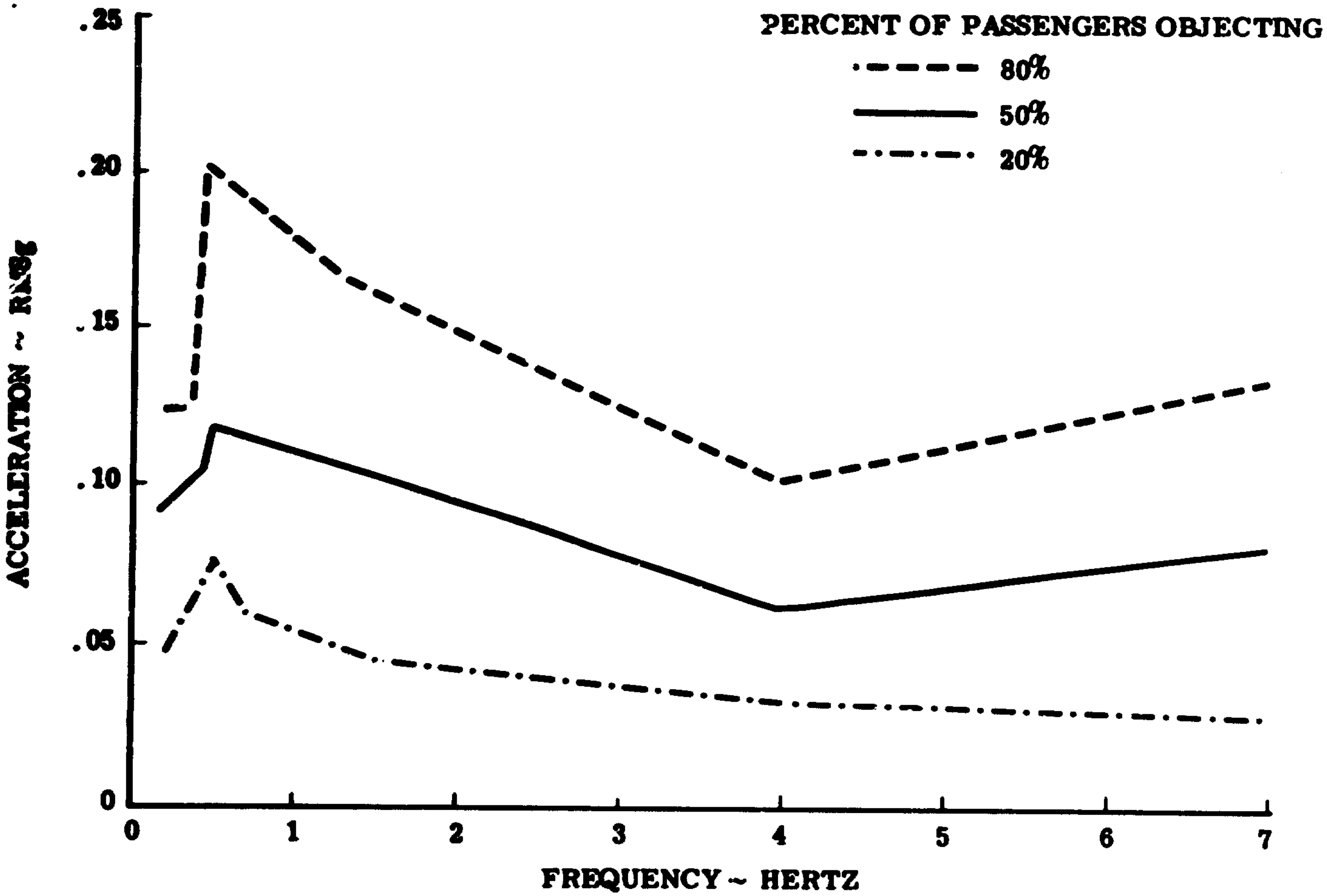

Figure 6

LATERAL-ACCELERATION OBJECTIONABLE THRESHOLDS FOR PASSENGER RIDE

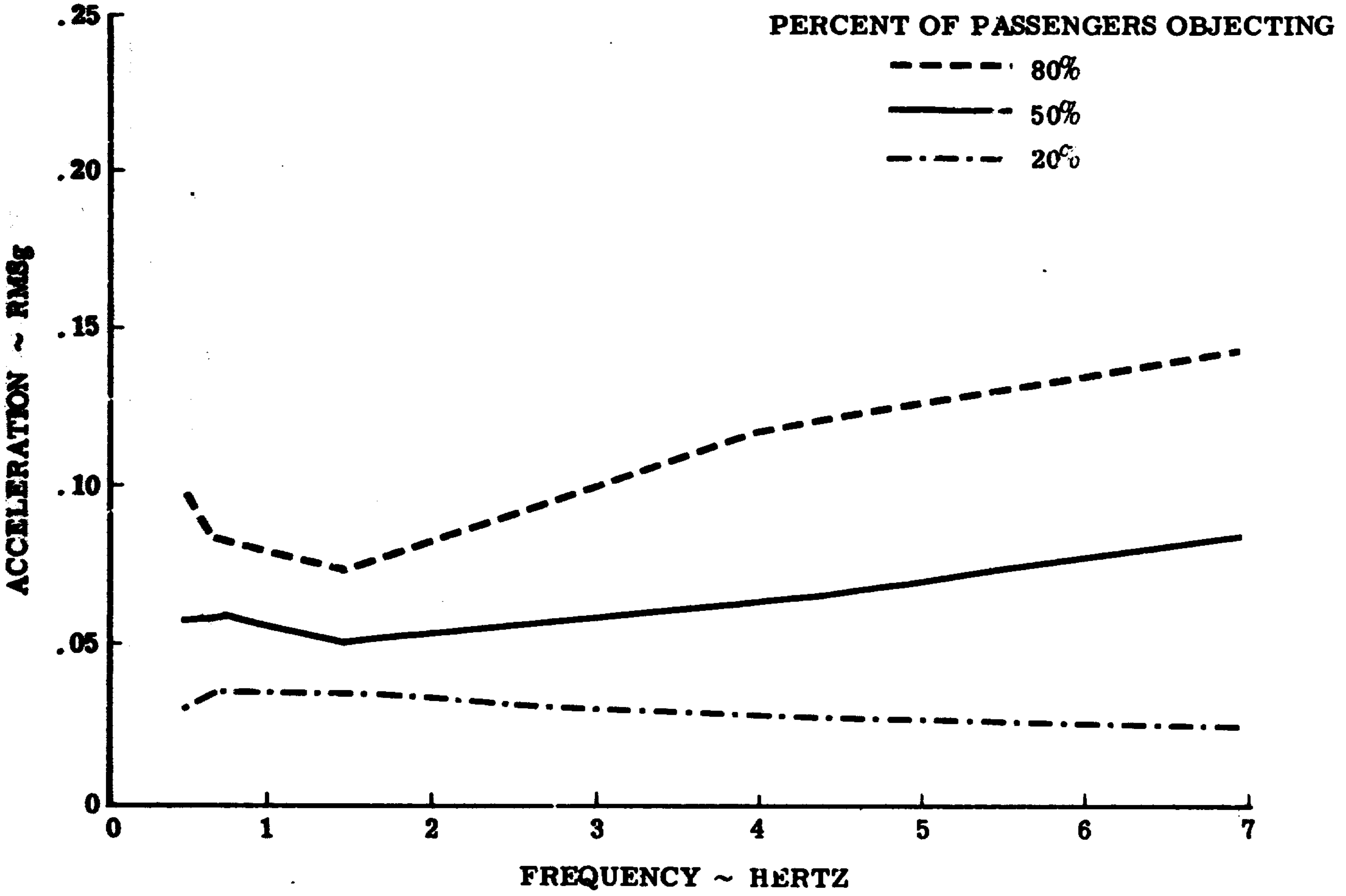

Figure 7

ACCELERATION LEVEL JUDGED OBJECTIONABLE

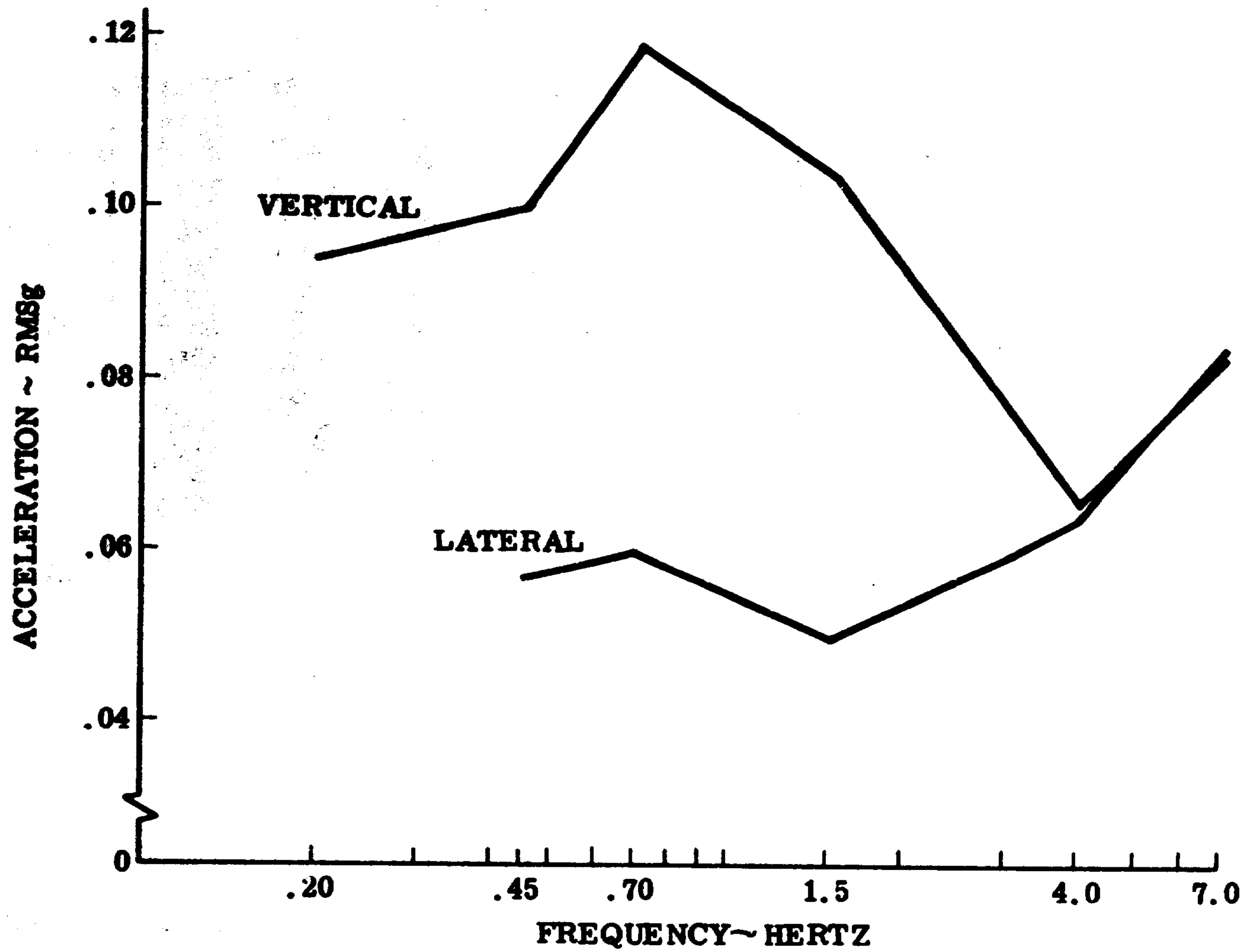

Figure 8

OBJECTIONABLE LEVELS OF TWO-AXIS VIBRATION

VERTICAL ACCELERATION VARIED AT CONSTANT ACCELERATIONS OF LATERAL VIBRATION

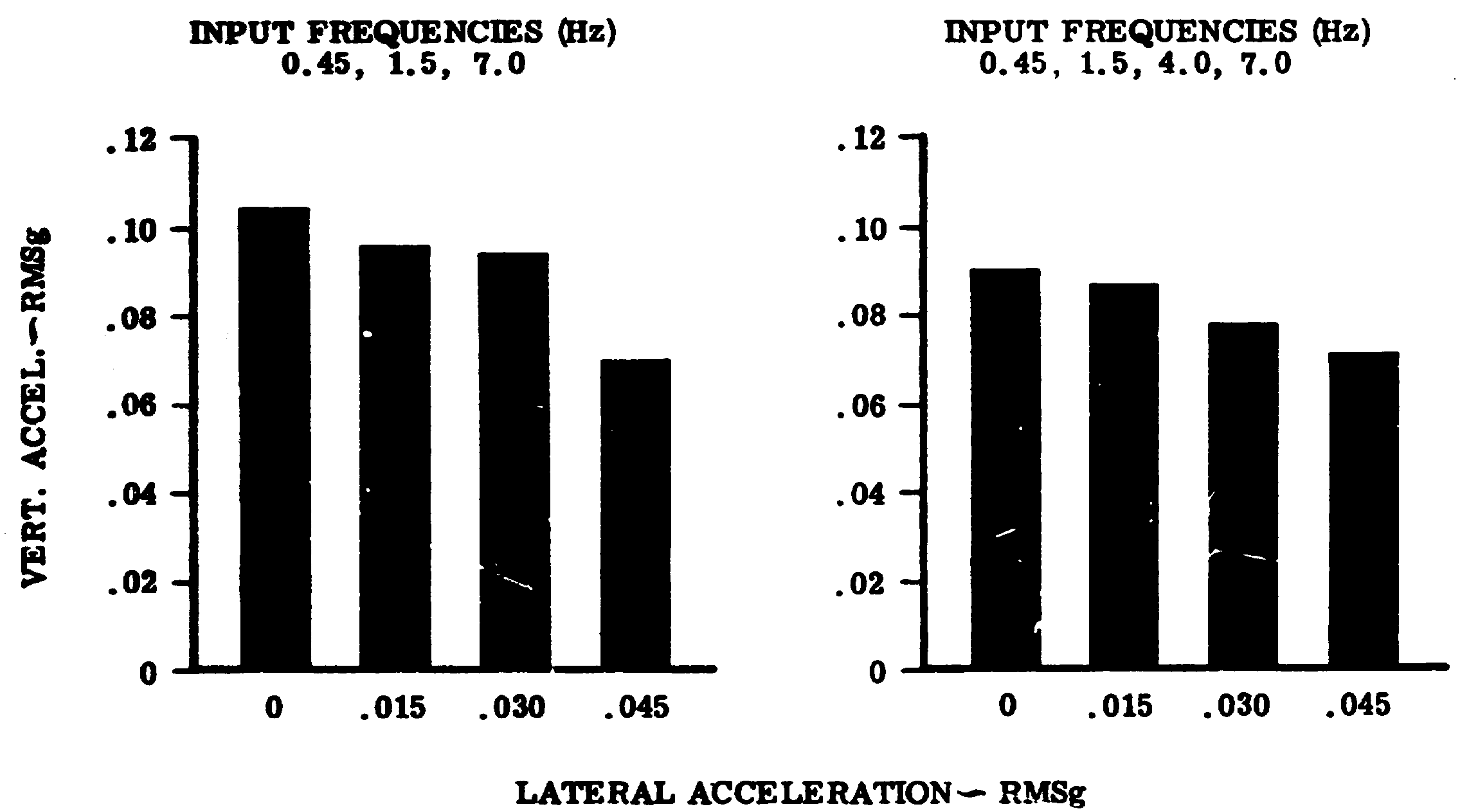

Figure 9

OBJECTIONABLE LEVELS OF TWO-AXIS VIBRATION

LATERAL ACCELERATION VARIED AT CONSTANT ACCELERATIONS OF VERTICAL VIBRATION

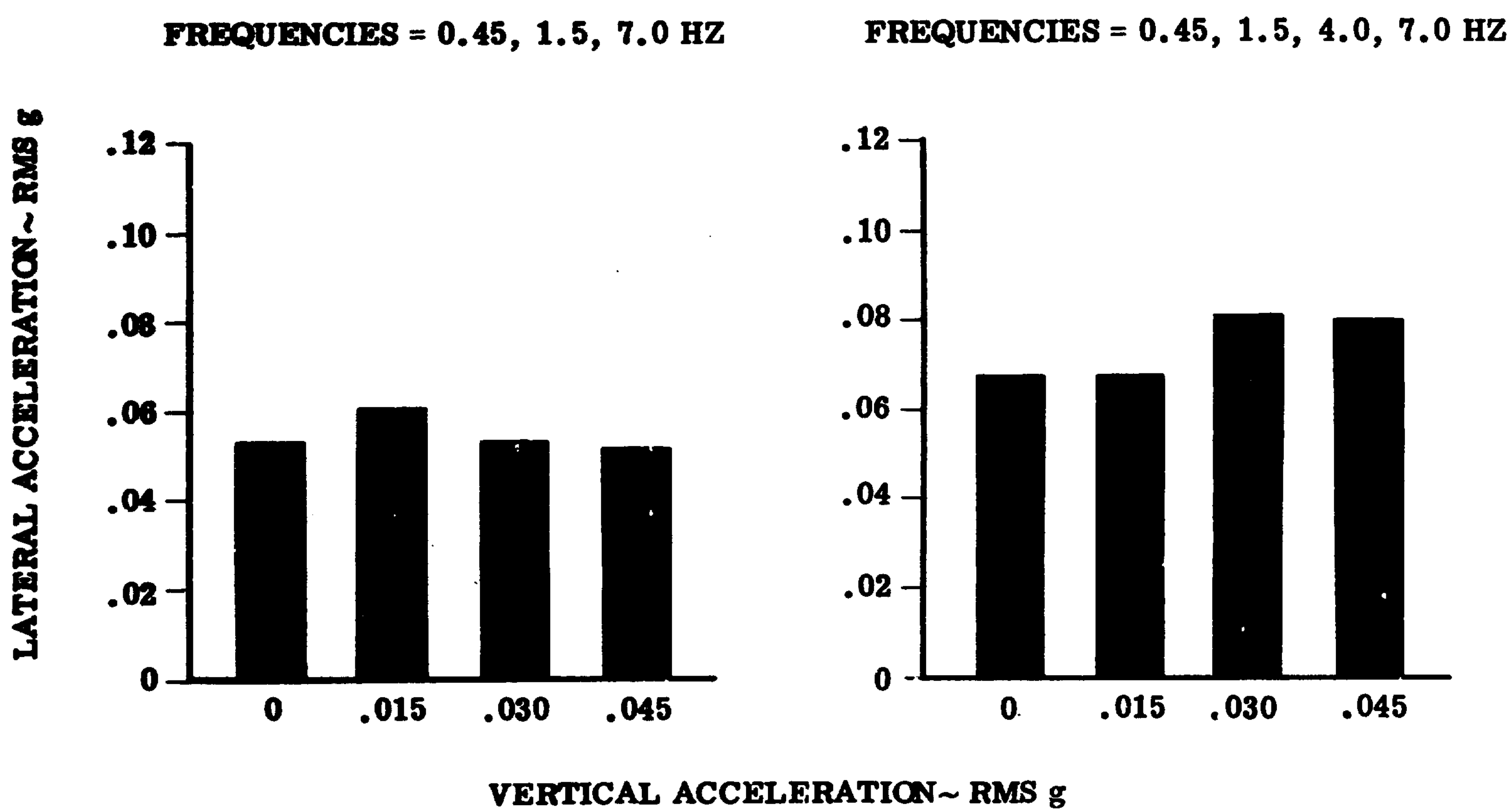

Figure 10

COMPARISON BETWEEN TWO-AXIS VIBRATION TEST RESULTS AND RIDE COMFORT CRITERION

NOTES: 1) TEST DATA NORMALIZED TO 2 HERTZ
2) TEST DATA INCLUDED ACCELERATION COMPONENTS AT .45, 1.5, 4.0, AND 7.0 HERTZ
3) TEST DATA ARE OBJECTIONABLE THRESHOLDS

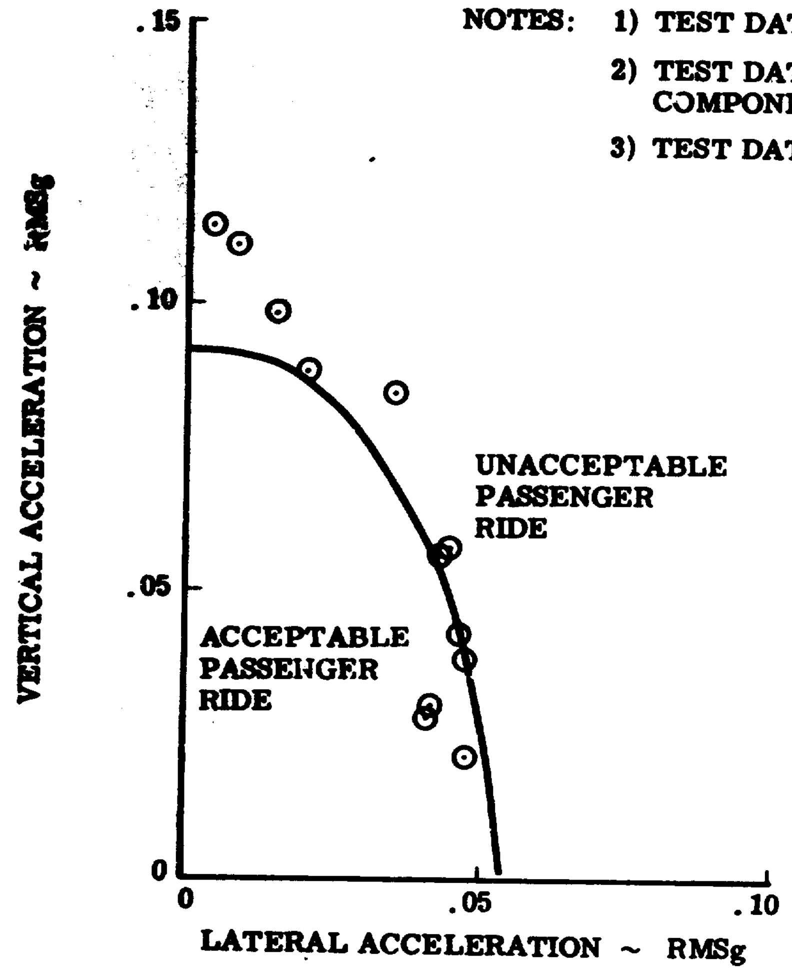

Figure 11

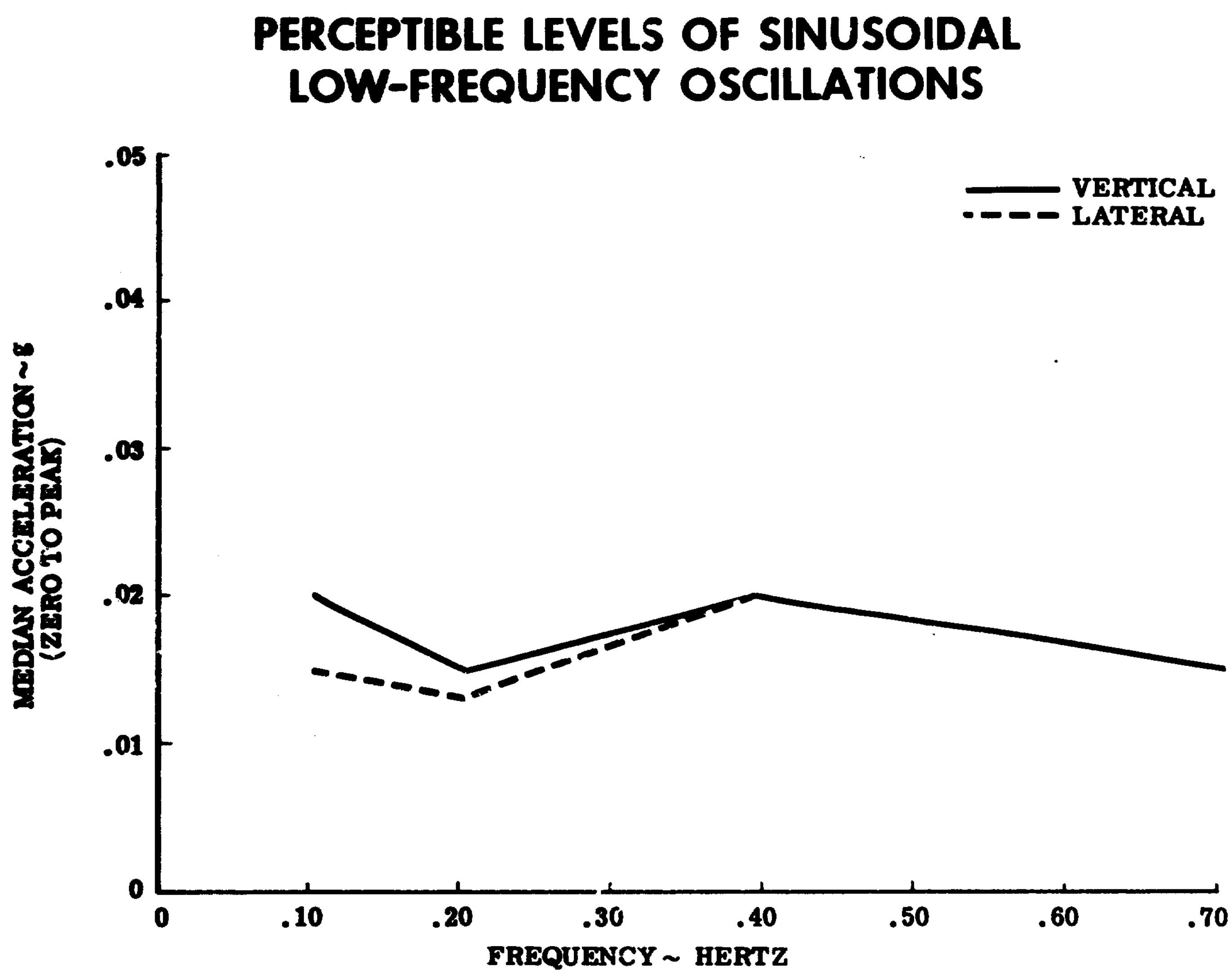
PERCEPTIBLE LEVELS OF SINUSOIDAL
LOW-FREQUENCY OSCILLATIONS
VERTICAL
LATERAL
MEDIAN ACCELERATION ~ g
(ZERO TO PEAK)
.05
.04
.03
.02
.01
0
0
.10
.20
.30
.40
.50
.60
.70
FREQUENCY ~ HERTZ

Figure 12

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ANALYTICAL AND EXPERIMENTAL EVALUATION OF PROPOSED RIDE COMFORT CRITERIA

E. Wayne Vinje

United Aircraft Research Laboratorie
East Hartford, Connecticut

SUMMARY

N73-10018

An exploratory study was conducted to evaluate the effectiveness of indices proposed by different investigators to relate vehicle vibrations to passenger comfort. The indices considered included criteria for sinusoidal vibrations, unweighted and weighted amplitude exceedance counts, the integral of the unweighted and weighted power spectral density and absorbed power. These functions were initially examined analytically to determine the manner in which they each weight vibration amplitude and frequency. Similarities among them are noted. Index values were then computed from measured vibrations and compared with the associated comfort ratings. The data for these comparisons were obtained from ride comfort evaluations of passenger trains.

Results indicate that at a given passenger location a deterioration in comfort rating generally correlates with increased values of the indices computed for lateral vibration. However, for equal comfort ratings, large differences exist in the magnitude of the lateral vibration indices computed for different passenger locations. This result casts doubt on the effectiveness of these indices as absolute indicators of ride quality. The previous discussion also applies to index values computed from vertical vibration except that the correlation with ratings is less pronounced at a given location.

INTRODUCTION

One of the most significant factors which affects passenger comfort is the relatively low frequency (0 to 30 Hz) vibration environment. Criteria which define limits for this vibration environment must properly weight those characteristics of the motion which have an important effect on comfort. Such criteria must also be sufficiently well-founded and precise so as to avoid overspecification when the criteria are employed in vehicle development. Stipulating a vibration environment which is more benign than is necessary for comfort can lead to increased vehicle complexity, weight and cost. The need for realistic, precise criteria has increased with the development of light-weight, high-speed passenger vehicles. The tradeoffs between the passenger vibration environment and vehicle performance, weight, etc., are appreciable.

A number of methods for quantitatively relating comfort to vibration environment have been proposed. Among these techniques or indices are (1) boundaries of acceptable vibration level versus frequency developed from subjective responses to sinusoidal vibration, (2) the amplitude level exceedance count approach, (3) the unweighted and weighted power spectral density and their integrals, and (4) the absorbed power index.

This study consisted of an analytical and experimental evaluation of the aforementioned methods for relating vibration to comfort. These different techniques were applied to vibrations measured during an experimental evaluation of passenger train ride quality. The results of these analyses were correlated with subjective ratings of the ride obtained during the test. The objective of this study was to determine whether any of the methods provided an acceptable means for specifying the vehicle vibration environment necessary for comfort.

SYMBOLS

a	acceleration, meter/sec^2 or g's
AP	absorbed power, watt or newton-meter/sec
f	frequency, Hz
g	gravitational acceleration, meter/sec^2
F_{in}	input force to the passenger, newton
K	acceleration frequency weighting function for the absorbed power index, newton-sec^4/meter
PSD	power spectral density, g^2/Hz
t	time, sec
T	averaging period, sec

v_{in} velocity input to the passenger, meter/sec

Y_a transfer function relating acceleration input to passenger to his acceleration response

Y_F transfer function relating passenger acceleration to force input, newton-sec^2/meter

Y_{sv} seat transfer function for the vertical direction

ω frequency, rad/sec

DESCRIPTIONS OF THE RIDE QUALITY INDICES

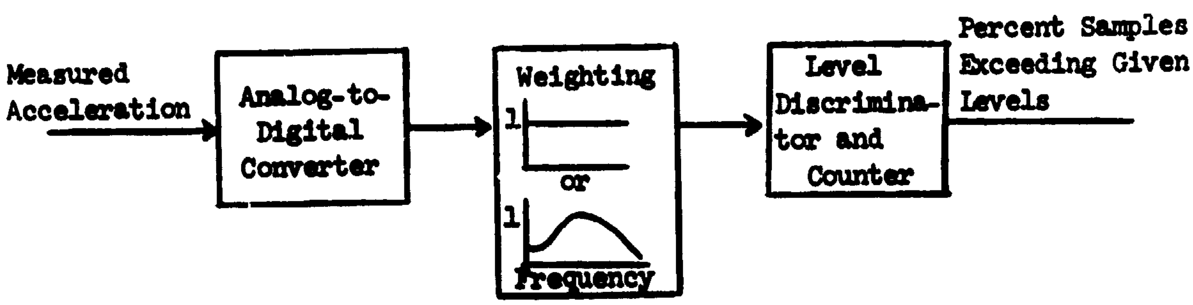
Comfort Contours for Sinusoidal Vibrations

A number of investigators have conducted tests designed to relate the amplitude and frequency of sinusoidal vibrations to passenger comfort (references 1, 2, 3 and 4). These studies generally consisted of placing subjects on shake platforms, subjecting them to sinusoidal motion (vertical and horizontal) for varying durations, and recording that level of acceleration (for a given frequency) at which subjects indicated that the motion was marginally comfortable to uncomfortable. Boundaries have been developed from these results which separate acceptable from uncomfortable vibrations. The results from different investigators differ; however, the contours shown in figure 1 are representative of those which are generally accepted for vertical and lateral sinusoidal motion. These contours have been derived primarily from references 1 and 2. Note that both curves have a characteristic minimum which occurs at about 5 Hz for vertical motion and 2 Hz for lateral. Also, the human is generally thought to experience discomfort at lower amplitudes for lateral vibrations than vertical. The amplitudes for the two contours differ by a factor of about 1.4 at their respective minima (reference 2). Longitudinal vibrations were not considered in this study because they were insignificant in the vehicles evaluated.

The results from these studies are, of course, completely valid only for sinusoidal vibrations. There is no obvious means for modifying the boundaries such that they are applicable to the more general types of random and random plus quasi-sinusoidal vibration present in most passenger vehicles. (Miwa in reference 5 has developed a method for quantitatively relating vibration consisting of multiple sinusoids to the human's sensation of motion, however.) The sinusoidal vibration contours may be most useful, therefore, as a weighting function. If it is assumed that the human responds subjectively to vibrations in a linear fashion, the normalized inverse of the sinusoidal comfort curves can be used to weight more general vibrations. The assumption of linearity implies that changes in amplitude, jerk content, the time variation in acceleration, etc., do not affect the manner in which humans subjectively weight the frequency of vibration. The linearity assumption is obviously not entirely accurate (see, for example, reference 3). However, it may be useful as an approximate method for accentuating the effect of those frequencies which are most important in affecting comfort. Frequency weighting curves based on the contours from figure 1 are shown in figure 2 (they have been modified slightly from those in reference 6).

Amplitude Level Exceedance Count

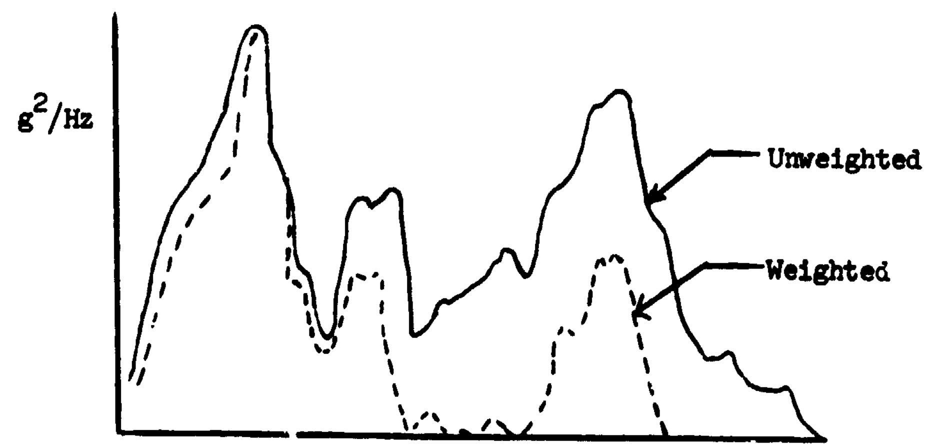
The amplitude level exceedance count approach (reference 7) is based on computing the percent of the total number of samples which exceed a preselected vibration amplitude or, equivalently, the percent time that level is exceeded. An increase in this percentage is presumed to correlate with an associated increase in passenger discomfort. Thus, the percentage would be an index of comfort. The vibration used in the exceedance count method may be weighted with the inverse of the sinusoidal comfort contours (vertical or lateral) prior to its comparison with various amplitude levels. Sketch A indicates how this approach might be implemented.



Sketch A. Flow Diagram for Computation of Amplitude Level Exceedance Percentages

Power Spectral Density and Its Integral

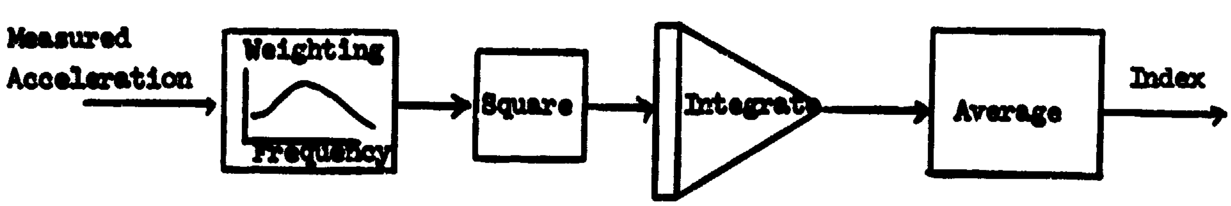
This approach involves analyzing the frequency content of the passenger vehicle vibration environment. The frequency distribution can also be weighted with the inverse of the sinusoidal comfort curve to accentuate those frequencies presumed to be important. Finally, summing the resulting unweighted or weighted vibration contribution from all frequencies provides a numerical index which may be related to comfort (reference 8). The spectral content of the vibration is generally determined by computing a power spectral density plot (PSD). Weighting the power distribution with the sinusoidal vibration weighting function (vertical or lateral, figure 2) then gives a graphic illustration of those frequencies which the sinusoidal vibration results would indicate are important in affecting discomfort (sketch B). The weighted PSD



Sketch B. Power Spectral Density Plot for Unweighted and Weighted Vibration

can then be used as a design tool since it indicates which frequencies should be suppressed. The associated index is obtained by integrating the power distribution over all frequencies.

A more direct analog method for computing the same index is shown in sketch C. Note that the weighted PSD index weights amplitude as well as



Sketch C. Method for Computing the Integral of the Weighted PSD Index frequency. This is because the square of the vibration amplitude is used in the computation. This index then implies that increases in amplitude are nonlinearly related to comfort. As indicated previously, such a nonlinear weighting of amplitude may be justified by previous experimental data (reference 3). Also note that the power spectral density index and the amplitude level exceedance count index are mathematically related if the vibrations considered have a Gaussian amplitude distribution. In this case, the percent of samples which will exceed a given amplitude are related to the square root of the PSD index through the Gaussian probability density function (reference 9).

Absorbed Power Index

The absorbed power method is one of the more interesting approaches taken in an attempt to correlate vibration environment with comfort (reference 10). This index is related to the rate at which the body dissipates vibrational energy. It is an attempt to correlate vibration with a subjective (or psycho-physiological) assessment of comfort through the human body's physiology. The index is defined in the time domain by

$$AP = \lim_{T \to \infty} \frac{1}{T} \int_0^T F_{in}(t) \cdot v_{in}(t)\, dt \qquad (1)$$

where

AP = absorbed power index, watt
F_{in} = force, newton
v_{in} = velocity, meter/sec
T = sample interval, sec
t = time, sec

or in the frequency domain by

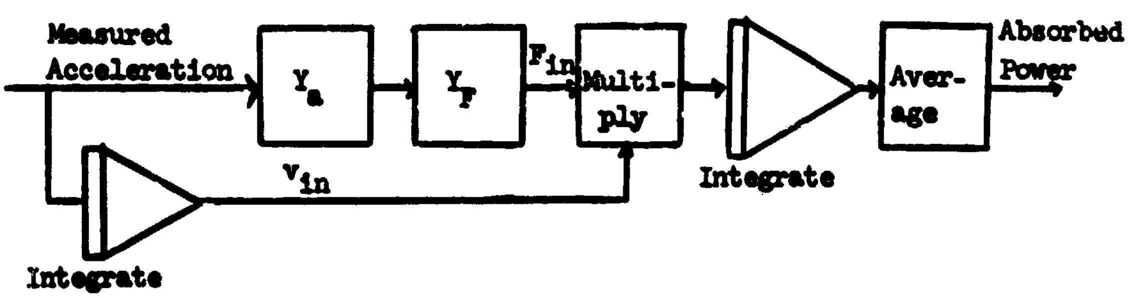
$$AP = \int_0^{\infty} K(\omega) \cdot a^2(\omega)\, d\omega \qquad (2)$$

$K(\omega)$ = frequency weighting parameter, newton-sec^4/meter
a = acceleration, meter/sec^2
ω = frequency, rad/sec

Note that the absorbed power index is similar to the weighted PSD index in that both are based on the integral of the square of acceleration. In order for the absorbed power index to be computed, the averaged physiological transfer functions

$$Y_a(j\omega) = \frac{\text{output acceleration}}{\text{input acceleration}}$$
$$Y_F(j\omega) = \frac{\text{input force}}{\text{output acceleration}} \quad (3)$$

must first be determined from a large number of test subjects. These transfer functions are determined by taking measurements at appropriate locations on the human body while the subject is being vibrated. Both sinusoidal and random accelerations have been used in the measurement of the transfer functions and they are not the same for both types of vibration. After $Y_a(j\omega)$ and $Y_F(j\omega)$ have been determined, the absorbed power index can be computed as shown in sketch D. The acceleration environment is measured and multiplied by $Y_F(j\omega)$



Sketch D. Schematic of Absorbed Power Index Computation Method

and $Y_a(j\omega)$ to obtain F_{in}, while simultaneously being integrated to form v_{in}. These functions are then multiplied and averaged to form absorbed power. In laboratory experiments, changes in test subject's perception of vibration were found to correlate with changes in the absorbed power index.

The transfer functions $Y_a(j\omega)$, $Y_F(j\omega)$ have not been measured for lateral vibrations. It is difficult to define such transfer functions for lateral inputs to the human body. Also, the frequency weighting produced by the absorbed power approach applied to the vertical direction (using the transfer functions developed for sinusoidal inputs) is very similar to the vertical comfort contour for sinusoidal vibrations (figure 3). One might expect, therefore, that for vertical vibrations the absorbed power index (using the $Y_F(j\omega)$ and $Y_a(j\omega)$ for sinusoidal inputs) would yield results similar to the weighted power spectral density approach.

DESCRIPTION OF THE RIDE COMFORT TESTS

The vibration and subjective comfort data used to evaluate the comfort indices were obtained from a ride quality evaluation of two passenger trains. These tests were conducted in conjunction with Sikorsky Aircraft, NASA Langley Research Center, U. S. Department of Transportation, and the Canadian National Railways. Data were measured for the two trains on succeeding days over the same route.

Objective Measurements

Vibration data were measured simultaneously at two floor locations within each train and were recorded on magnetic tape. Linear acceleration data were obtained in three axes with each of the vibration measurement packages. The location of each package was changed at intervals throughout each run. Vibration measurements were correlated with track location by recording the mileposts along the track on the tape recorder. Sound level measurements were also made at different locations within the train. In addition, measurements of the vibration environment were made using the Canadian National Railways ride quality analyzer. This is a device which measures vibration and computes a function similar to the weighted power spectral density index.

Subjective Measurements

Subjective data related to the ride were obtained at car locations adjacent to the vibration measurement packages. Ride quality varied during the run because of changes in train speed, track condition, etc. The ride comfort, sensation of the motion and the acceptability of the sound level were all rated using the scales shown in table 1. The comfort and sensation of the car motion were both rated in an attempt to separate, to some extent, the effects of vibration amplitude and frequency. That is, the sensation of motion might be large, but if it were of the proper frequency, the sinusoidal comfort contours imply that it would not necessarily be uncomfortable. It was felt that obtaining these two types of information would help in determining those characteristics of the ride which were disagreeable. The comfort and sensation scales shown in table 1 were adapted from similar scales used in ride quality evaluations by the Japanese National Railways (reference 2). The sound level was rated to enable an analysis of the correlation between sound level and the motion sensation and comfort.

The test subjects also gave their opinions on questions related to their ability to perform tasks common to passengers or passenger attendants in the presence of the train motion. These questions are also listed in table 1. Periodic ratings of the ride were made over track intervals of the subject's choice. The subjects were also asked to rate the ride for any track interval over which they felt the character of the ride had changed from their assessment of its previous quality. Six subjects evaluated ride quality during the test of train A and nine subjects rated train B.

EVALUATION OF THE RIDE QUALITY INDICES

The approach used to evaluate the ride quality indices initially involved separating the comfort rating results from each train into categories according to rating number, i.e., 1, 2, 3, etc. Only data obtained for track consisting of 11.9 meter lengths were considered. Average sensation and sound ratings associated with each comfort rating category were then computed. The percent affirmative answers to each of the questions associated with the given comfort rating category was also computed. Correlation between comfort rating and the sensation, sound and question response was examined. Milepost intervals were then compiled according to comfort rating, location within the train, and the train considered. For each group of milepost intervals associated with a given rating level, amplitude level exceedance counts and PSD integrals were computed using unconditioned and conditioned values of the appropriate vertical and lateral vibrations. The vibrations had been converted from analog (continuous) to digital form prior to these analyses which were conducted using digital computer programs. The exceedance count and PSD index results were then averaged over all the milepost intervals in each comfort rating, location and train category. Longitudinal vibrations were not considered because they were very small.

The unconditioned vibration considered in this analysis was that measured during the tests with no frequency filtering or weighting. Two types of conditioned vibration were used in the exceedance and PSD index computations. The first set of conditioned vibration data was composed of the unfiltered lateral vibrations and the vertical vibration data which had been modified using a second-order, low-pass filter. This filter represented the transfer function expected from the train seats in the vertical direction (reference 6).

Thus, the filtered vertical vibration was closer to that imparted to the subjects than the unfiltered vertical vibrations. The seat filter used was

$$Y_{SV} = \frac{(17.3)^2}{(j\omega)^2 + 2(0.18)(17.3)j\omega + (17.3)^2} \qquad (4)$$

A seat filter was not applied to the lateral vibration because a train seat probably does not modify lateral inputs as much as it does vertical vibration. Those lateral inputs affecting human upper torso, neck and head motions, which are significant in determining comfort rating, are similar for a subject seated on a bench or in a train seat. The third set of vibration data considered was obtained by weighting the second set of vertical and lateral data with the inverse of the sinusoidal comfort contours. The lateral and vertical weighting curves used are shown in figure 2.

DISCUSSION OF RESULTS

Subjective Ride Evaluation

Subjective results for the three passenger car locations considered in this study (center and rear of the same car for train A, center of car for train B) are shown in figures 4, 5, and 6. The data shown in each figure consist of the percent of the total comfort ratings which fall into a given comfort rating category, the average sensation and sound ratings associated with a given comfort rating, and the percent yes answers to the questions versus comfort rating (see table 1 for a key to the coding used for the questions).

The results for the center of the car in train A (figure 4) indicate that the ride there was relatively good. A high percentage (about 40 percent) of the ratings were 1 and the remainder were 2. The averaged sensation rating increased as comfort ratings increased, indicating a direct correlation between deterioration in comfort rating and the subject's sensation of motion. The sound level rating did not change, and the response to the questions was not greatly different for either comfort rating. However, the subjects were less sure of their ability to drink a cup of hot coffee in the vibration environment associated with a comfort rating of 2.

The comfort ratings for the rear of the car in train A (figure 5) show larger percentages of the total responses in the 2 to 3 category, indicating a poorer ride. The average sensation and sound ratings are similar for the better ratings (1 and 2) but increase sharply for the 3 rating (uncomfortable ride). The responses to the questions are sensitive to the ride ratings and again there is an abrupt decrease in affirmative responses for comfort ratings of 3.

The distribution of comfort ratings from the center of car in train B (figure 6) would indicate that its ride quality was between that of the two locations in train A. As for the rear of the car in train A, the average sensation and sound ratings for the car in train B change little with comfort rating for the better ratings and increase abruptly for the uncomfortable rating. The percent of positive responses to the questions (answers indicative of a good ride) also change little with comfort rating until the rating reaches 3.

In summary, the subjective data generally indicate that average sensation and sound ratings change less between comfort ratings indicative of a good ride (1 and 2) than when the ride deteriorates from comfortable (2) to uncomfortable (3). The response to the questions also indicate less sensitivity to changes in comfort rating for a good ride than for the change from comfortable to uncomfortable. Finally, the comfort and sensation ratings may indicate that the frequency content of the vibrations had a lesser effect on rating than the amplitude of the motion. That is, when the character of the ride changed significantly (change in comfort rating from 2 to 3), the sensation ratings always increased significantly, probably reflecting larger amplitude train motion.

Comparison of Amplitude Level Exceedance Index With Comfort Ratings

Table 2 presents amplitude level exceedance percentages versus comfort rating for all locations evaluated and for the three sets of conditioned vibration data considered (i.e., unfiltered, vertical channel filtered with the seat filter, and vertical seat filter plus vertical and lateral sinusoidal comfort curve weighting). For the unfiltered vibration the lateral percentages generally show a relative increase with comfort rating at a given location. The vertical exceedance percentages do not increase as comfort ratings deteriorate for train B, however. Note also that, for the same ratings, the lateral and vertical exceedance percentages (unfiltered vibration) at the rear of the train A car and the center of the train B car are much larger than for the center of the car in train A. In addition, the vertical exceedance percentages are generally larger than the corresponding lateral values for the unfiltered vibration.

Filtering the vertical vibration with the seat filter increases the vertical exceedance percentages for the train A locations and decreases them for train B. Apparently, there is more low-frequency vertical vibration in train A and this is amplified by the seat filter resonance peak (at about 3 Hz). The disparity in vertical exceedance percentages between trains A and B, which is evident after the seat filter is applied, correlates with subjects' comments on the character of the ride on the two trains. Subjects rarely mentioned the vertical motion when commenting on the train B ride. However, at times they thought the vertical inputs in train A were noticeable although not nearly as perceptible as the lateral motion. Filtering the vertical vibrations with the seat model reduces the variation in vertical exceedance percentages with comfort rating. Only slight changes are evident in these percentages at a given location and they do not necessarily increase with rating.

Weighting the lateral vibration and the filtered vertical vibrations with representations for the inverse of the sinusoidal comfort boundaries (figure 2) results in generally smaller exceedance percentages. The lateral percentages generally increase with increased comfort ratings but this is not necessarily true for the vertical results. Also, the vertical percentage levels from train A are much larger than the corresponding lateral results; and for train B, the vertical percentages are much smaller than those for the lateral axis. The vertical exceedance percentage data, then, substantiate the subject's comments that the vertical vibrations were of less importance than lateral vibrations in affecting comfort.

As discussed, the lateral exceedance percentages generally increase with comfort rating for both the unconditioned and conditioned vibration data. This effect can be seen more easily in figure 7, where lateral and vertical exceedance percentages for a single level are listed versus comfort rating at each location. Again, however, it is important to note that, for the same car (train A), equal ratings at the two locations correspond to widely different lateral exceedance percentages (e.g., the weighted lateral vibration percentage for a rating of 1 at the rear of the car is three times that for a 1 rating at the center). There is, however, a somewhat better correlation between lateral percentage magnitude and rating if one compares the weighted vibration data between the centers of the train A and train B cars.

Comparison of Power Spectral Density Index With Comfort Ratings

Unweighted and weighted power spectral density indices for vertical and lateral vibration are compared with comfort rating in figure 8. A combined vertical and lateral index composed of the vertical index plus twice the lateral index is also shown in figure 8. The relative weighting of two for the lateral value was used because the human seems to be about 1.4 times more sensitive to lateral vibration than vertical (see figure 1 in which the vertical minimum is 1.4 times the lateral). Since the PSD index operates on the square of vibration amplitudes, the weighting factor of 2.0 results.

In general, the data in figure 8 show effects similar to those discussed for the unweighted and weighted exceedance data in table 2 and figure 7. This would probably be expected to some extent; however, the power spectral density index does weight the larger amplitude vibration more heavily than the amplitude level exceedance count approach. Both the unweighted and weighted lateral PSD indices generally increase with comfort ratings (figure 8), but, again, there are large differences in the magnitudes of the index for equal ratings at different locations (train A). This comment also applies to the PSD index values for vertical vibration. As for the amplitude level exceedance approach, then, it does not appear that the magnitude of the power spectral density index correlates particularly well with comfort rating.

Because of the similarity in frequency and amplitude weighting between the PSD index and the absorbed power index, the preceding discussion indicates that the absorbed power index would probably not correlate in an absolute sense with comfort rating, either.

CONCLUDING REMARKS

The results of this study indicate that the indices examined (amplitude level exceedance count, weighted power spectral density and absorbed power) correlate to some extent with changes in comfort rating. However, the large differences in the magnitude of these indices which were shown to exist for the same rating at different locations casts doubt on their effectiveness as absolute indicators of ride quality. By implication, this result also indicates that weighting curves based on the inverse of the sinusoidal comfort contours may not properly condition vibrations.

The lack of correlation between index magnitude and comfort rating across locations may be due, to some extent, to the human's tendency to rate the ride relative to the average ride character at a given location rather than relative to some absolute standard. However, the lack of correlation between index magnitude and comfort rating is probably more a result of deficiencies in the indices. It is probable, for example, that the indices considered do not weight the effect of large, but relatively infrequent, vibration inputs as heavily as the human does in deciding his comfort rating. As an extreme example, if a subject experienced a vibration that threw him out of his seat once every other mile, he would probably not rate the ride comfortable. However, the nature of the indices considered is such that vehicle motion of this type is averaged over a long period and, therefore, is not heavily weighted. On the contrary, the indices examined tend to weight sustained lower level vibrations much more heavily and indications are that the human passenger may not. Also, the effects of jerk may be very significant in forming human opinion of comfort. Jerk effects (higher frequency harmonics) are attenuated by the sinusoidal comfort contour weighting functions.

Research is being continued at the United Aircraft Research Laboratories to investigate the effects described here and others in an attempt to develop better objective indices for ride comfort.

REFERENCES

1. Goldman, D. E.: The Biological Effects of Vibration. Shock and Vibration Handbook. McGraw-Hill Book Company, New York, 1957.

2. Carstens, J. P. and D. Kresge: Literature Survey of Passenger Comfort Limitations of High Speed Ground Transport. United Aircraft Research Laboratories Report D-910353-1, prepared under U. S. Department of Transportation Purchase Order P-7995-5, July 1965.

3. Pradko, F., R. Lee and V. Kaluza: Theory of Human Vibration Response. ASME Paper No. 66-WA/BHF-15, December 1966.

4. Bryce, W. D.: A Human Criterion for the Acceptance of Transverse Seat Vibration. Journal of Sound and Vibration, Vol. 3, No. 3, March 1966.

5. Miwa, T.: Evaluation Methods for Vibration Effect. Industrial Health, Vol. 5, pp. 183-220, 1967, and Vol. 6, pp. 1-27, 1968.

6. Begin, H.: The Riding Quality Analyser. Canadian National Railways Technical Research Centre, St. Laurent, Quebec, Memorandum No. 14, May 1968.

7. Bodeau, C. A.: Can We Measure Riding Comfort Electrically? SAE Paper No. 59-34T, March 1959.

8. Butkunas, A. A.: Power Spectral Density and Ride Evaluation. Journal of Sound and Vibration, Vol. 1, No. 12, December 1967.

9. Cramer, H.: The Elements of Probability Theory. John Wiley and Sons, New York, 1955.

10. Pradko, F., T. R. Orr and R. A. Lee: Human Vibration Analysis. SAE Paper No. 650426, May 1965.

TABLE 1

RIDE COMFORT MEASUREMENTS
MADE ON TRAINS A AND B

Objective Measurements

- Three-axis vibration measurements made simultaneously at two locations. These locations were changed at intervals during the run

- Sound decibel levels measured at different points in train cars

- Ride quality analyzer measurements

Subjective Measurements

- Sensation and comfort rated at locations of accelerometer packages using the following scales

None	Slight	Distinct	Strong
1	2	3	4

Sensation

Relaxing	Comfortable	Uncomfortable	Intolerable
1	2	3	4

Comfort

- Sound levels rated at locations of accelerometer packages

Low	Acceptable	Unacceptable	High
1	2	3	4

Sound

TABLE 1 (Concluded)

- Questions answered during ride evaluation

  Could you drink a cup of hot coffee (designated C in figures 4, 5, and 6)?

  Could you serve a hot meal to a passenger (M in figures 4, 5, and 6)?

  Could you write (W in figures 4, 5, and 6)?

  Could you read (R in figures 4, 5, and 6)?

  Do you sit without stiffening or bracing yourself against train motion (B in figures 4, 5, and 6)?

  Comment on motion or sound characteristics which are particularly annoying.

TABLE 2

PERCENT TIME GIVEN ACCELERATION LEVELS EXCEEDED FOR UNFILTERED, FILTERED AND WEIGHTED VIBRATIONS

TRAIN	LOCATION IN CAR	COMFORT RATING	Vibration Unfiltered with No Weighting						Seat Filter on Vertical No Weighting						Seat Filter on Vertical Weighting[1] Filters on Lateral and Vertical					
			Lateral			Vertical			Lateral			Vertical			Lateral			Vertical		
			.08g	.06g	.04g	.08g	.06g	.04g	.08g	.05g	.03g	.08g	.05g	.03g	.04g	.03g	.015g	.04g	.03g	.015g
A	CENTER	1	0.0	0.1	1.2	0.2	1.0	6.9	0.0	0.4	4.3	0.7	5.1	20.3	0.1	0.5	9.1	0.7	3.2	24.7
		2	0.0	0.3	2.7	0.3	1.4	8.6	0.0	0.8	7.6	0.9	6.9	24.4	0.1	0.7	13.2	0.8	3.9	27.8
A	REAR	1	0.6	2.0	8.0	0.6	2.9	13.0	0.6	4.0	16.1	3.1	14.4	36.7	1.2	4.1	26.2	5.4	13.2	42.6
		2	0.4	1.7	7.4	0.7	3.5	14.5	0.4	3.5	15.6	3.0	13.7	34.9	1.7	5.2	27.5	5.4	12.9	41.7
		3	0.6	2.8	10.9	0.8	3.9	15.3	0.6	5.3	20.3	3.7	14.6	35.4	2.4	6.9	32.3	6.6	14.4	42.8
B	CENTER	1	3.2	1.5	7.9	1.2	5.2	18.1	0.2	3.4	12.2	0.0	9.3	3.9	0.0	0.4	11.8	0.0	0.1	3.7
		2	0.4	2.2	9.2	1.7	7.2	22.4	0.4	4.6	20.3	0.0	0.2	2.9	0.2	0.7	10.9	0.0	0.1	3.3
		3	0.4	2.2	10.2	1.3	5.9	19.6	0.4	4.8	21.9	0.0	0.3	4.0	0.1	0.7	14.9	0.0	0.1	3.7

1 Inverse of sinusoidal comfort curve weighting (figure 2).

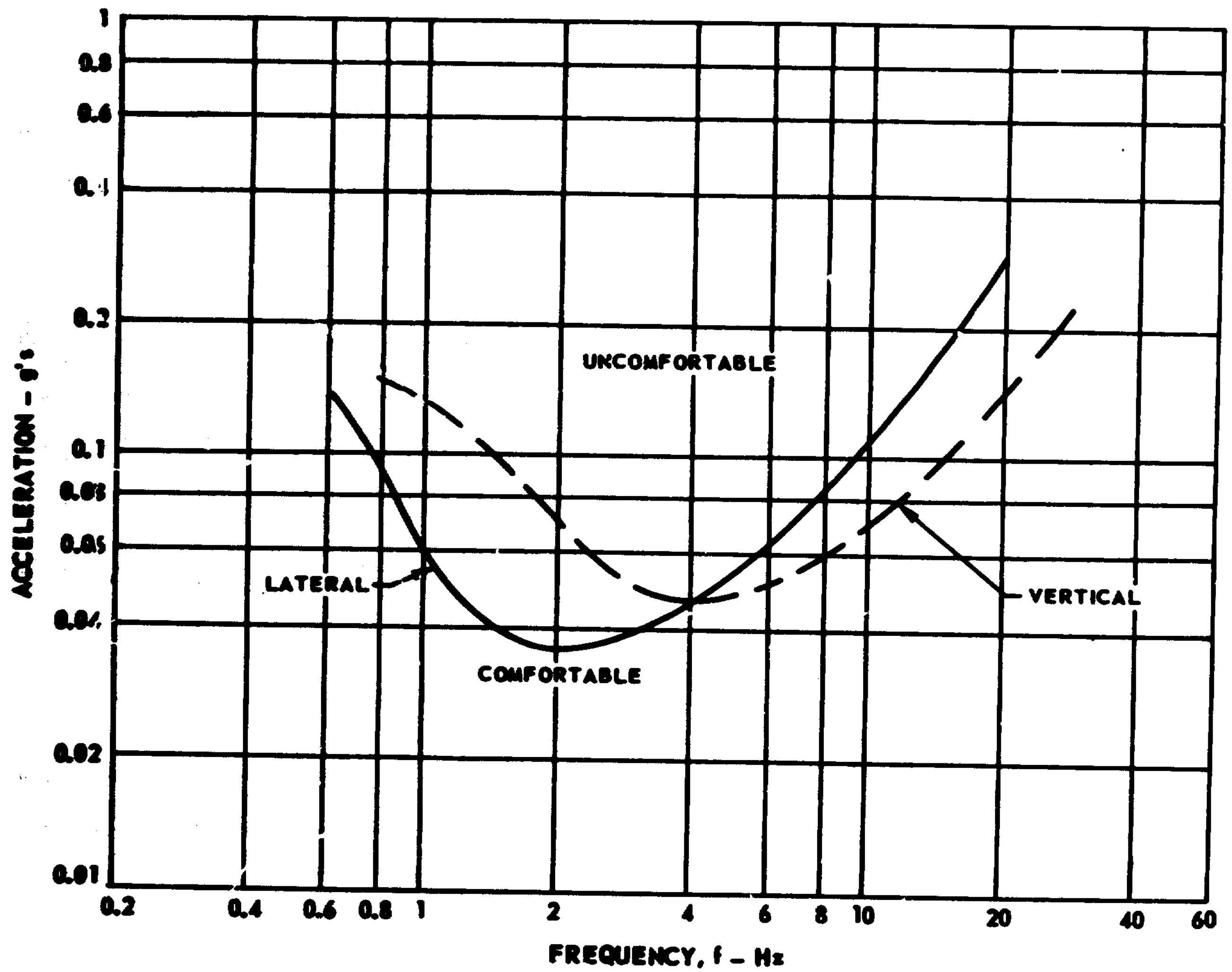


Figure 1.- Representative boundaries relating vertical and lateral sinusoidal vibrations to comfort.

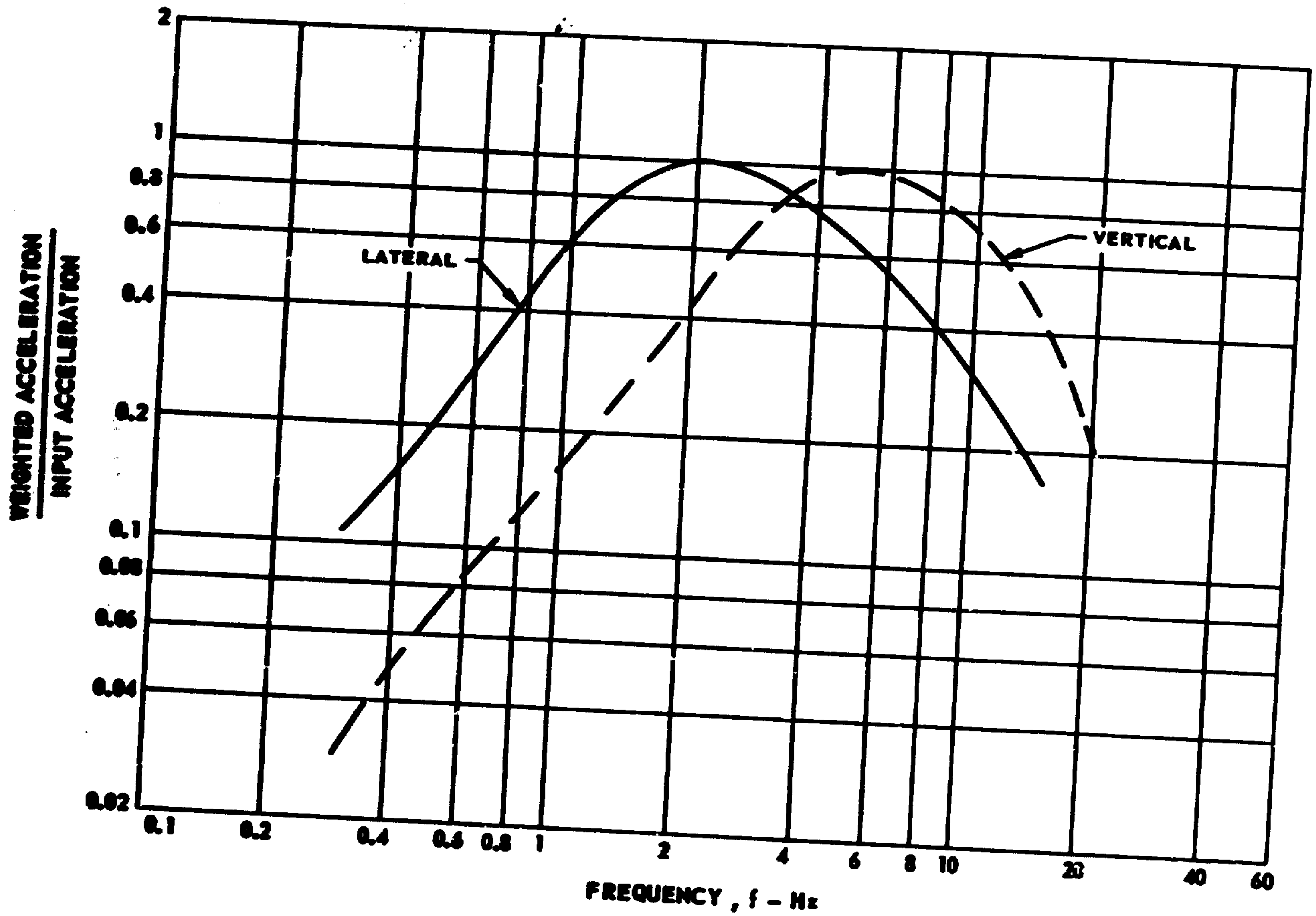


Figure 2.- Vertical and lateral acceleration weighting based on sinusoidal comfort criteria.

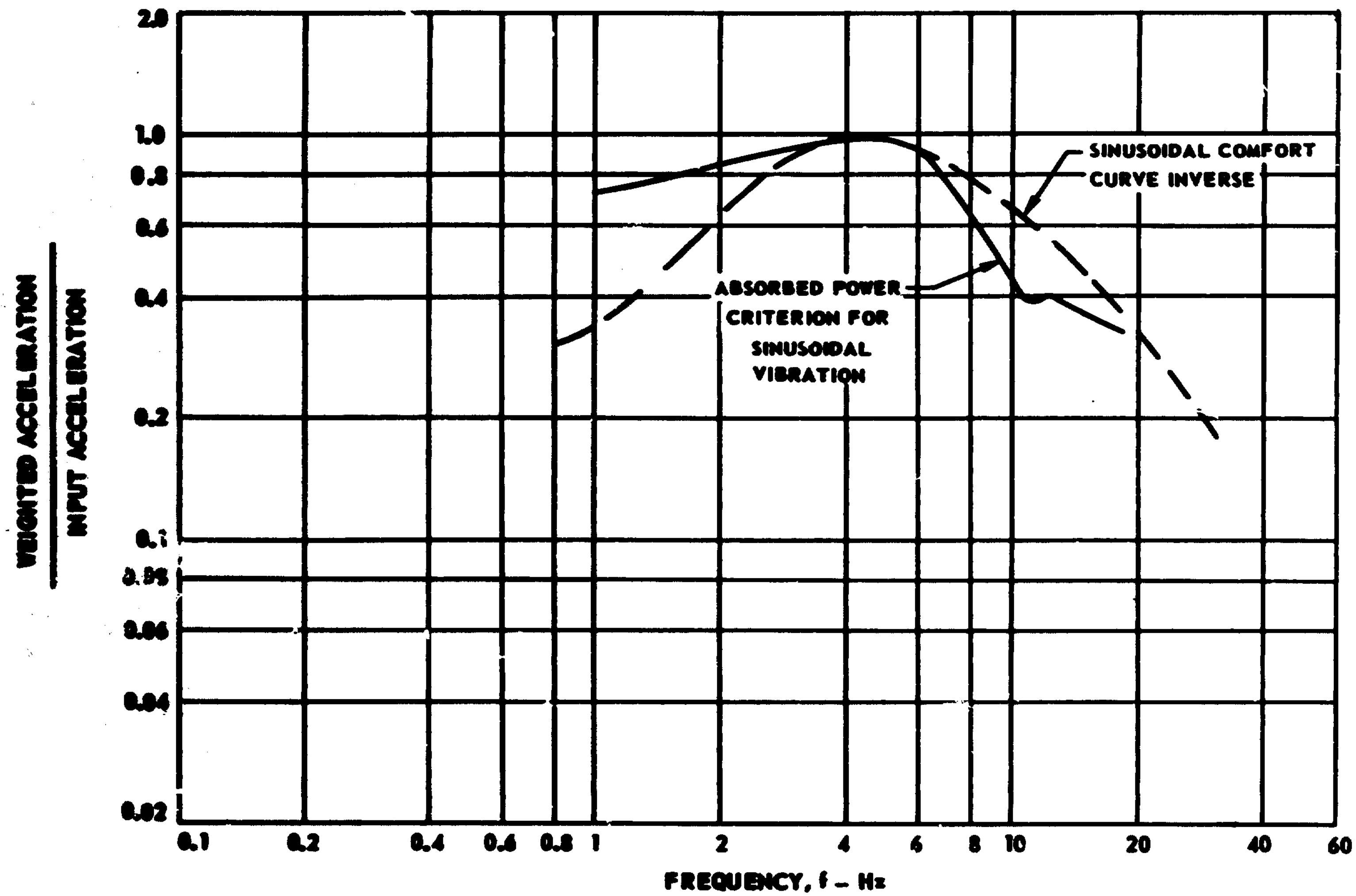


Figure 3.- Comparison of weighting based on the absorbed power criterion with weighting from sinusoidal vibration comfort boundaries.

SYMBOL	○	□
COMFORT RATING	1	2

COMFORT RATINGS (37 TOTAL) WERE ALL LESS THAN 3 AT THIS LOCATION. SEE TABLE 1 FOR DESCRIPTIONS OF RATING SCALES AND QUESTIONS

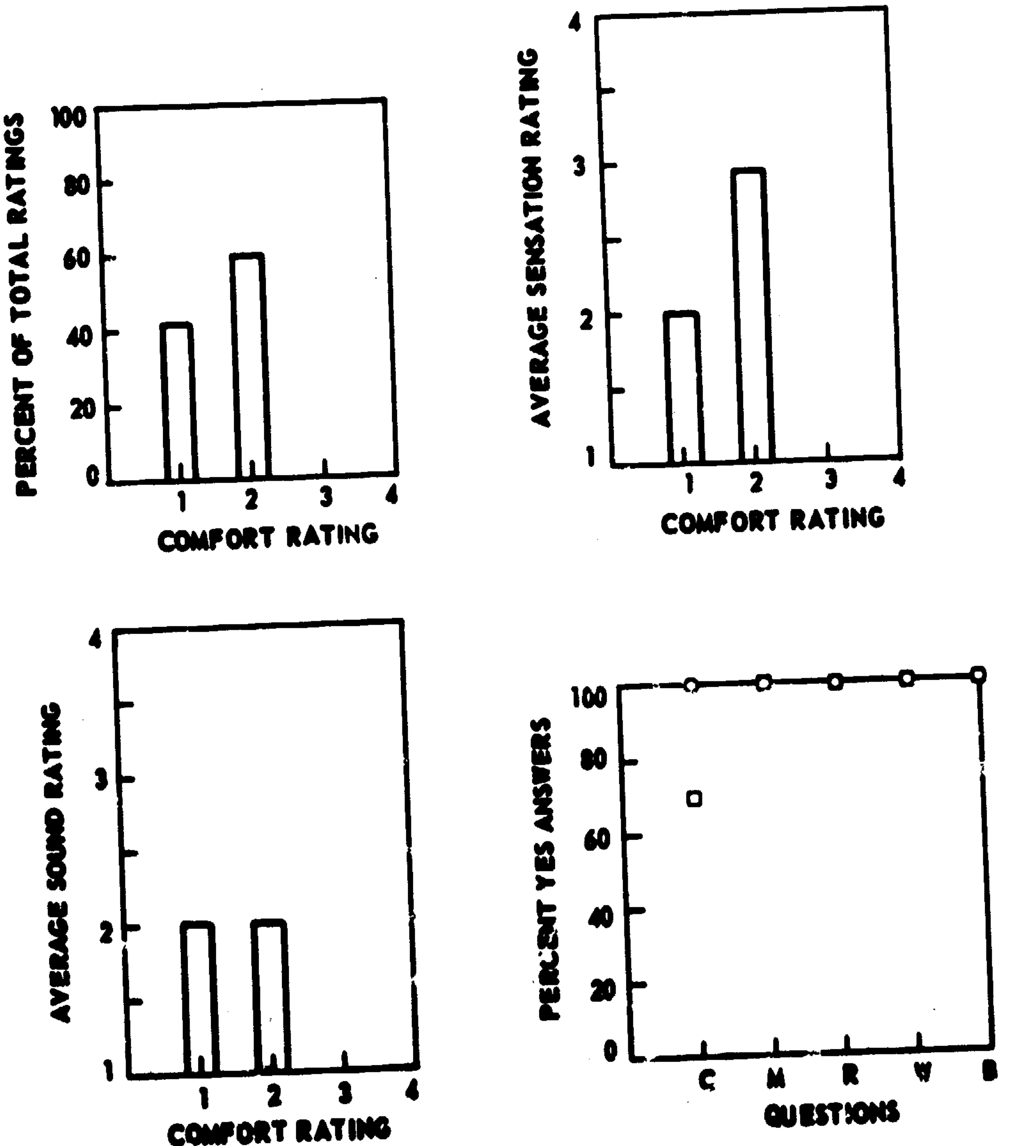


Figure 4.- Relationship between comfort rating and the associated subjective indicators of ride quality for train A – center of car.

SYMBOL	○	□	△
COMFORT RATING	1	2	3

COMFORT RATINGS (54 TOTAL) WERE ALL LESS THAN 4 AT THIS LOCATION. SEE TABLE 1 FOR DESCRIPTIONS OF RATING SCALES AND QUESTIONS

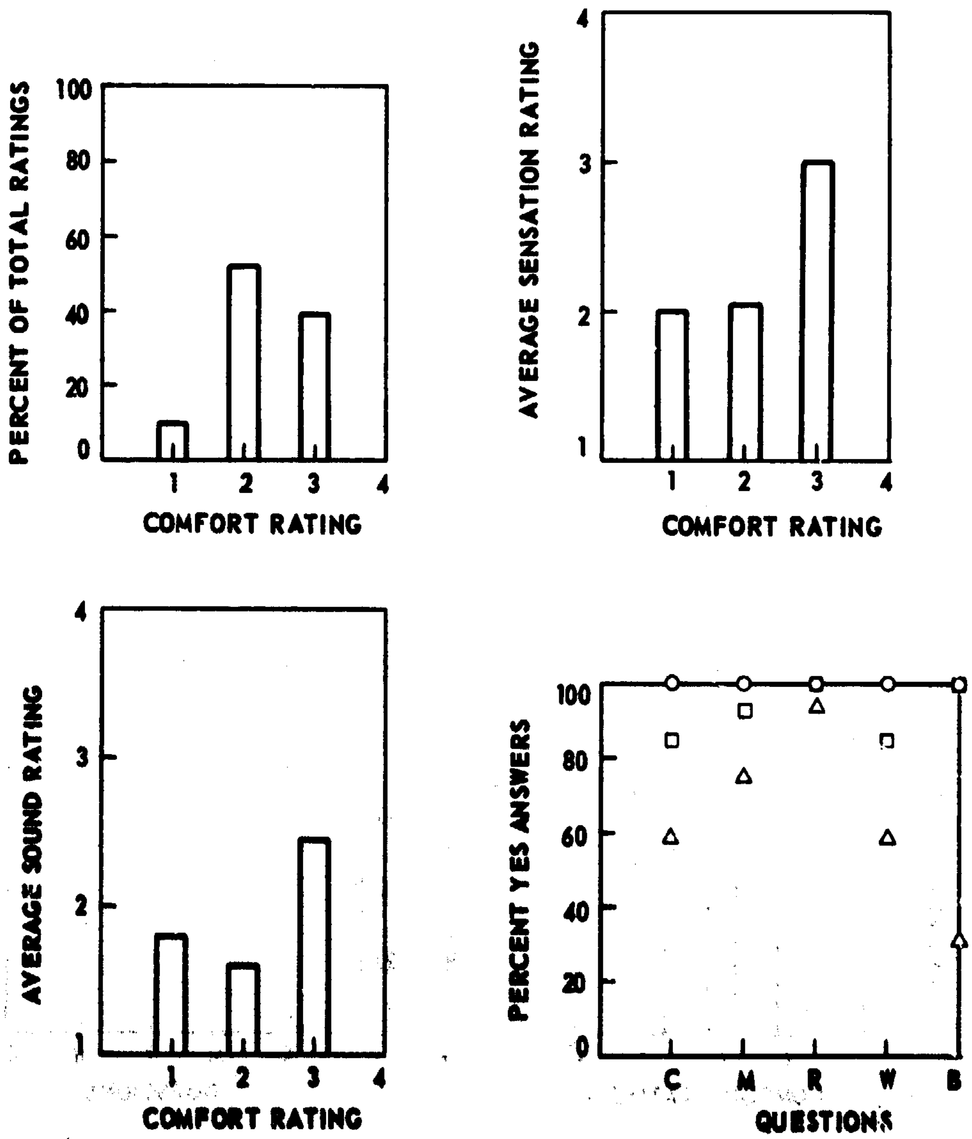


Figure 5.- Relationship between comfort rating and the associated subjective indicators of ride quality for train A — rear of car.

SYMBOL	○	□	△
COMFORT RATING	1	2	3

COMFORT RATINGS (33 TOTAL) WERE ALL LESS THAN 4 AT THIS LOCATION. SEE TABLE 1 FOR DESCRIPTIONS OF RATING SCALES AND QUESTIONS

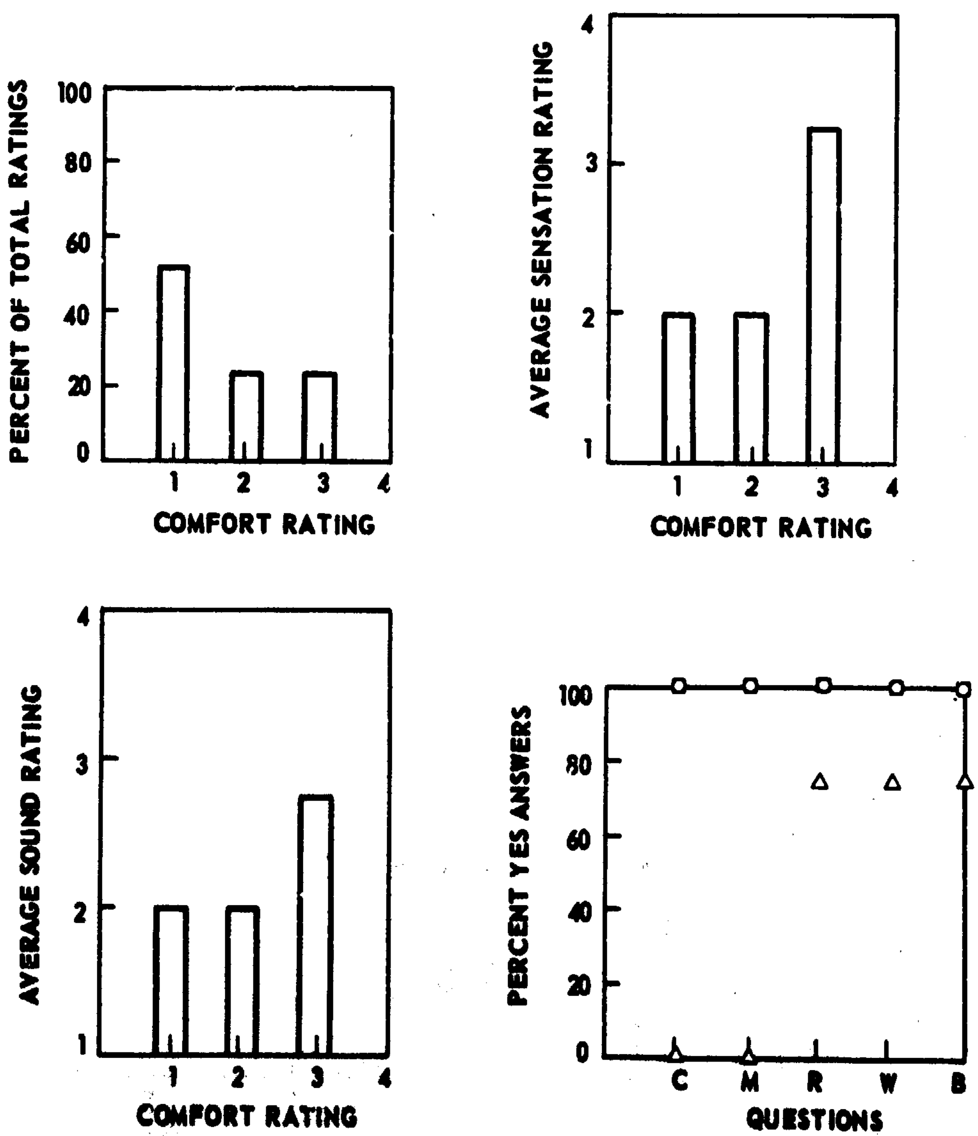
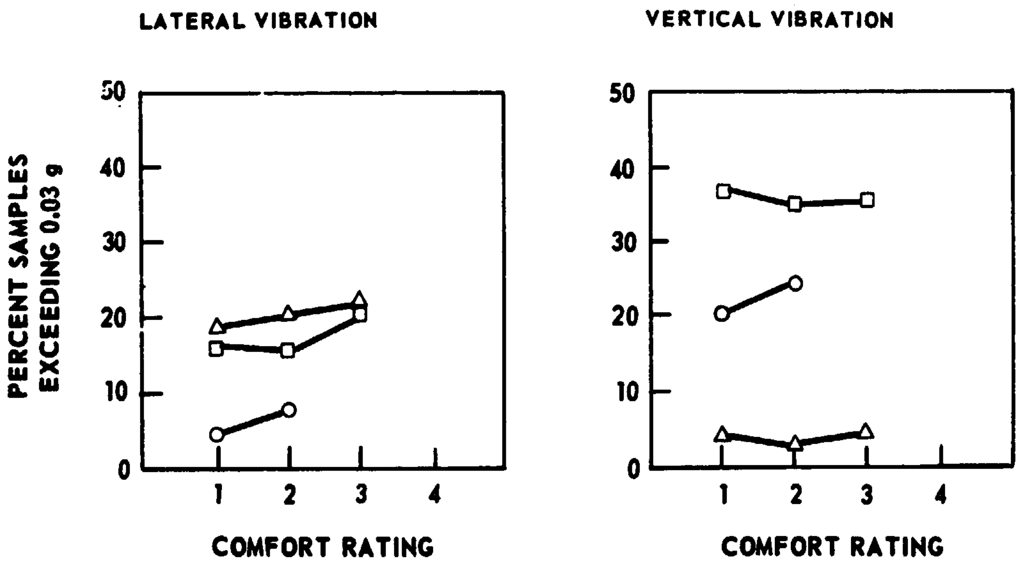
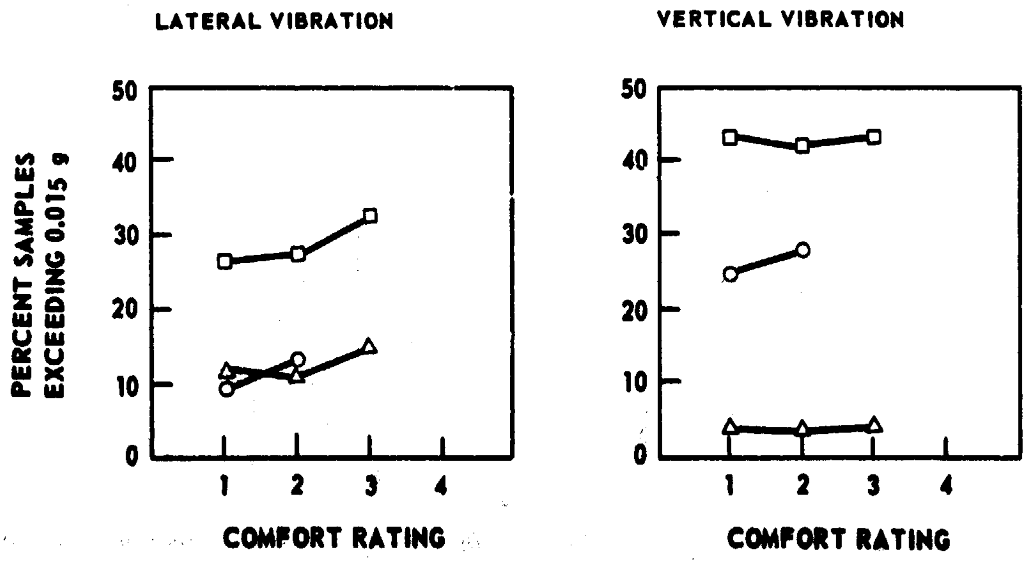


Figure 6.- Relationship between comfort rating and the associated subjective indicators of ride quality for train B — center of car.

SYMBOL	○	□	△
LOCATION	CENTER TRN A	REAR TRN A	CENTER TRN B



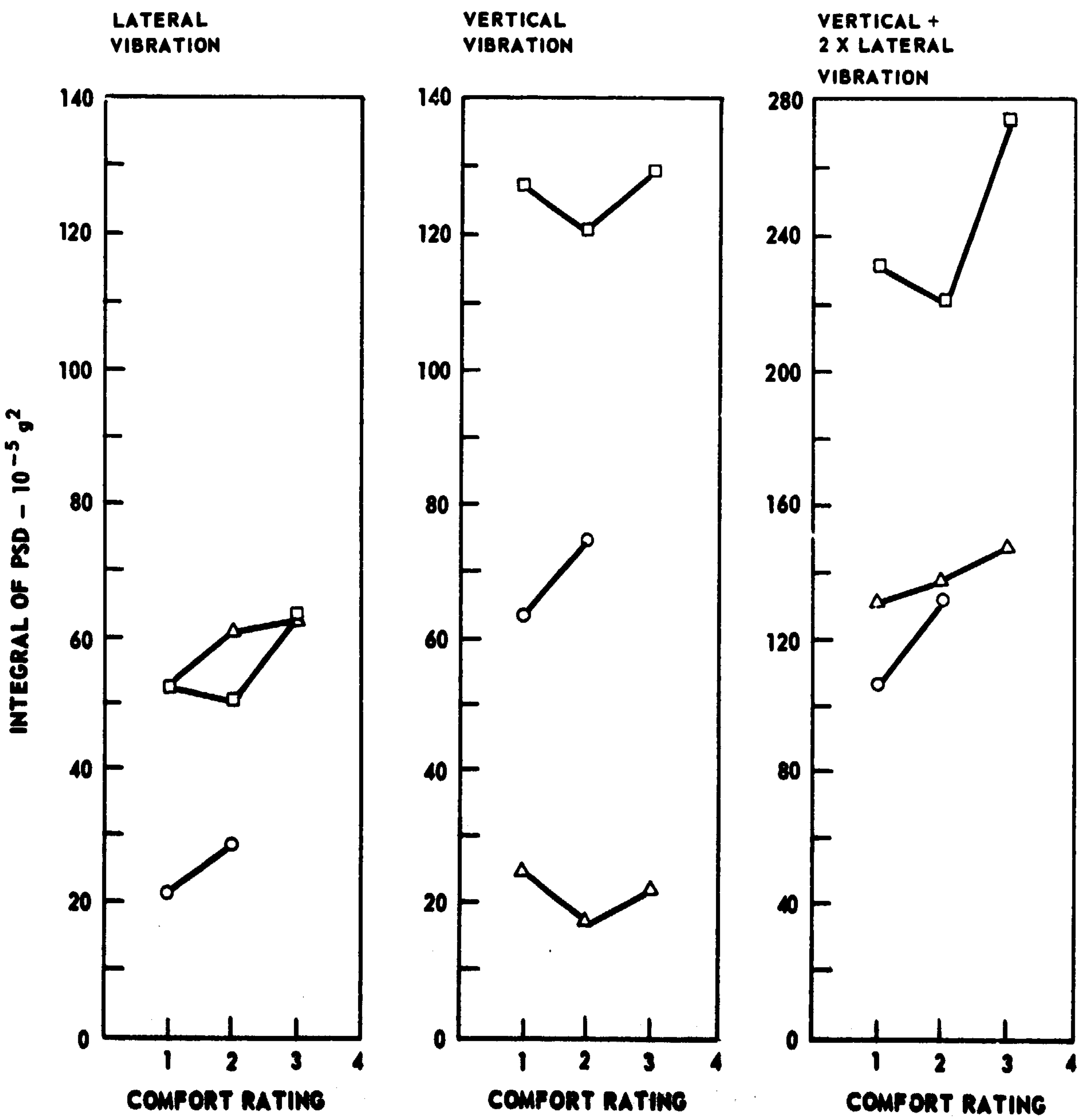
(a) Seat filter on vertical vibration, no weighting.



(b) Seat filter on vertical vibration, vertical and lateral vibrations weighted with inverse of sinusoidal comfort curves of figure 2.

Figure 7.- Variation of amplitude level exceedance index with comfort rating.

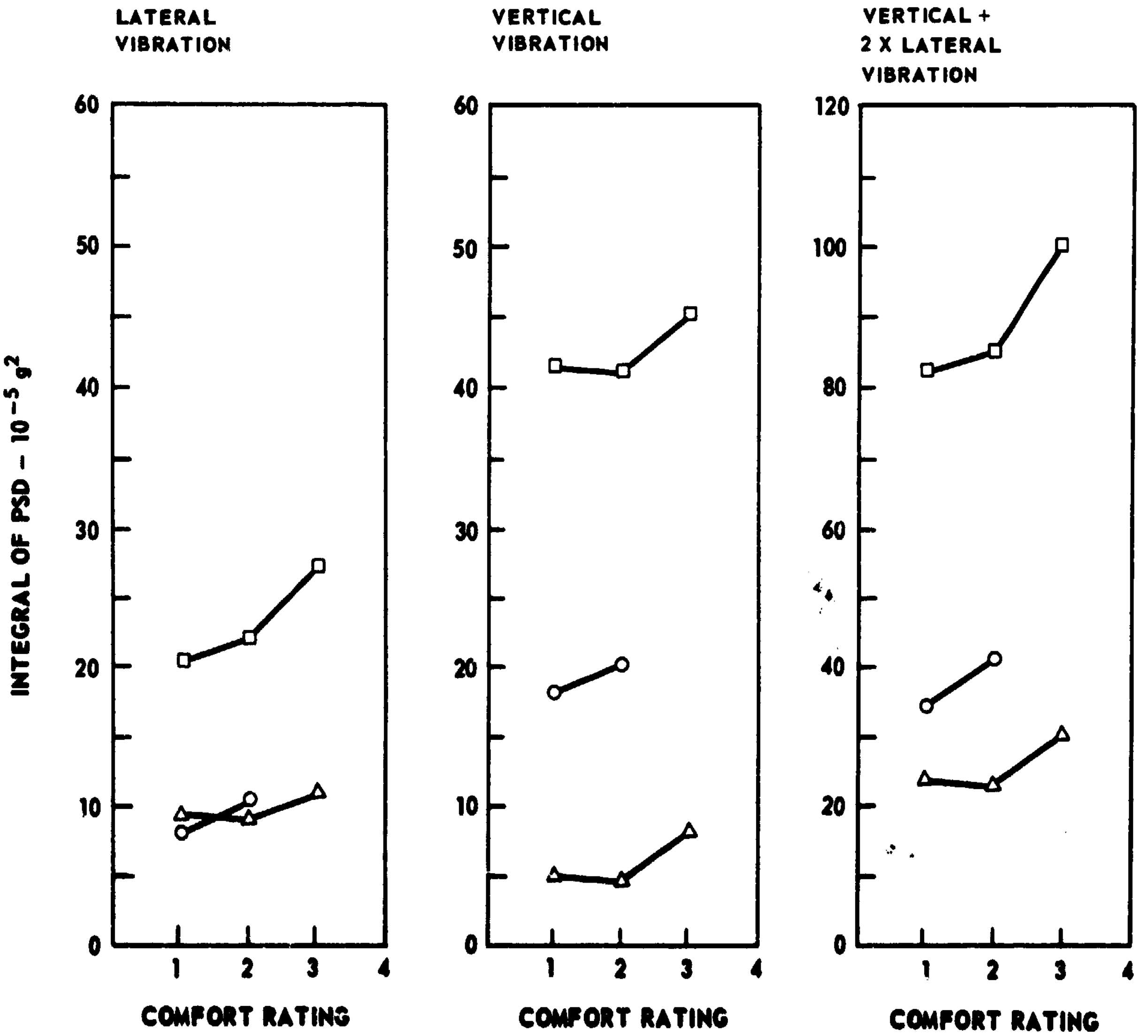
SYMBOL	○	□	△
LOCATION	CENTER TRN A	REAR TRN A	CENTER TRN B



(a) Seat filter on vertical vibration, no weighting. Note that ordinate scale of plot on right is twice that of other two plots.

Figure 8.- Variation of integral of power spectral density index with comfort rating.

SYMBOL	○	□	△
LOCATION	CENTER TRN A	REAR TRN A	CENTER TRN B



(b) Seat filter on vertical vibration, vertical and lateral vibrations weighted with inverse of sinusoidal comfort curves of figure 2. Note that ordinate scale of plot on right is twice that of other two plots.

Figure 8.- Concluded.

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HELICOPTER CREW/PASSENGER VIBRATION SENSITIVITY

By Richard Gabel and Donald A. Reed

THE BOEING COMPANY
Vertol Division
Philadelphia, Penna.

N73-10019

SUMMARY

Results of a recent test investigation of helicopter crew and passenger vibration sensitivity are presented. Pilot subjective ratings are established for discrete frequencies and the impact of combinations of harmonic frequencies is examined. A passenger long term comfort level and a short term limit are defined for discrete frequencies and compared with pilot ratings. The results show reasonable agreement between pilot and passenger. Subjective comfort levels obtained for mixed frequency environments clearly demonstrate the need for a multi-frequency criterion.

INTRODUCTION

In a helicopter, unsteady airloads on the rotors and structural characteristics of both the rotor blades and airframe give rise to a complex vibration environment. Available discrete frequency vibration comfort criteria, illustrated by the summary of Figure 1 from a previous study (Reference 1), display a significant variation in both terminology and the resulting subjective comfort levels. The threshold of discomfort was established in the Reference 1 study using the lower envelope of the literature data. While the information of Figure 1 has proved useful, flight experience with a number of helicopters indicated the need for a more refined criterion.

The multi-harmonic nature of helicopter vibration presents a further complication. In any given situation, the levels at each of the component rotor harmonics can be well within acceptable limits and still combine to produce an overall unacceptable comfort level. This fact is well recognized, but little if any quantitative information is available.

A brief test program was undertaken in an effort to provide some answers to these questions. Primary objectives were as follows:

1) Define discrete frequency levels which provide a comfortable environment for both pilot and passenger over a 2-3 hour period.

2) Considering practical factors, define an equivalent multi-harmonic environment.

TEST OF CREW SUBJECTS

Since the intention of the program was to obtain data applicable to aircraft, and helicopters in particular, a cushioned helicopter crew seat was utilized. A photograph of the test arrangement is shown in Figure 2. Vertical excitation of the seat was obtained by mounting the seat directly on the armature of a large electrodynamic shaker. A hard foot rest, also mounted on the shaker, was provided.

Two experimental test pilots experienced in vibration evaluation were used as test subjects. All testing was conducted with the subjects in normal street dress. The test subjects provided a qualitative assessment of the imposed vibration environment using a Cooper type numerical rating from 0 to 10 which is used for flight test evaluation. Emphasis was placed on establishing the long term comfort level.

PILOT VIBRATION RATING SYSTEM	
1-2	Definitely Perceptible
3	Long Term Comfort Level
5	Limit of Acceptability
7	Fatiguing
10	Short Term Limit

Single Frequency Results

Pilot ratings for discrete or single frequency excitation are presented in Figure 3. Above 12 Hz, the pilot long term comfort level lies slightly above the threshold of discomfort developed from the literature; while below 12 Hz, the long term comfort level falls appreciably lower. At 4 Hz the pilot long term comfort rating is only 40% of the discomfort threshold value. Information available on a number of crew seat cushions indicates that the natural frequency of a man on the cushion generally falls in the range of 3 to 6 Hz. The resulting dynamic amplification of the seat motion is, therefore, probably responsible in large measure for the low levels at frequencies below 12 Hz. Nonetheless, the indicated levels are representative of those required with a seat cushion designed to meet non-vibratory comfort standards.

Multi-Harmonic Results

Figure 4 presents a summary of significant mixed frequency results. A combination of six harmonic frequencies (Test A), with individual amplitudes corresponding to a constant pilot rating of 3 (long term comfort level), was found to double the degree of discomfort, resulting in a pilot rating of 6. When the component amplitudes were reduced by 50% (Test B), an improvement of only 16 to 17% was obtained in the comfort level. From an examination of the single frequency ratings of Figure 3, neither of these results are totally unexpected since the harmonic content of the mixed frequency is heavily biased toward the more sensitive low frequency range. Furthermore, the use of harmonic combinations such as 3 and 4, 3 and 5, etc., give rise to beats which correspond to lower harmonic frequencies. Test C confirms the merit of the preceding arguments and indicates that both the amplitudes and harmonic content had to be reduced to achieve a pilot rating of 3. The harmonic content of Test C is such that the lower beat frequencies correspond to a 3rd and 4th harmonic.

TEST OF PASSENGER SUBJECTS

A total of 8 non-pilot test subjects took part in this portion of the program. Only two of the subjects had any background in subjective vibration evaluation. Test conditions and equipment were the same as those for the pilot evaluation; however, no attempt was made to use a numerical rating system. The subjects were asked only to identify a long term comfort level and a short term limit.

Long Term Comfort Level

The scatterband of vibration amplitudes identified by the passenger subjects as a long term comfort level is shown in Figure 5. Pilot ratings and the threshold of discomfort from the literature are shown for comparison. The long term comfort level identified by the pilots is seen to lie within the passenger scatterband, and the scatterband is roughly centered between the perception level and the pilot's limit of acceptability. It is also observed that the discomfort threshold from the literature falls within the passenger scatterband above approximately 9 Hz and is very close to the mean value between 20 and 30 Hz. Below 9 Hz the discomfort threshold deviates rapidly from the passenger scatterband. Finally, the reduction in scatter with decreasing frequency clearly indicates the increased subjective sensitivity at low frequencies.

Short Term Limit

The passenger identified short term limit is indicated by the scatterband of Figure 6. Unfortunately, the equivalent pilot rating was not defined; however, an estimated value is shown. Above 15 Hz the equivalent estimated pilot rating lies close to the mean of the passenger scatterband; while below 15 Hz, the passenger data is significantly lower. Once again, the reduced scatter in the low frequency range is indicative of increased sensitivity.

CONCLUDING REMARKS

1. Harmonic frequencies, representative of a helicopter mixed frequency environment, combine to produce beats which correspond to lower harmonic frequencies. This apparent increase in the low frequency content results in an increased subjective sensitivity to multi-harmonic vibration.

2. The usefulness of a mixed or multi-harmonic frequency criterion for helicopter applications is evident. From a practical viewpoint, a means of simply identifying the offensive components of a given environment would also be of value.

3. Discrete frequency testing shows little significant difference between pilot and passenger definition of a long term comfort level. Below 9 to 10 Hz the level was lower than predicted from a previous review of the literature. The tight scatterband in this range ($\pm$ .012 G's maximum) indicates a high subjective sensitivity to low frequencies.

4. An overall comparison with the literature appears to indicate that the cushioned crew seat influences the results. Relative to the established threshold of discomfort, the trend of the long term comfort level shows amplification at the low frequencies and isolation of the high frequencies.

REFERENCES

1. Gabel, R., Henderson, B. O., and Reed, D. A.: Pilot and Passenger Vibration Environment Sensitivity. Journal of the American Helicopter Society, Volume 16, No. 3, July 1971, pp.39-43.

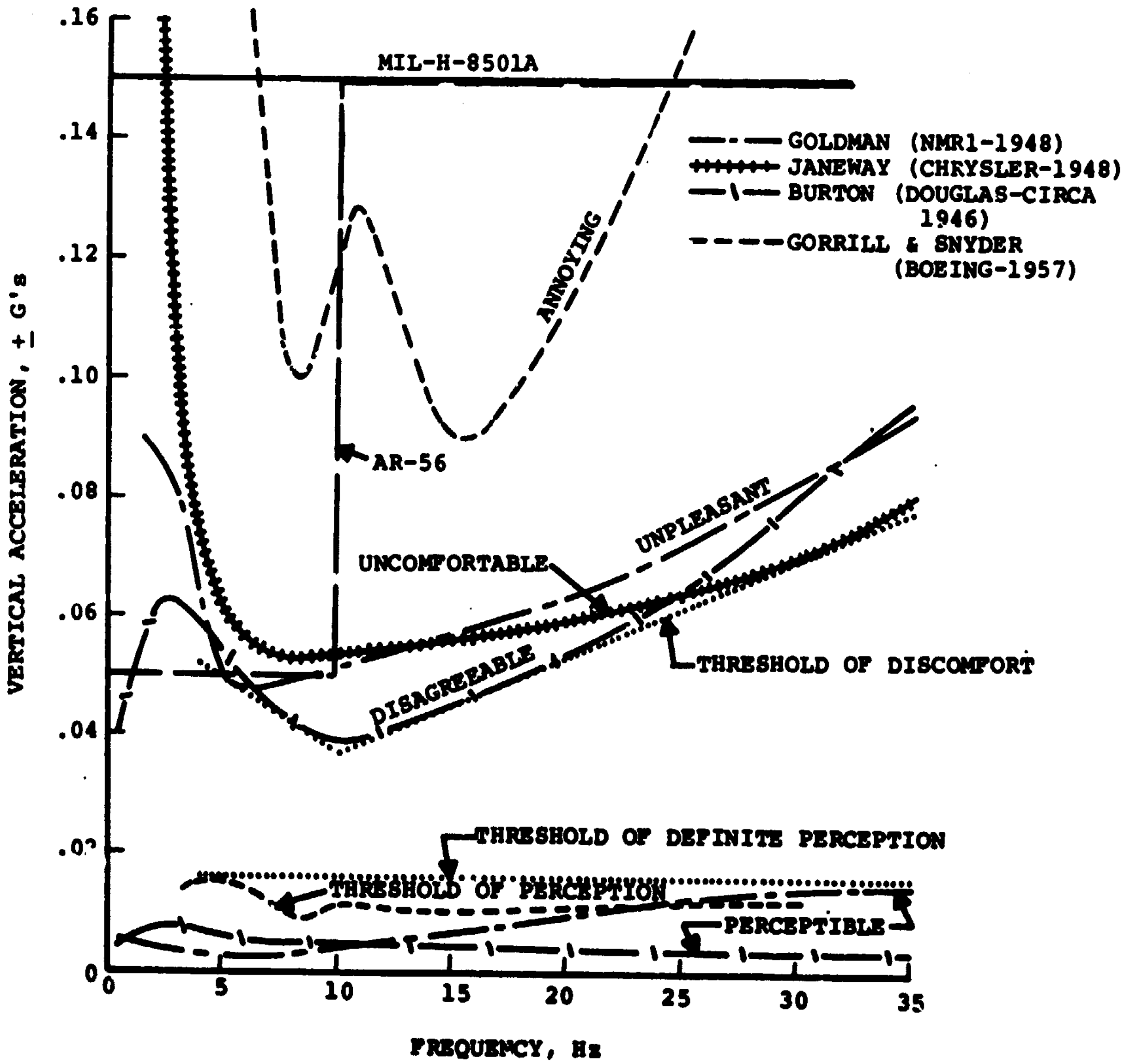

Figure 1.- Summary of published criteria.

Figure 2.- Test arrangement for pilot/passenger vibration evaluation.

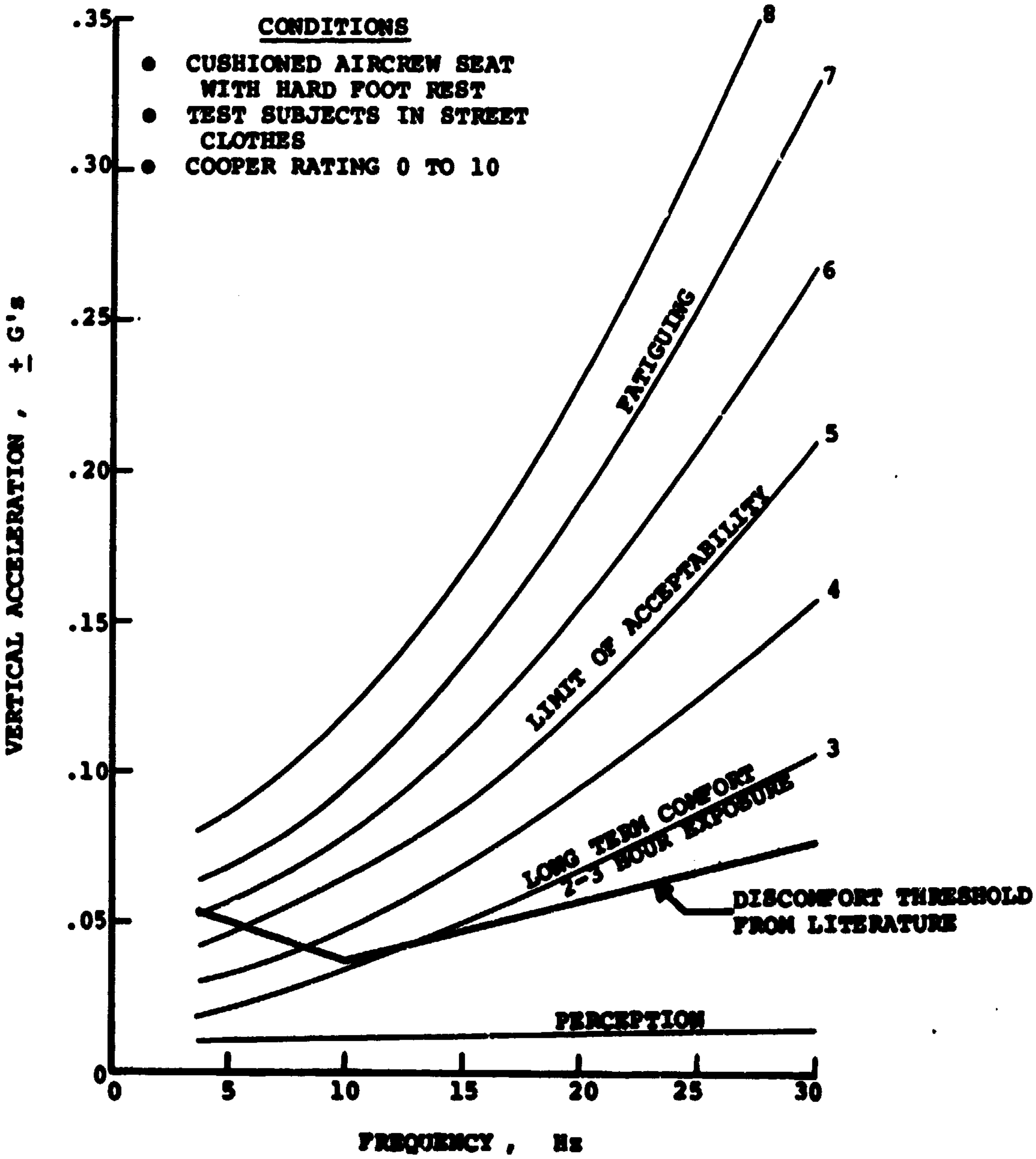

Figure 3.- Single frequency pilot comfort rating.

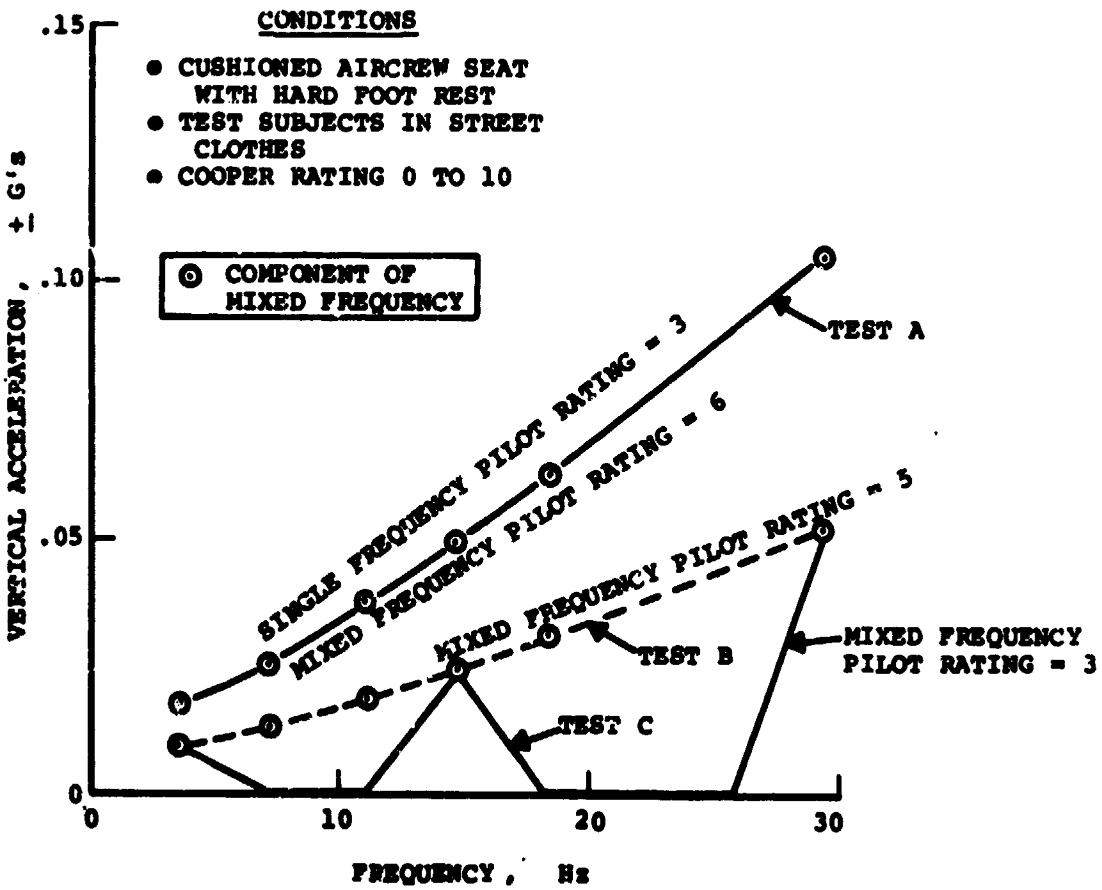

Figure 4.- Comparison of single and mixed frequency pilot comfort ratings.

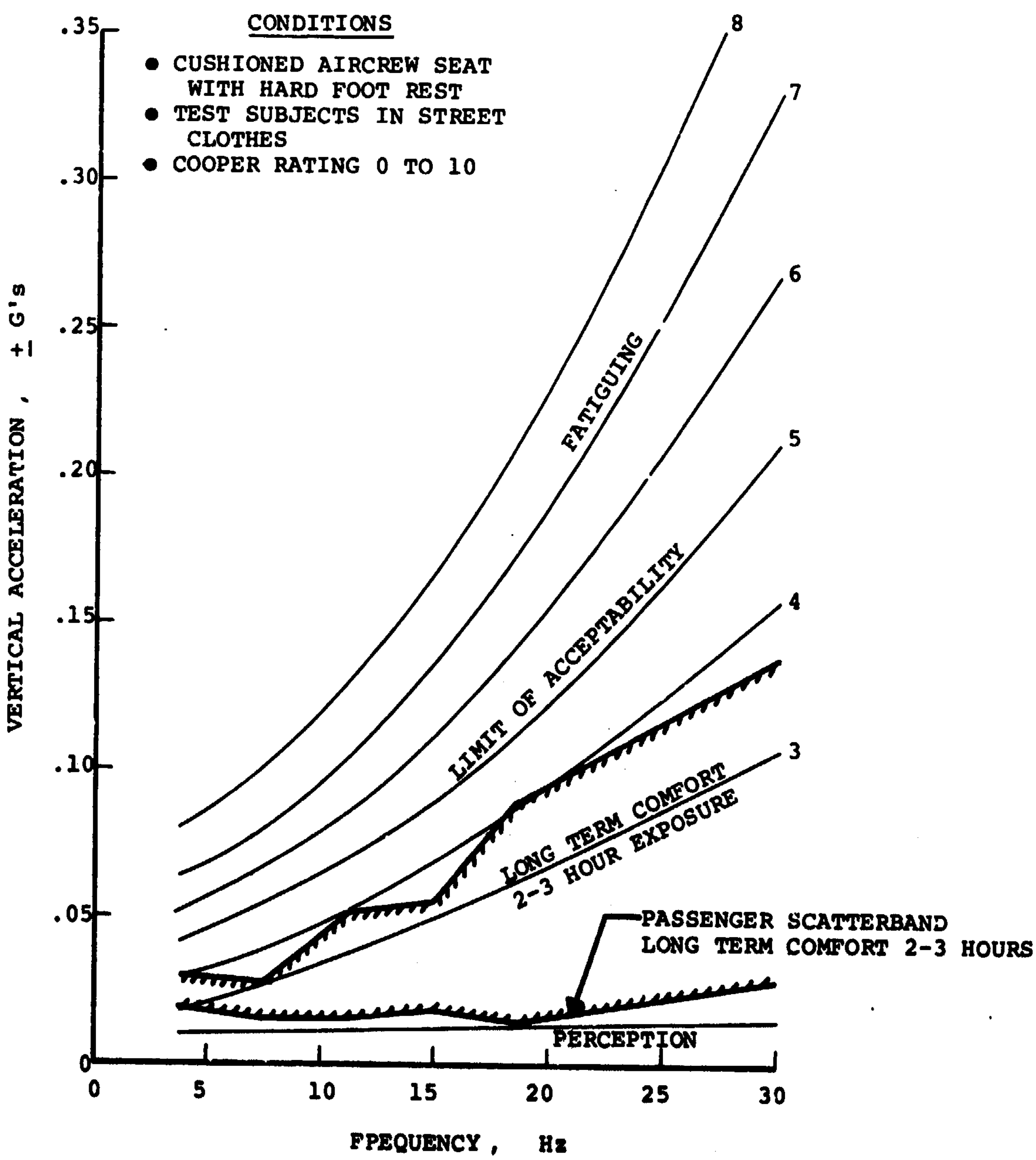

Figure 5.- Comparison of pilot rating and passenger long term acceptable comfort.

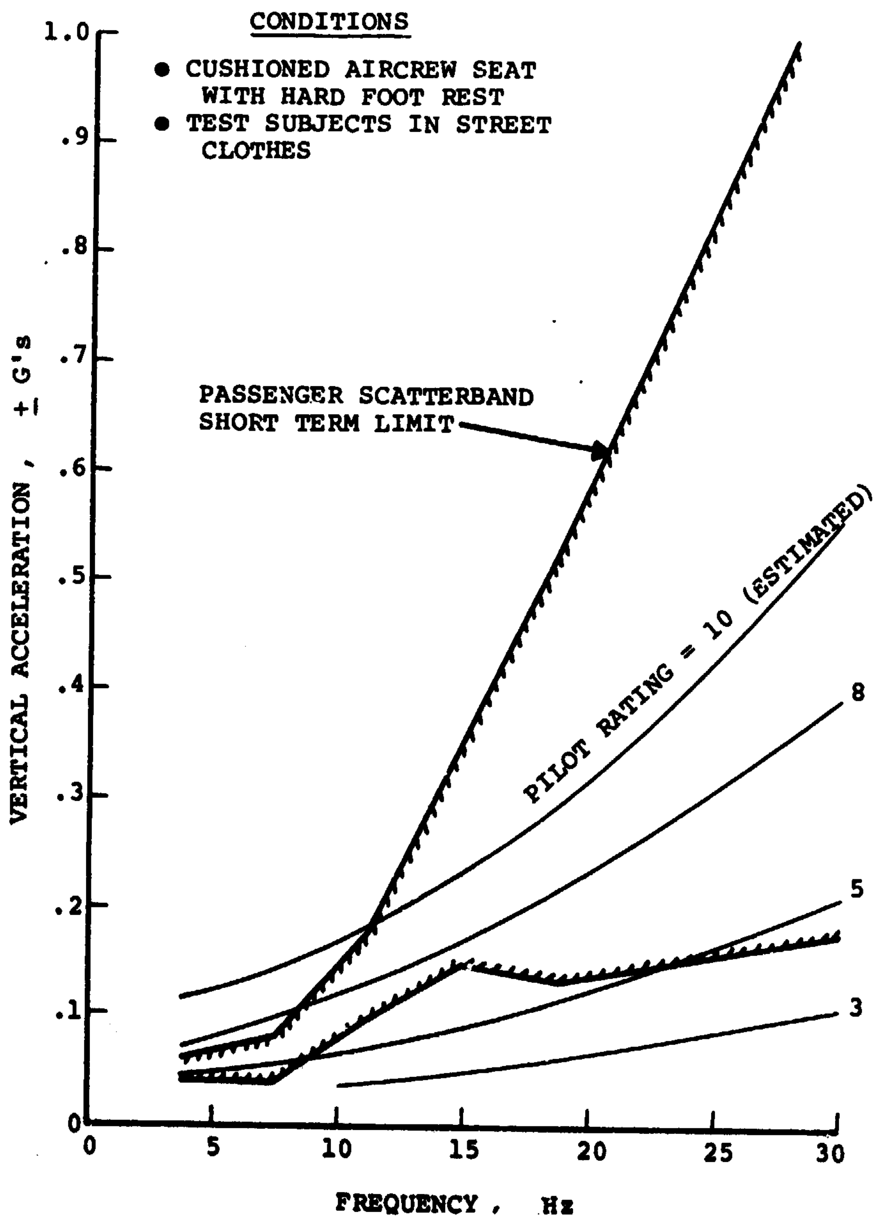

Figure 6.- Comparison of pilot rating and passenger short term limit.

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SOME OF THE MECHANISMS UNDERLYING MOTION SICKNESS[1]

By Ashton Graybiel

Naval Aerospace Medical Research Laboratory

SUMMARY

N73-10020

Motion sickness is a convenient clinical term to designate one category of vestibular side effects resulting from too rapid a transition into certain stressful motion environments. The primary etiological factor is a loss of stability in the vestibular system caused by repetitive sensory inputs that are abnormal in terms of the central vestibular patterning encountered. The immediate result of this instability is the elicitation of vestibular reflex disturbances that may include "sensations," visual illusions, and nystagmus. Evidence is presented supporting the opinion that motion sickness is an epiphenomenon superimposed on any responses in the reflex category due to vestibular influences that cross a temporary or "facultative" linkage to reach nonvestibular sites where first-order motion sickness symptoms have their immediate origin. Part of this evidence is based on the causal relation of reflex vestibular disturbances and motion sickness, including the fact that, in the slow rotation room, direction-specific adaptation of both types of responses may be shown.

INTRODUCTION

It was not until the turn of the last century that it was generally agreed that the sensory organs of the inner ear served functions other than hearing. It seems almost incredible that it remained for Goltz as late as 1870 (ref. 1) to draw the important inference from Flourens' studies (ref. 2) (in which Flourens caused loss of equilibrium in pigeons by sectioning the semicircular canals) that if disequilibrium is caused by labyrinthine lesions, the same site must be involved with equilibratory function. After Goltz, within a period of 5 years the theoretical basis underlying stimulation of the mechanoreceptors in the semicircular canals and otolith organs was elaborated. The three

[1]This research was conducted under the sponsorship of the Office of Life Sciences, National Aeronautics and Space Administration, Order W13433.
Opinions or conclusions contained in this report are those of the author and do not necessarily reflect the views or endorsement of the Navy Department.

pairs of canals (essentially gravity independent) are stimulated by impulse angular accelerations, and the two pairs of otolith organs are stimulated by gravity and by impulse linear accelerations. This theoretical basis has stood fairly well the test of time (refs. 3 to 5).

Centuries before Goltz, vestibular side effects such as motion sickness and dizziness were subjects for scientific discourse, but it was James (ref. 6) in 1882 who reasoned that if Goltz' deduction was correct, "deaf mutes" with loss of labyrinthine function should not experience dizziness. James demonstrated that in many of his subjects, manifestations of dizziness were either mild or absent. Moreover, none of the subjects in this group who had been exposed to rough weather at sea had experienced motion sickness. Thus, it was established that the vestibular system plays a dual role in the present-day lives of even typically normal women and men. One role is represented by the elegant manner in which the vestibular system functions under natural terrestrial-stimulus conditions and the other, by the ease with which this system either provides unwanted information or is rendered unstable under unnatural stimulus conditions.

During natural activities we are not aware of the functioning of the vestibular system, and under these conditions it is exceedingly difficult to conduct experiments because the investigator is severely limited in manipulating and measuring the stimuli and in identifying and measuring responses. Consequently, nearly all experiments depend on using an unnatural stimulus that elicits side effects either under field or laboratory conditions. Field operations have the great advantage of relevancy but drawbacks in terms of measuring the stimulus conditions in the conveyance and the responses elicited in pilot, subject, or passenger. Under laboratory conditions the experimenter uses a device either to simulate stimulus conditions in a conveyance and then measure the responses elicited, or to elicit specific (vestibular) side effects by programming or otherwise manipulating stimulus conditions. In either case, from an analysis of the data obtained, certain implications may be drawn concerning mechanisms underlying the symptomatology.

In the discussion to follow an attempt will be made to demonstrate that vestibular side effects tend to fall into two main categories, reflex vestibular disturbances and motion sickness; and that direction-specific adaptation of both occurs in a slowly rotating room. The fact that adaptation of reflex vestibular disturbances must involve the vestibular system suggests the same is true of motion sickness. Before presenting selected experimental findings it is helpful to have in mind a conceptual framework into which these findings are supposed to fit.

CONCEPTUAL FRAMEWORK

The schema in Figure 1 represents an attempt to fit important elements concerned with vestibular input-output relations into a conceptual framework (ref. 7).

Natural Stimulus Conditions

Blocks I to IV A show the functioning of the vestibular system under natural stimulus conditions. During natural activities the responses to which the vestibular system contributes are characterized by automaticity, reliability, and egality among members of a species or subspecies. In man the vestibular system contributes to perception of the upright and, by influencing motor behavior, aids in maintenance of postural equilibrium and in stabilization of the retinal image. During natural activities there is little if any manifestation of vestibular "disturbance."

Unnatural Stimulus Conditions

The abnormal accelerative stimuli and their influence on the peripheral organs with resulting alteration in sensory inputs are shown by means of coded lines in Blocks I to III. Reflex vestibular disturbances are revealed mainly through effector mechanisms that normally articulate with the vestibular system; however, to provide for any additional polysynaptic pathways the responses are shown in Block IV B. Responses include a characteristic sensation of tumbling or rotation, illusions, nystagmus, dizziness, and neuromuscular incoordination. In general, reflex vestibular responses have the following in common: (1) short latencies, (2) maximal response to the initial stimulus, (3) response decline to repeated stimulation, and (4) no perseveration of responses except when explicable on the basis of physical restoration of mechanoreceptors in the peripheral organs or compensatory phenomena incidental to restoring stability in the vestibular system or to both.

Another category of vestibular side effects comprises an epiphenomenon superimposed on any manifestation of the first category and best known under the general term motion sickness. Motion sickness is elicited by certain repetitive accelerative stimuli that not only disturb the vestibular system (Blocks I to III), but also allow vestibular influences to escape their normal bounds and stimulate nonvestibular servation systems (Blocks V to VII). To effect this, it is necessary to postulate: (1) a loss of stability in the vestibular servation system, (2) a facultative linkage (probably in the brain stem reticular formation), and, possibly, (3) an additional "escape mechanism" of a humoral nature. First-order responses in turn act as stimuli eliciting second-order responses, and so on, until, in severe motion sickness, the entire organism may be involved. The typical symptoms of frank motion sickness are well known, but we have only fragmentary knowledge of the sequential ordering of first, second, and higher order responses.

An analysis of the typical symptomatology reveals the following characteristics: (1) delay in appearance of symptoms after the onset of the stressful stimuli, (2) gradual or rapid increase in severity of symptoms, (3) modulation by secondary etiological factors, (4) perseveration after sudden cessation of stimuli, and (5) response decline indicating recovery. Further abstractions reveal: (1) great individual differences in susceptibility and in the acquisition and decay of adaptation, (2) transfer of adaptation effects, and (3) conditioning.

Recovery from frank motion sickness during continual exposure to stress is complicated. First, the nonvestibular systems (Block VI) must be freed from vestibular influences as the result of adaptation taking place in the vestibular system (Block III) and, possibly, elsewhere. The point in time when this occurs is difficult or impossible to determine because it is not immediately reflected by the disappearance of symptoms. Symptoms perseverate (after nonvestibular systems have been freed of vestibular-generated influences) until restoration takes place (spontaneously) through homeostatic mechanisms. The time of engagement and disengagement between the vestibular and nonvestibular systems is best determined when a subject is exposed to severe stress for only a short period.

EXPERIMENTAL MOTION SICKNESS

Devices

A slow rotation room (SRR) in a laboratory setting (fig. 2) provides an excellent facility for the study of experimental motion sickness. The subject is exposed to stressful accelerations (mainly cross-coupled angular accelerations) when he rotates his head out of the plane of the room's rotation, and the onboard experimenter can avoid the stress by avoiding these head movements. The intensity of the stressful accelerations can be controlled by standardizing the head movements and varying the angular velocity of the room's rotation. We have used a chair (fig. 3) with adjustable pads (front, back, left, and right), acting as "stops" permitting rotation of the head (and body) through arcs up to 90 degrees. Eight movements, "over" and "back," in the four directions are randomized, and taped recordings set cadences that vary from 2 to 6 seconds. The angular velocity of the SRR can be varied up to 30 rpm clockwise or counterclockwise. By controlling this stressful type of stimulus, the experimenter manipulates the sensory input for the purpose of eliciting (or preventing the elicitation) of vestibular side effects that can be identified and measured.

Scoring Side Effects

After each discrete head movement the subject signals ("yes" or "no") whether he detects a sensation or movement, an apparent visual movement (oculogyral illusion), or a tendency to be deflected from the plane in which the movement is carried out (refs. 8 and 9). The severity of motion sickness symptoms is given numerical scores according to the diagnostic criteria in table 1 (ref. 10). A score of 15 points represents the highest level of mild motion sickness.

The Stress Profile

Some typical stress profiles are shown in figure 4. The initial incremental adaptation schedule (IAS) is followed either by a one-step return to zero velocity (fig. 4 a) or by a reverse IAS (fig. 4 c). If direction-specific central vestibular repatterning occurs during the initial IAS, the subject is adapted to the rotating environment and has lost his adaptation to the stationary environment. Consequently, after return to zero velocity, although head movements generate normal stimuli, the sensory input encounters an abnormal pattern and vestibular side effects may be elicited. Because the stimulus is normal, the so-called challenge is weak compared with the abnormal stimulus when the direction of rotation is reversed, which is termed a strong challenge. After the initial IAS and return to zero velocity, delays (during which the subject remains with head fixed) may be instituted either before the execution of head movements at zero velocity (fig. 4 b) or before the reverse IAS (fig. 4 d).

Selected Experimental Findings

Motion sickness. — Figure 5 summarizes the measurements made in two young, typically normal men. On the left it is seen that the subject was symptom free (zero scores) during the initial IAS but experienced mild symptoms when head movements were executed after a one-step return to zero velocity. Inasmuch as the stimuli generated at zero velocity were normal, the elicitation of symptoms implies that the normal sensory inputs encountered other than a normal, central vestibular patterning, which could have been acquired only during the initial IAS and must have been direction specific. The same reasoning holds for the measurements made in the other subject, the difference being that the severity of symptoms elicited on return to zero velocity necessitated an abort.

Figure 6 summarizes the measurements made in two tests in a healthy young man. In the first test SH was symptom free not only during the initial IAS, but also during the challenge at zero velocity. The test 6 days later differed in that the direction of rotation was reversed immediately after completion of the initial IAS. The fact that testing was aborted after the execution of 104 head movements at 1 rpm demonstrates at once the greater challenge on reversal compared with that at zero velocity and the fact that direction-specific adaptation had been acquired during the initial IAS. The greater challenge after reversal of direction compared with return to zero velocity is a reasonable expectation.

Figure 7 shows the measurements made in a young man 22 years of age. In the first test direction-specific adaptation effects were demonstrated when testing was aborted during the challenge on return to zero velocity. Nine days later in test 2, FR was virtually symptom free when the direction of rotation was reversed. The absence of frank motion sickness is explained by the 8-hour delay between the initial and reverse IAS. The fact that the head was fixed during the delay implies that the direction-specific adaptation effects disappeared, to a large extent at least, spontaneously.

Simultaneous measurement of reflex vestibular disturbances and motion sickness. — Figure 8 summarizes the findings in two successive tests in a young man 23 years of age. The incidence of reflex vestibular disturbances (RVD) increased greatly during the execution of head movements after the return to zero velocity (test 1), but despite this evidence of loss of stability in the vestibular system proper, motion sickness was virtually absent. In the second test the incidence of RVD during the initial IAS was lower than in the first test, probably reflecting the retention of adaptation effects. On reversing the direction of rotation, the incidence of RVD rose sharply (at 1 rpm), but the subject remained virtually immune to motion sickness. Indeed, the unvarying scores of 1 point raise a doubt concerning their validity.

The findings shown in figure 9 were obtained in a healthy male 22 years of age. In test 1 the subject did not manifest symptoms of motion sickness during the IAS, although the incidence of RVD was high. During the challenge after return to zero velocity very mild symptoms of motion sickness were experienced along with a substantial increase in the incidence of RVD. In test 2 during the initial IAS very mild symptoms of motion sickness were experienced, and there was a rapid incremental increase in the incidence of RVD. On reversal of rotation, testing was aborted after 40 head movements due to nausea, and the RVD incidence was 100 percent.

Figure 10 summarizes the findings in two young healthy subjects well above the average in their susceptibility to motion sickness (based on past history). The data in figure 10 a show that testing was aborted due to frank motion sickness after 20 head movements were executed at 5 rpm during the IAS. The low incidence of RVD is noteworthy, rising only to 15 percent at terminal velocity. In figure 10 b testing was discontinued after 24 head movements were executed at 4 rpm during the IAS; in this case, the incidence of RVD rose rapidly.

Comment. — These findings indicate that, as a result of the acquisition of direction-specific adaptation effects, an increase in incidence of RVD plus either the initial appearance or increase in severity of motion sickness can occur. It seems reasonable to conclude that the increased incidence of RVD must have been due to the previous acquisition of direction-specific effects in the vestibular system. This conclusion is supported by earlier studies in the SRR, demonstrating that adaptation of the oculogyral illusion and of nystagmus (which are typical vestibular reflex phenomena) involves the generation of a compensatory response of opposite sign (refs. 11 and 12). Although in general there seems to be a causal relation between the elicitation of RVD and motion sickness responses, there is evidence that this relation is imperfect. Some subjects may be highly susceptible to motion sickness and manifest a low incidence of RVD, while others manifest a high incidence of RVD in the absence of motion sickness. It would appear that either the incidence of RVD is often a poor indication of instability in the vestibular system (which is unlikely), or that there is something in the nature of a gating mechanism, regulating the passage of influences across the brain stem reticular formation.

PREVENTION OF MOTION SICKNESS

Table 2 lists some factors of importance in the prevention of motion sickness. Although the selection process and the acquisition and retention of adaptation effects are the best ways to prevent motion sickness, they are not exploited (except for self-selection) under ordinary circumstances.

Antimotion sickness drugs may be extremely effective (ref. 13), and the side effects, after single doses at least, are inconsequential for the great majority of healthy persons. Some problems remain before drugs known to be effective are placed on the market, and much work remains before the ideal drug is identified.

It is difficult to overestimate the importance of head fixation in the prevention of motion sickness (ref. 14). This suggests that a seat design favoring head fixation deserves consideration.

In most motion environments, susceptibility is reduced if the eyes are covered or closed. A good substitute for reading is music. If feasible, a program specifically designed to center a person's attention elsewhere than on the motion environment and symptoms of motion sickness is worthwhile.

REFERENCES

1. Goltz, F.: Ueber die physiologische Bedeutung der Bogengänge des Ohrlabyrinths. Pflüg. Arch. ges. Physiol., vol. 3, 1870, pp. 172-192.

2. Flourens, P. M. J.: Recherches Expérimentales sur les Propriétés et les Fonctions du Système Nerveux dans les Animaux Vertébrés. Recherches sur les Conditions Fondamentales de l'Audition, Chapitres XXVII-XXXI, J. B. Baillière, Paris, 1842, pp. 438-501.

3. Breuer, J.: Ueber die Funktion der Bogengänge des Ohrlabyrinthes. Med. Jb., Wien, vol. 6, 1874, pp. 72-124.

4. Crum Brown, A.: On the Sense of Rotation and the Anatomy and Physiology of the Semicircular Canals of the Internal Ear. J. Anat., Lond., vol. 8, 1874, pp. 327-331.

5. Mach, E.: Grundlinien der Lehre von den Bewegungsempfindungen. Wilhelm Engelmann, Leipzig, 1875, 127 pp.

6. James, W.: The Sense of Dizziness in Deaf Mutes. Am. J. Otol., vol. 4, 1882, pp. 239-254.

7. Graybiel, A.: Structural Elements in the Concept of Motion Sickness. Aerospace Med., vol. 40, 1969, pp. 351-367.

8. Reason, J. T.; and Graybiel, A.: Progressive Adaptation to Coriolis Acceleration Associated with 1-rpm Increments in the Velocity of the Slow Rotation Room. Aerospace Med., vol. 41, 1970, pp. 73-79.

9. Graybiel, A.; and Knepton, J. C.: Direction-specific Adaptation Effects Acquired in a Slow Rotation Room. NAMRL-1162, 1972.

10. Graybiel, A.; Wood, C. D.; Miller, E. F. II; and Cramer, D. B.: Diagnostic Criteria for Grading the Severity of Acute Motion Sickness. Aerospace Med., vol. 39, 1968, pp. 453-455.

11. Graybiel, A.; Guedry, F. E.; Johnson, W. H.; and Kennedy, R. S.: Adaptation to Bizarre Stimulation of the Semicircular Canals as Indicated by the Oculogyral Illusion. Aerospace Med., vol. 32, 1961, pp. 321-327.

12. Guedry, F. E.; and Graybiel, A.: Compensatory Nystagmus Conditioned During Adaptation to Living in a Rotating Room. J. Appl. Physiol., vol. 17, 1962, pp. 398-404.

13. Wood, C. D.; and Graybiel, A.: Theory of Antimotion Sickness Drug Mechanisms. Aerospace Med., vol. 43, 1972, pp. 249-252.

14. Johnson, W. H.; Stubbs, R. A.; Kelk, G. F.; and Franks, W. R.: Stimulus Required to Produce Motion Sickness. I. Preliminary Report Dealing with Importance of Head Movements. J. Aviat. Med., vol. 22, 1951, pp. 365-374.

Table 1

Diagnostic Categorization of Different Levels of Severity of Acute Motion Sickness

Category	Pathognomonic 16 points	Major 8 points	Minor 4 points	Minimal 2 points	AQS* 1 point
Nausea syndrome	Nausea III†, retching or vomiting	Nausea II	Nausea I	Epigastric discomfort	Epigastric awareness
Skin		Pallor III	Pallor II	Pallor I	Flushing/Subjective warmth ≥ II
Cold sweating		III	II	I	
Increased salivation		III	II	I	
Drowsiness		III	II	I	
Pain					Persistent Headache ≥ II
Central nervous system					Persistent Dizziness: Eyes closed ≥ II; Eyes open III

Levels of Severity Identified by Total Points Scored

Frank Sickness (FS)	Severe Malaise (M III)	Moderate Malaise A (M IIA)	Moderate Malaise B (M IIB)	Slight Malaise (M I)
≥ 16 points	8 – 15 points	5 – 7 points	3 – 4 points	1 – 2 points

*AQS – Additional qualifying symptoms.
†III – severe or marked, II – moderate, I – slight.

Table 2

PREVENTION OF MOTION SICKNESS

SELECTION
- ARBITRARY SELECTION
- SELF - SELECTION

ADAPTATION
- UNPROGRAMMED
- PROGRAMMED

ANTIMOTION SICKNESS DRUGS
- GROUP BIOASSAY
- INDIVIDUAL BIOASSAY

MINIMIZE STRESSFUL ACCELERATIONS
- HEAD FIXATION
- SEAT LOCATION
- (? RECUMBENCY)

SECONDARY ETIOLOGICAL FACTORS
- VISUAL INFLUENCES
- FIXATION OF ATTENTION
- STATE OF HEALTH
  - PSYCHOBIOLOGICAL DEFECTS
  - DISEASES

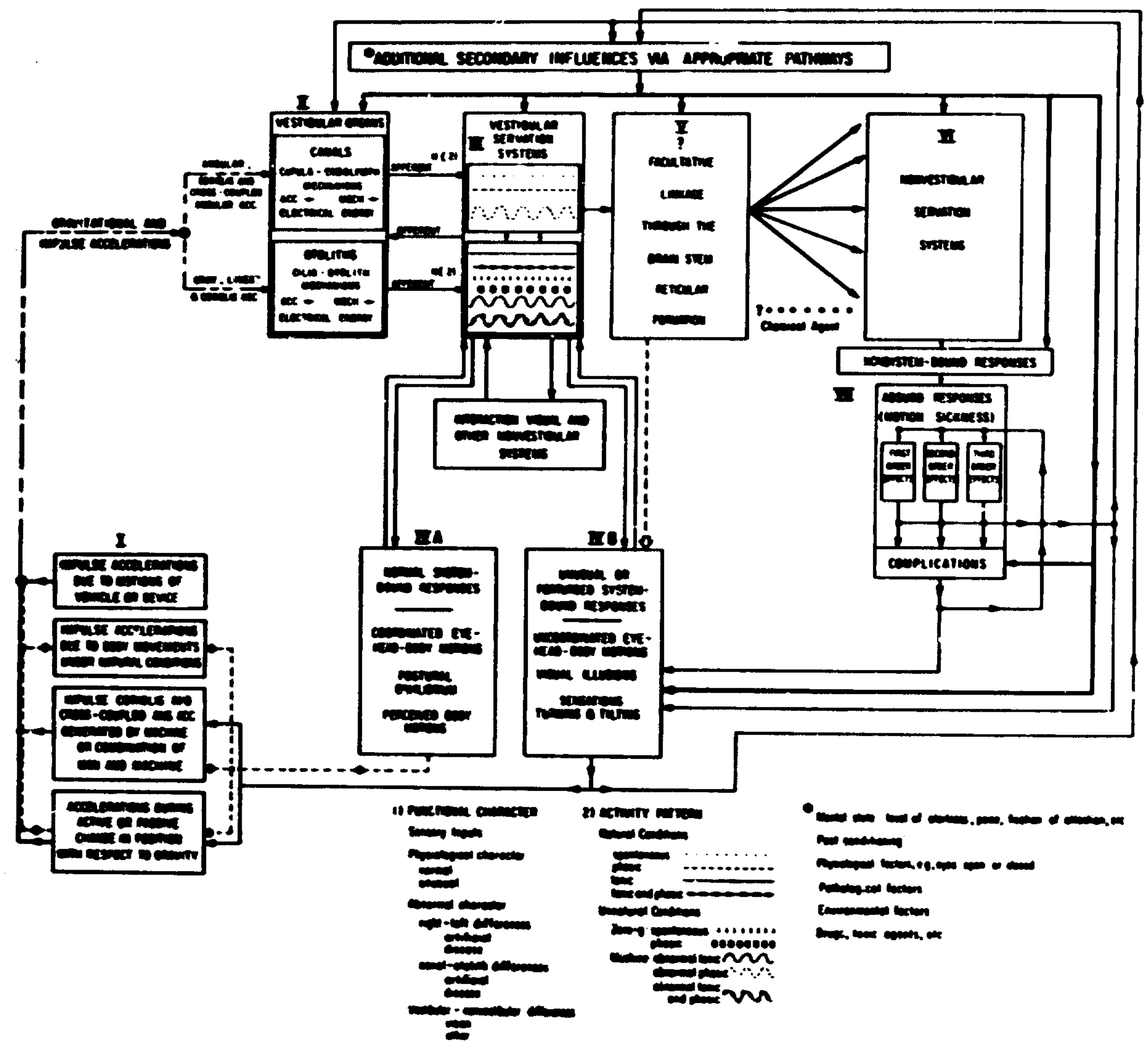


Figure 1.- Schema depicting input-output relations that make distinctions among normal vestibular responses, reflex phenomena, and motion sickness. (See text.)

Figure 2.- Artist's sketch of the "new" slow rotation room in Pensacola.

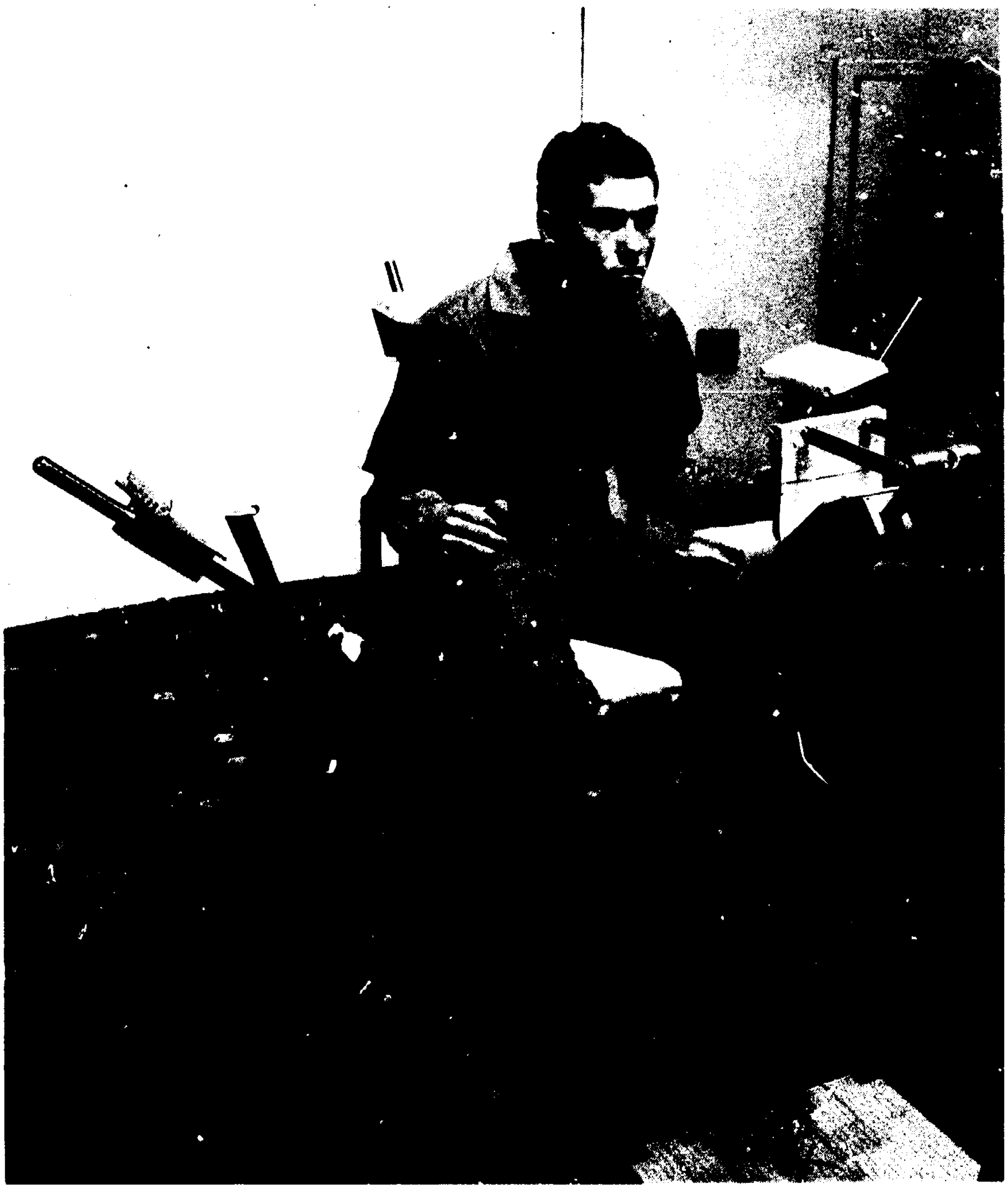


Figure 3.- Chair device used in the slow rotation room to assist in standardizing the head movements used in generating abnormal (and normal) stimulation of the vestibular organs.

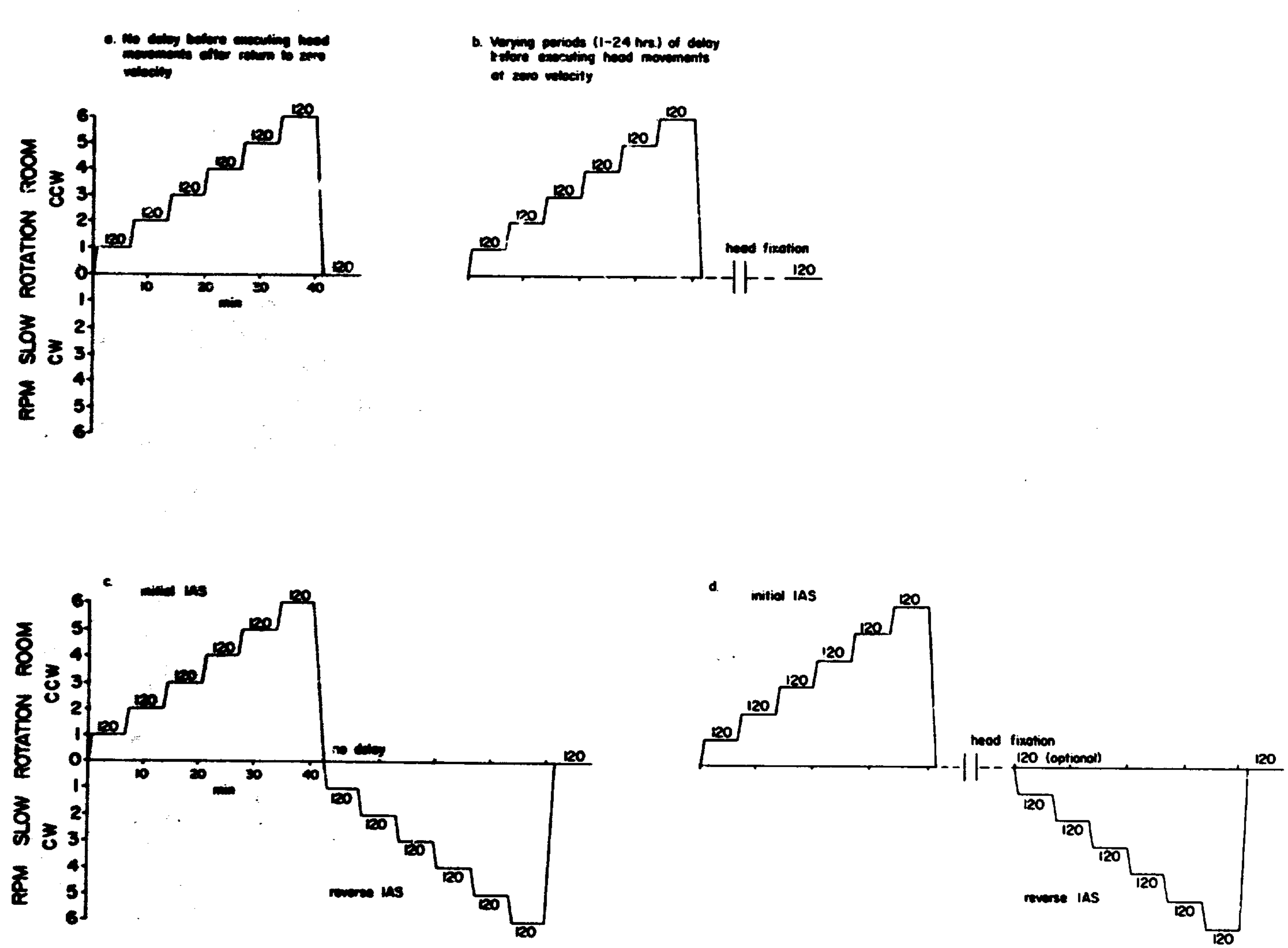


Figure 4.- Variations in a typical stress profile. The initial incremental adaptation schedule (IAS) is followed either by a one-step return to zero velocity (a) or by a reverse IAS that follows immediately (c) or after a delay (d). A delay also may follow the initial IAS (b). The number of head movements executed at each "step" in this profile was 120 unless testing was aborted.

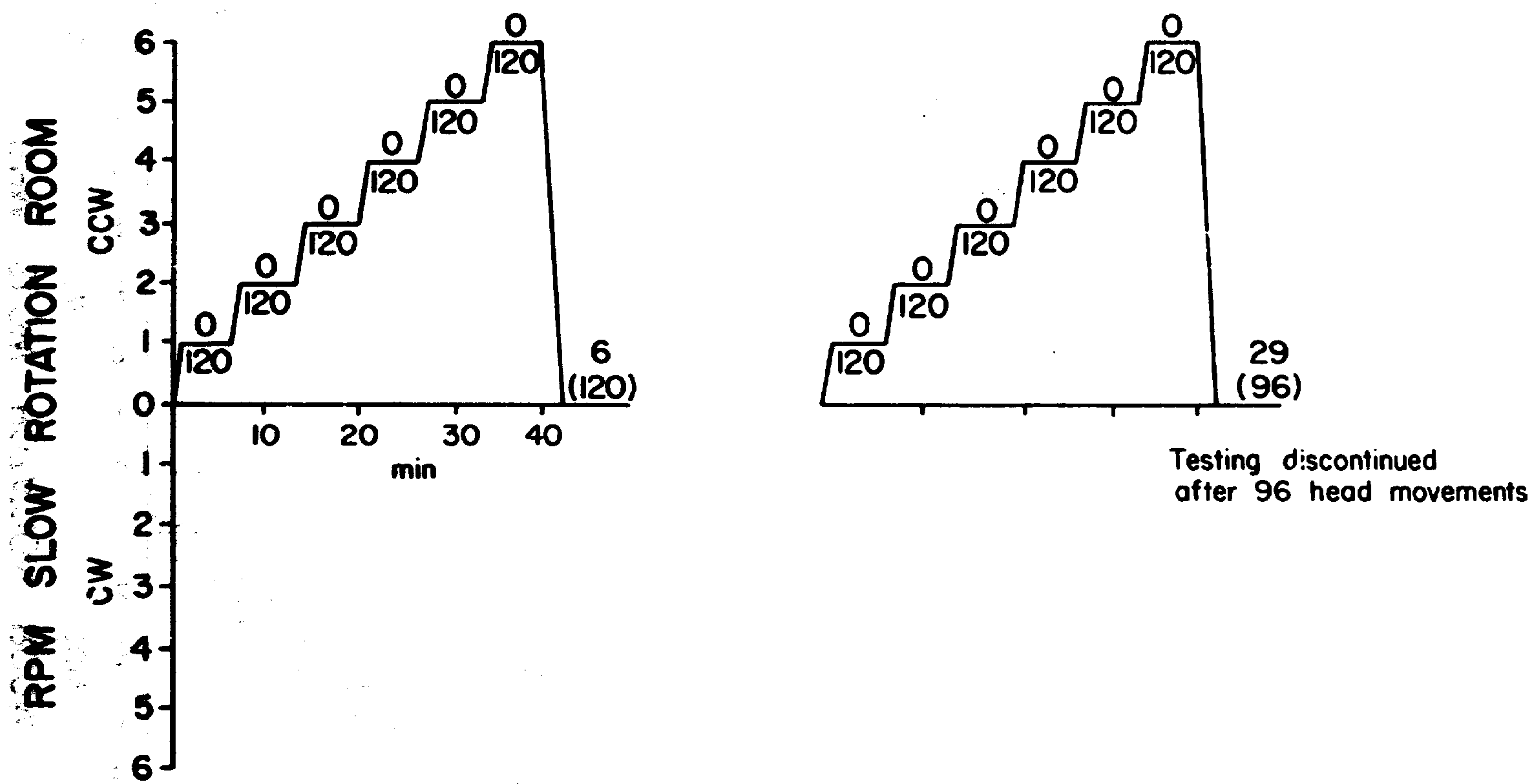


Figure 5.- Stress profiles and motion sickness scores (above line in this and subsequent figures) in two subjects. Both were symptom free during the incremental adaptation schedule, but after return to zero velocity one subject experienced mild symptoms (left) and the other experienced frank motion sickness before completion of 120 head movements.

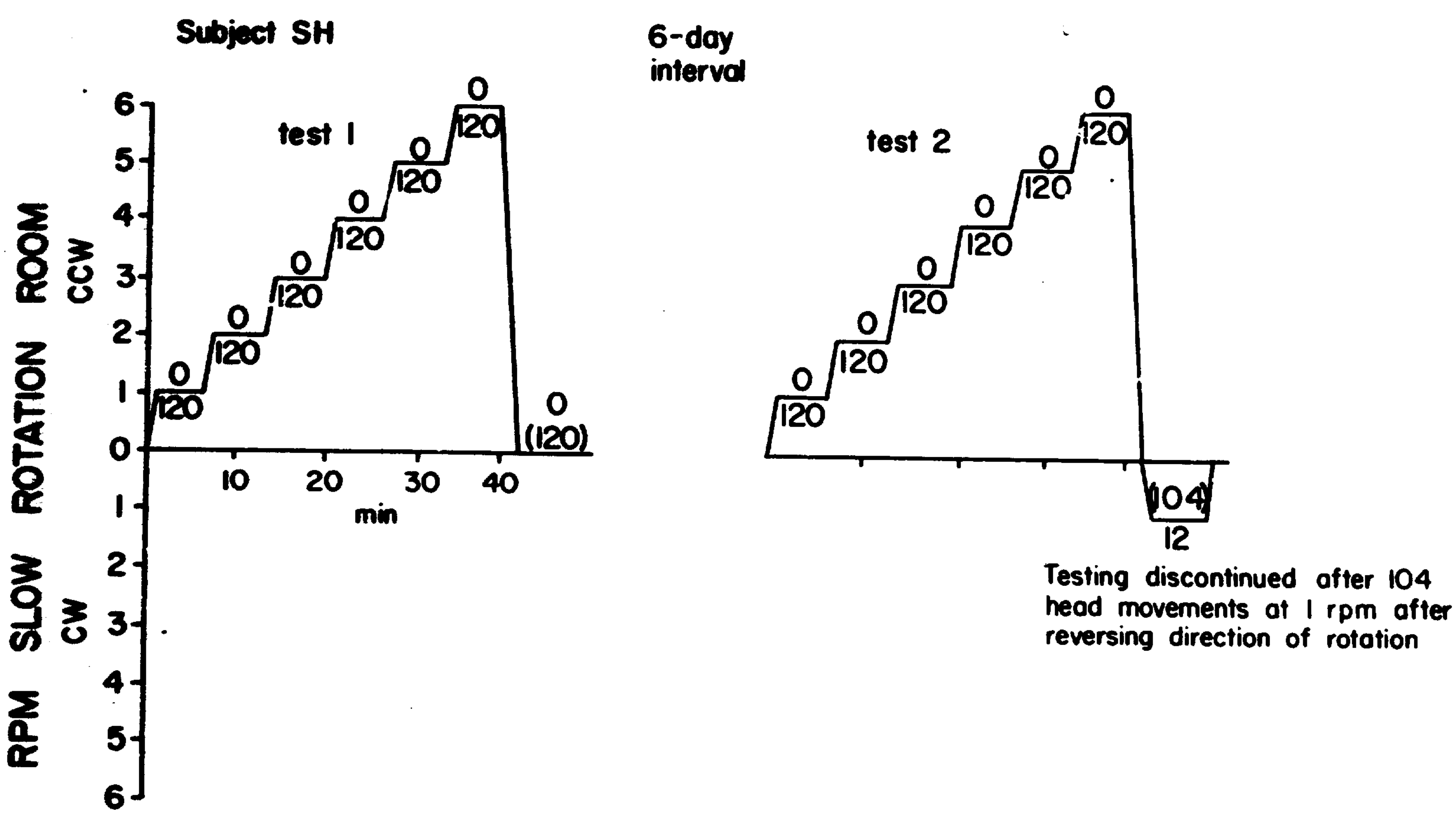


Figure 6.- Stress profiles and motion sickness scores in a healthy young subject. In both tests symptoms were not elicited during the initial IAS. In test 1 symptoms were not elicited during the challenge at zero velocity but the endpoint was soon reached (test 2) after the direction of rotation was reversed.

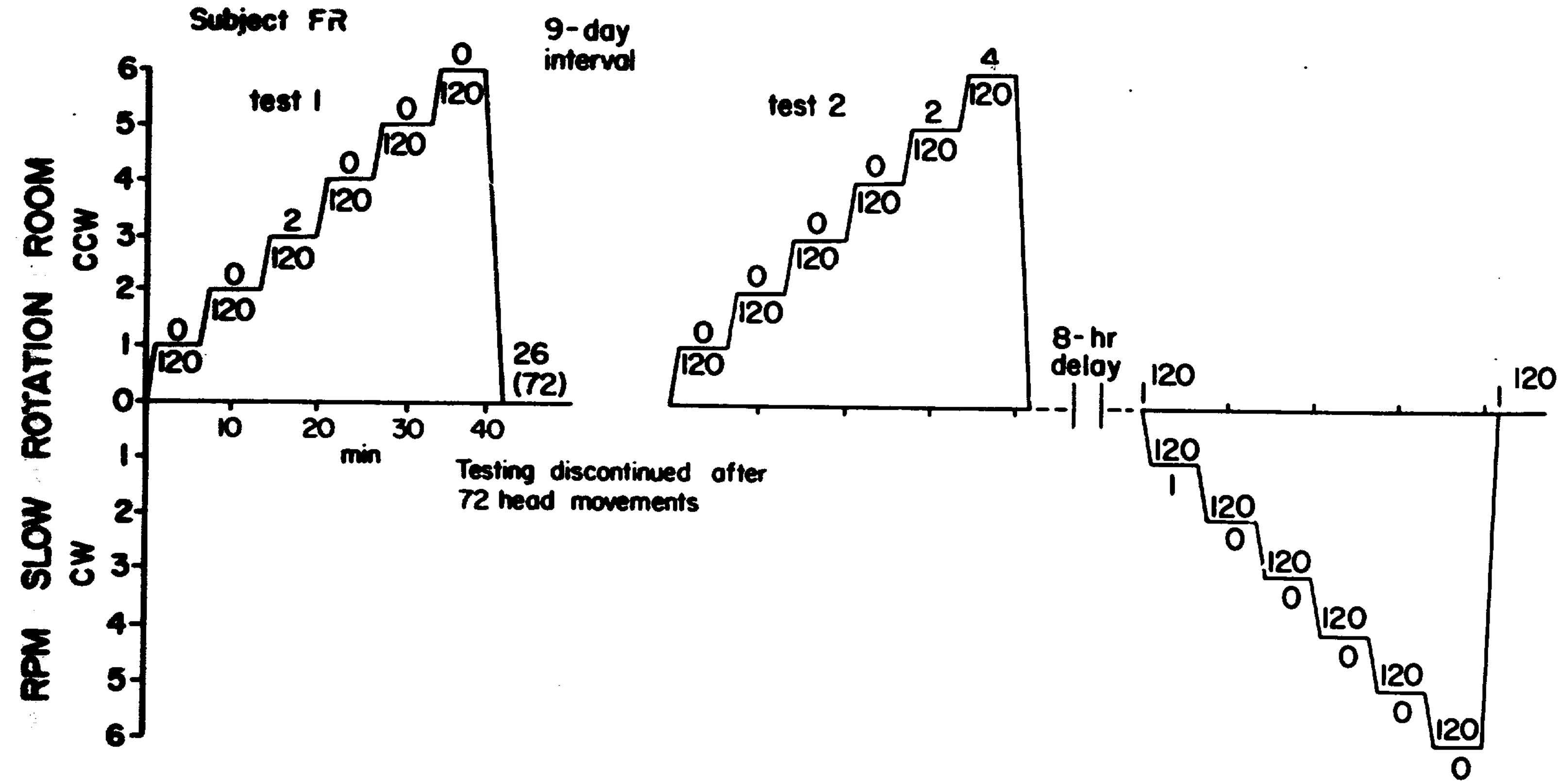


Figure 7.- Stress profiles and motion sickness measurements in a healthy young man. In test 1 the experiment was aborted during the relative mild challenge after return to zero velocity. In test 2 the subject was virtually symptom free during the reverse IAS due to the decay in direction-specific adaptation effects during the 8-hour delay between the initial and reverse IAS.

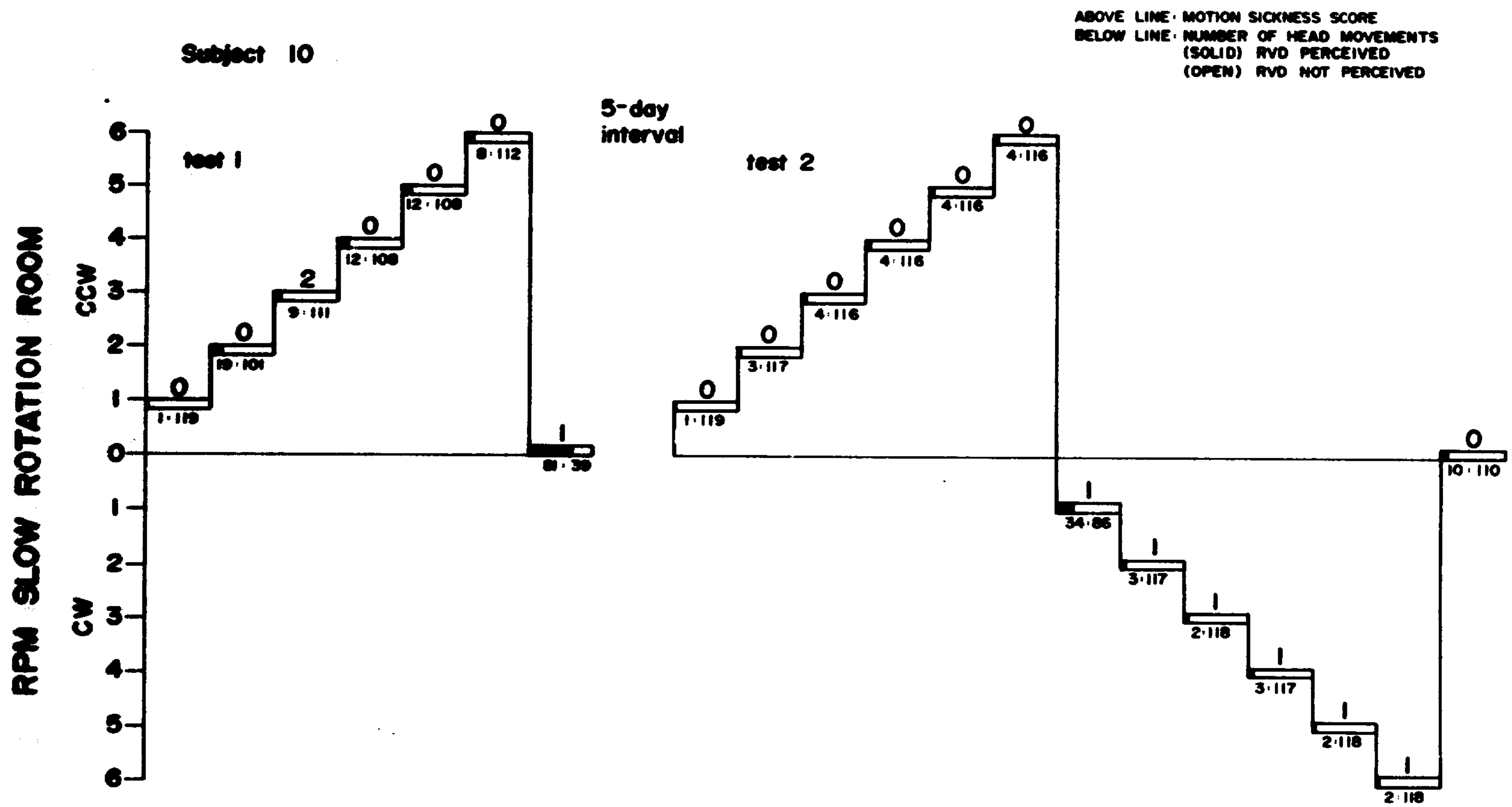


Figure 8.- Stress profiles, motion sickness scores, and occurrence of reflex vestibular disturbances (RVD) in a healthy young man. In test 1 note the great increase in incidence of RVD during the challenge at zero velocity but the virtual absence of motion sickness. Even after reversal of direction in test 2 motion sickness was virtually absent although there was a significant increase in RVD.

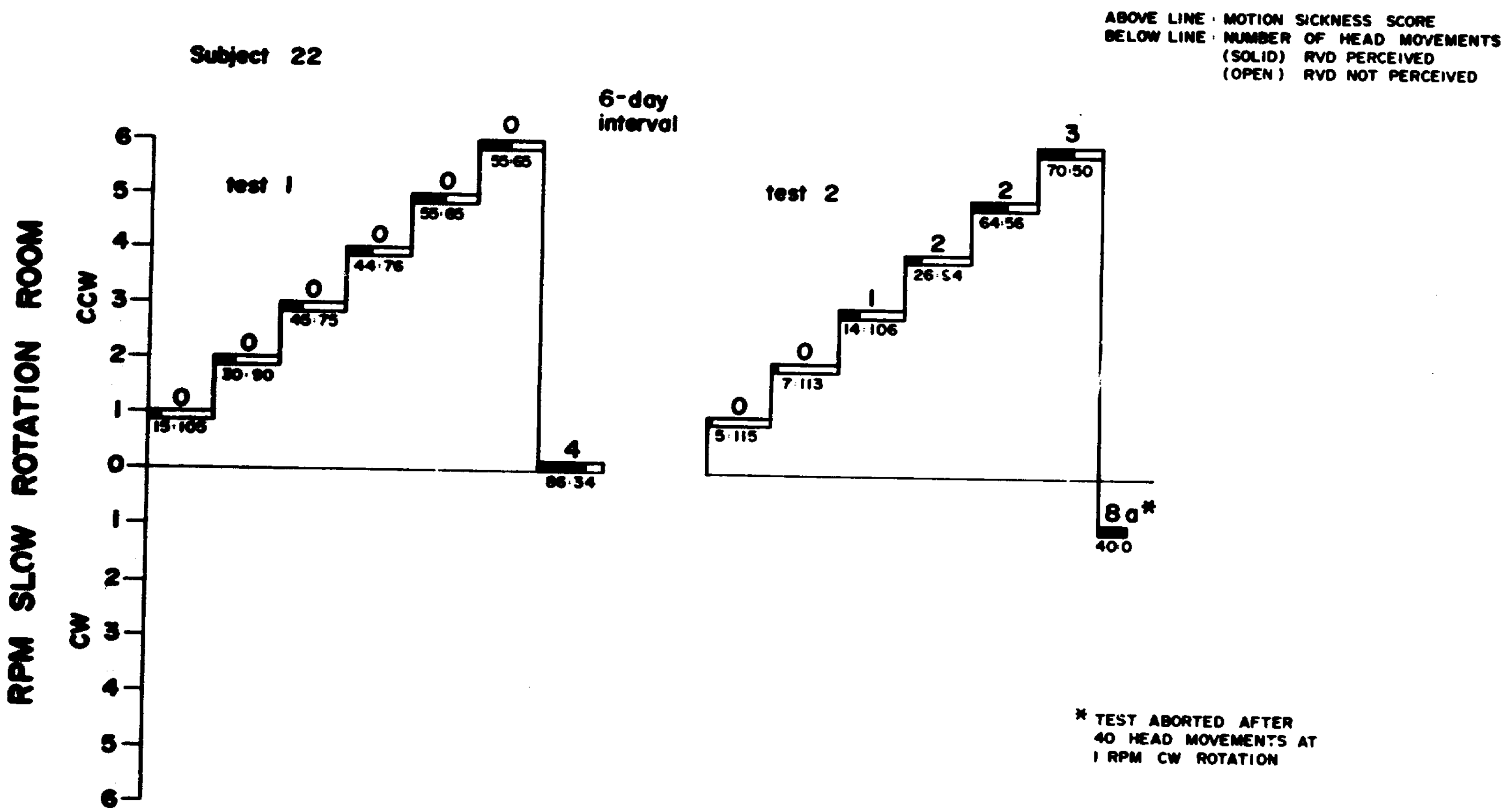


Figure 9.- Stress profiles, motion sickness scores, and incidence of RVD in a healthy young man. In both tests there was evidence of the acquisition of direction-specific RVD and motion sickness shown by the increase in scores after return to zero velocity and after reversal of direction of rotation.

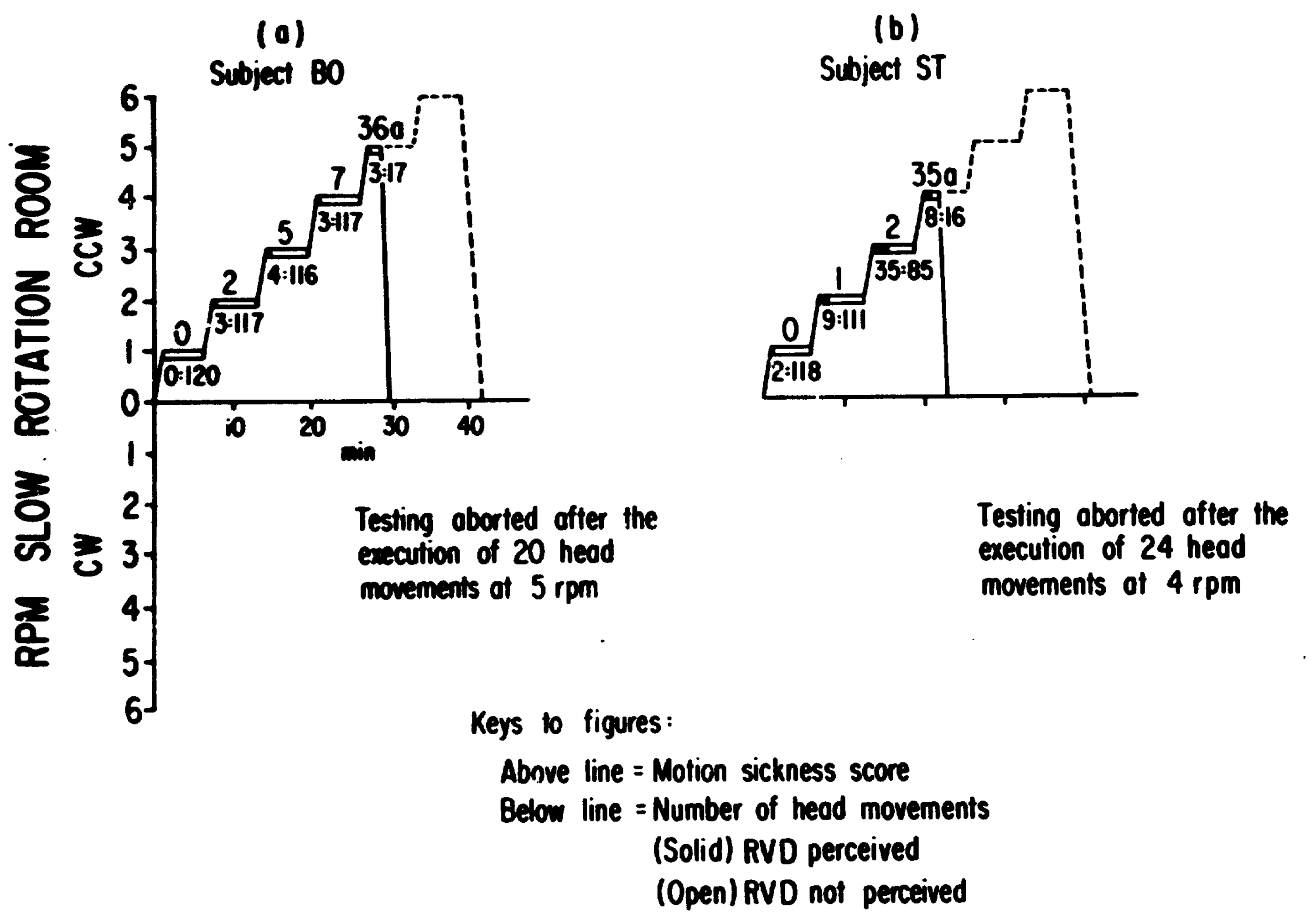


Figure 10.- Stress profiles, motion sickness scores, and incidence of RVD in two healthy young men well above average in susceptibility to motion sickness. Note the low incidence of RVD in BO **and relatively normal** incidence in ST.

RIDE EVALUATION IN AEROSPACE AND SURFACE VEHICLES

by

A. B. Broderson and H. E. von Gierke

Aerospace Medical Research Laboratory
Aerospace Medical Division
Air Force Systems Command
Wright-Patterson Air Force Base, Ohio 45433

and

J. C. Guignard

University of Dayton Research Institute
University of Dayton
Dayton, Ohio 45469

N73-10021

ABSTRACT

The vibration environment in a wide range of aerospace and surface vehicles is examined, and definitions related to ride evaluation are reviewed. Three provinces of research and application of ride data are recognized, namely (1) ride affecting passenger and operator comfort; (2) ride affecting human efficiency; and (3) ride affecting the health and safety of occupants occupationally or repeatedly exposed. Specific reference is made to the proposed ISO guide on human exposure to whole-body vibration. The applications as well as the advantages and limitations of this guide for evaluating vehicle ride are discussed. The derivation of the limits is reviewed with regard to the supporting data and the compromises necessary for wide applicability. Special discussions are included of the frequency and time dependence of these limits and approaches in progress for adjusting them according to different criteria of application. A limitation of the ISO proposal is its restriction to frequencies above 1 Hz (because susceptibility to motion sickness makes the human response below this frequency range highly variable, preventing a general consensus). Wide acceptance of the proposal by various groups, and adoption as a Military Standard and as a proposed ASCC Agreement demonstrates its general applicability to both air and ground vehicles. Methods of measuring ride (including the use of ride meters) are briefly discussed. Recommendations are made concerning future research in this field.

INTRODUCTION

All transportation vehicles (aerospace, land surface, and marine) subject their occupants to whole-body motions other than those intended. These extraneous motions (accelerations or vibrations) arise from the propulsion mechanisms and the interaction between the vehicle and the medium in which it travels (e.g., air turbulence; surface unevenness; water waves).

Such undesirable vehicle motions have long been a major factor in occupant acceptance of the mode of transportation. The system designer cannot be content with vehicles which conform solely to physical standards of functionality, reliability, and economy; he must additionally consider human performance capabilities in the vehicle environment, comfort, and acceptability, factors which, unfortunately, are often vaguely defined. Equations cannot yet be written for human performance nor can formulae adequately define comfort. The tendency has been to lump these entities into the term "ride quality", which has to some extent compounded the imprecision.

The International Organization for Standardization has proposed a Draft International Standard (ISO/DIS 2631) entitled "Guide for the Evaluation of Human Exposure to Whole-Body Vibration" (ref. 1). Although this guide applies in general terms to human vibration in vehicles as well as in other exposure situations, it promises to be a significant step forward in defining and evaluating major factors which comprise the "ride quality" problem and in providing a uniform basis for the collection of data on the ride environment. The purpose of this paper is to review these factors, describe the ISO approach, discuss the applicability of ISO criteria to problems in the ride quality arena, and to outline areas where future efforts are planned or needed in both research and standardization.

DEFINITIONS

Some appreciation of the difficulties involved may be gained by considering some definitions and implications of commonly used terms such as ride, quality, and evaluation.

In this context, the word ride is usually used to describe the dynamic response motions of a vehicle or its occupant to whatever forcing functions move it as intended or excite its structure and cause it to vibrate, jostle, sway, roll, jolt, pitch, heave, and otherwise move in ways not intended. Ride is thus an objective measure of motion; it is not normally used as a relative term which depends upon the vehicle mission or human exposure situation, although it may erroneously imply something about either. Vehicle ride is simply a "subset" of ride and refers specifically to the vehicle's characteristics; it is the "ride" that results because of the vehicle's inability to overcome unintended dynamic forcing functions. "Vehicle ride" refers to dynamic responses particular to the vehicle itself, while "ride" also encompasses dynamic characteristics of maneuvering or imposed by the terrain followed.

The words quality and evaluation are somewhat interdependent since quality is determined by an evaluation process. Quality attributes "goodness" or acceptability to the ride with respect to its negative aspects such as discomfort, task interference, or annoyance; quality of ride can have meaning only in context with the specific vehicle class and the population exposed. An evaluation is necessary to determine quality and this depends upon the persons asked to evaluate, their exposure condition, the instructions given them, and their expectations. Thus evaluation is a relative rating or value judgment of quality based upon a prescribed rating procedure. Difficulty has arisen because the basis (rating scale; procedure) for evaluation or "quality" evaluated has been different among various investigators: in some studies subjects evaluated the "quality" of their ride experience and in others they evaluated the "quality" of the vehicle in which the ride was experienced. Usually, the term "ride quality" is used as a means of relative evaluation of the ride of one vehicle which may be better or worse than the ride of another vehicle of the same intended purpose. But, in general, the term "quality" is difficult to define because manufacturer reputation, vehicle handling, riders' fears and prejudices, and other factors affect the assessment. Moreover, there are advantages in restricting evaluation to prescribed bases and procedures. In any case, evaluation of vehicle ride entails establishing a scale for rating the desirable or undesirable characteristics of the vehicle ride ranging from comfort, acceptability, and desirability to discomfort, disturbance of various performance functions, and intolerability.

Two examples may be helpful. First, one could say that the ride (total motion environment) from A to B was very rough, but the "ride quality" of the vehicle in which he traveled was good. The "ride" may have simply indicated that the terrain was rough and hilly and curvy, an environment the vehicle was not intended fully to overcome. But the "ride quality" of the vehicle may have been very good in that it met or surpassed expectations for the conditions met. In the second example, one could say that the "ride quality" of the touring car he drove from A to B was good but the "ride quality" of an earthmover traveling over the same journey was terrible. This would be an inappropriate statement: one should not compare the characteristics of one vehicle in its intended environment with that of another type of vehicle not intended for the same purpose; for other prejudices may influence the comparison.

Another distinction is important when using the term "quality", namely, that between "ride quality" and "handling quality". While "ride quality" describes the system's capability to reduce dynamic disturbances to the occupant, "handling quality" describes the dynamic responsiveness of the system from the closed-loop, man-machine viewpoint of the operator. They are different entities but they are intertwined for a pilot or vehicle controller, since operator input may affect ride.

In summary, "evaluation" is a rating or value judgment using a prescribed, preferably standardized scale and procedure. "Ride" and "vehicle ride" are objective measures of motion and therefore, with proper care, "ride" and "vehicle ride" may be properly and usefully "evaluated". On the other hand, "quality" is difficult to evaluate since it is judged by a multiplicity of ill-defined criteria. To some it may merely be part of some general concept of "transportation quality" embracing numerous factors in addition to the dynamics of riding (e.g., convenience, economy, amenities, or other environmental agents such as noise). Therefore "ride quality" and "vehicle ride quality" are not recommended terms. The following definitions are offered as a basis from which to proceed:

1. Ride. An independent, objective measure of the total dynamic motions experienced by a vehicle as a result of the vehicle's own power, maneuvers, and the interactions with the environment through which it travels.

2. Vehicle ride. A vehicle characteristic which describes the extranecus or unintended (i.e., excluding intended maneuvers) dynamic motions experienced in the vehicle.

3. Ride evaluation. A quantitative evaluation of an experienced ride environment, including both intended and unintended motions, based solely on occupant reaction to the dynamic motions present, i.e., without regard for the type of vehicle occupied or its intended function, judged against a prescribed scale and procedure.

4. Vehicle ride evaluation. A quantitative evaluation of the "vehicle ride" (excluding intended maneuvers) of a specific vehicle or type of vehicle, based upon subjective value judgments and/or objective rating procedures in relative comparison with other vehicles of similar intended purpose.

It is the authors' opinion that "vehicle ride evaluation" is quite difficult to achieve without first establishing a common approach to "ride evaluation". More progress will be made, and across a wider spectrum of vehicle types, by increased attention to the fundamental requirements of "ride evaluation".

The proposed ISO guide (ref. 1) for the evaluation of human exposure to whole-body vibration relates various human responses to the dynamic motions and exposure time experienced. Among other applications, it provides a uniform basis for quantitative ride and vehicle ride evaluation, except at very low frequencies (below 1 Hz). The guide makes no judgment on the permissibility or advisability of the occurrence of these responses in specific situations (e.g., vehicles). It recognizes that to a considerable extent human responses, primarily behavioral and performance effects, depend upon the attitude, motivation, age, experience, and many other biodynamic and psychological factors which characterize the exposure situation (refs. 2 and 3). It makes no allowance for such factors, although the feasibility of incorporating appropriate corrections is now being studied by the originating ISO subcommittee (ISO/TC 108/SC4). As such corrections are made available, the usefulness of the present ISO guide will be extended from "ride evaluation" to encompass "vehicle ride evaluation" as well.

VEHICLE DYNAMIC ENVIRONMENTS

One difficulty in distinguishing ride evaluation from vehicle ride evaluation is the fact that dynamic environments to which riders are subjected cover such a wide spectrum and include both intended and unintended motions. Human response to each portion of the spectrum is different both in type and degree. Since vehicle ride evaluation is determined largely by the human response to unwanted or extraneous influences, such as structural vibrations, it is inappropriate to consider those elements of motion which, even though oscillatory, are intended. To elaborate, it is entirely appropriate to include in vehicle ride evaluation those mechanical disturbances of whatever origin which are extraneous to the intended vehicle motion (e.g., vehicle structural vibrations or aircraft bending mode oscillations causing abdominal discomfort or visual disturbances); it is inappropriate, however, to consider in the evaluation of vehicle ride the commanded or "mission-dictated" rigid-vehicle motions, even though they may cause motion sickness or disorientation (e.g., during mission-dictated terrain following in military aircraft; or during unusually high-speed travel of ground vehicles over an undulating road or track). The latter are within the purview of "ride" evaluation but not "vehicle ride" evaluation. If discomfort due to intended or dictated motion is a problem, it is more properly attacked by reconsidering the vehicle's route or flight path, or by evaluating the "ride" itself as necessarily more severe, than by downgrading the "vehicle ride" evaluation.

VEHICLE DYNAMICS/HUMAN RESPONSES

Low-frequency motions (below 1 Hz) tend to induce motion sickness in susceptible people, while resonant vibrations at higher frequencies affect mainly the abdominal, thoracic, and spinal structures, neuromuscular function, and the visual system. Unlike motion sickness, body resonance phenomena affect all riders, with comparatively little individual variation in the response. The frequency dependence of resonance-related effects is more sharply enhanced at higher intensities throughout the frequency range. In the light of the known frequency-dependence of human response to vibration, it is instructive to review both the frequency and the intensity ranges of vibration commonly encountered by aerospace and surface vehicles. Figure 1 shows the frequency ranges (solid bars) for several vehicle types and the principal vehicle-component and environmental factors responsible for excitation. Vertical dash lines indicate zones of main biological responses and the scope (1-80 Hz) of the proposed ISO limits (ref. 1) of human vibration exposure. Figure 2 shows representative intensity-frequency envelopes typical of ride in several vehicle types. With the exception of the unpublished helicopter data and the F-4C data (ref. 4), this illustration is based on information in reference 5. Figure 3 shows some subjective assessments of ride in selected aerospace and surface vehicles. References 3, 6, and 7 explain the "pilots' rating of turbulence", the airliner "objectionable for passengers" limit, and the Railway Ride Index (RRI), respectively. (Helicopter data are as in fig. 2.) Figure 4 shows the frequency ranges of physiological responses commonly encountered. In this figure, the bars with dash extensions indicate uncertain ranges (ref. 3). Note the wide and indefinite range of human vibratory sensation. Note also that most significant effects of mechanical vibration on man occur at frequencies below the audio-frequency range (distinguished by close-dash vertical lines). The space-dash lines show the scope (1-80 Hz) of proposed ISO limits. A significant portion of the overall frequency range in question is covered by the ISO limits (ref. 1). (See figs. 1 and 4.)

It can be seen that the vehicle motion frequency range falls mainly within the band 0.1-30 Hz, within which we can further distinguish frequency ranges associated with particular kinds of human disturbance. The first band, 0.1-1.0 Hz, is associated mainly with motion sickness in susceptible people, which occurs during moderate to severe (high-amplitude) motions such as in ships in heavy seas, in high-speed ground transit systems moving over undulating terrain or tracks, or in aircraft where large-cell, high-velocity gusts displace the whole structure.

Vibrations in the range 1-30 Hz induce important resonance phenomena in the body and the associated physiological responses are therefore highly frequency-dependent. Such vibrations arise in ships, small craft, and air-cushion vehicles because of engine vibration and small-wave incidence; in wheeled vehicles because of surface irregularities in roads or tracks; in aircraft because of turbulent excitation or aeroelastic vibration modes; and in helicopters because of rotor blade passage and pitch oscillation.

Vibrations at frequencies much above 30 Hz are readily attenuated and become progressively less important in relation to human body motion and performance. Such vibrations, arising from such sources as engines and transmissions or from the passage of a vehicle over minor surface irregularities, can cause superficial discomfort, annoyance, and fatigue, merging with the effects of structure-borne interior noise.

In terms of dynamic range, vehicle vibration covers the entire range of human vibration sensation, from the threshold of perception around 0.001 g (acceleration-amplitude) to the limit of short-term voluntary tolerance around 1 g. (It is of interest to note that this is a range of about 60 dB, which is substantially narrower than the dynamic range of human hearing.)

BACKGROUND OF THE ISO DRAFT STANDARD

The field of applied human vibration research is replete with formulae or graphs purporting to embody a definitive approach to evaluation of "ride" in general or specific kinds of "vehicle ride quality". Much of this research has been of an ad hoc nature largely unsupported by investigations of the underlying physiology or psychology of the human response. The practical criteria for rating vibrations differ widely and have often been restricted to very specific situations, so that a host of qualitative terms for subjective vibration rating have evolved (e.g., "annoying", "uncomfortable", "disagreeable", "intolerable", etc.) along with adverbs such as "mildly" or "strongly" intended to indicate minor scale adjustments in the rating. The techniques have necessarily been subjective rather than objective, and the results diffuse and difficult to generalize. The extent of the interpreter's dilemma is reflected in such imprecise or even paradoxical terms as "mildly intolerable".

As a result of such diffuse approaches, the ride engineer has been faced with a confusing multiplicity of empirically derived rating procedures and exposure limits. (Figure 5, taken from reference 8, summarizes some of these by way of illustration. Note the range of variation in level and position but general similarity in form of the frequency functions. The multiplicity of limits such as these is rendered obsolescent by the adoption of the ISO standard (ref. 1).) Many limits apply only to narrow areas of practice (e.g., particular components of train or helicopter vibration). Moreover, the purpose (criterion) and scope of published limits is in many instances left unstated.

All such available studies have been considered by ISO for integration into a coherent, generalized approach based upon specific criteria, a term which will be more precisely defined shortly. For example, guidance in the acceleration region from roughly 0.2 to 1.0 g is based upon several investigators' results, including those of Dieckmann (ref. 9), and Miwa (ref. 10). A 0.1 g (1-20 Hz) limit for long-term exposure in USAF military aircraft had been proposed by Getline (ref. 11). Other subjective data came from studies by Dieckmann (ref. 9), Reiher and Meister (ref. 12), Janeway (ref. 13), and other work summarized by Goldman and von Gierke (ref. 2) and cited elsewhere (refs. 2 and 3). The short-time voluntary tolerance data considered by ISO (in formulating exposure limits) are from Magid, Coermann, and Ziegenruecker (ref. 14). Limits for x- and y-axis (which differ from those for z-axis) vibration were based on a number of reports, including those of Loach (ref. 15) and of Miwa (ref. 10) who has established a subjective response scale for whole-body vibration and cross-matched vertical and horizontal responses.

Data concerning the time-dependence of vibration response came from certain of the above mentioned studies, as well as from the work of Sperling and Mauzin of German and French railroads (described by Loach (ref. 15)); and from various military aviation and commercial airline studies (refs. 2 and 3). Human vibration tolerance has been found generally to decrease as time increases, at least in the range from 1 minute to several hours. The same time-dependence is often assumed for daily, repeated (e.g., occupational) exposure, although no dose-response relationship has yet been established for potentially hazardous occupational exposure. Such a relationship must clearly be of an objective nature and, since it is possible that chronic exposure might be physically harmful yet not subjectively severe (ref. 16), if and when established, should be incorporated into future ride and vehicle ride evaluation criteria.

THE ISO RECOMMENDATIONS

The ISO proposed standard (ref. 1) describes both "criteria" and "limits", and it is important to appreciate the distinction (ref. 3). In this context:

1. A <u>criterion</u> is a verbal expression of the purpose of control or limitation of vibration. It should, ideally, also specify the nature and proportion of the population to be protected as well as a statement of how the motions are to be defined and measured.

2. A <u>limit</u> is a numerical expression of the maximum amount of vibration compatible with the defined criterion. Different limits are required by different criteria of protection, and they necessarily vary with the direction and mode of vibration application.

Three main human criteria are recognized by the ISO document:

(a) Preservation of comfort.

(b) Preservation of working efficiency.

(c) Preservation of health or safety.

Limits set according to these criteria are applicable only to situations involving people in normal health, i.e., those who are considered fit to carry out normal living routines, including travel, and to undergo the stress of a typical working day or shift.

Corresponding to these criteria, three limits are proposed, namely:

(a) Reduced comfort boundary.

(b) Fatigue-decreased proficiency boundary.

(c) Exposure limit.

The "fatigue-decreased proficiency boundary" is illustrated and inter-criterion conversion factors stated in figures 6 and 7. The guiding principle of the document is to establish limits which are a simple compromise between relevant, available data, in the belief that provisional guidance, even though still debated, is preferable to none at all (ref. 17). Some restrictions and compromises were necessary to achieve international agreement, simplicity, and operational generality:

1. Limit/boundary shape. It was agreed that the limit/boundary shapes should be identical for all three criteria (reduced comfort; fatigue-decreased proficiency; exposure limit) for simplicity of interpretation of measured data, even though the laboratory data upon which the limits are based show a stronger frequency-dependence at higher intensities. This allows a sliding scale of correction factors and the construction of relatively simple and inexpensive electronic weighting networks for comparative ride and vibration measurements.

The overall limit or boundary shape for z-axis vibration was determined from the data to be trough-shaped (fig. 6a), with the greatest human sensitivity in the 4-8 Hz range (the range of whole-body resonance). The shape for x- and y-axis vibration accords with the observed maximum in human sensitivity and impedance below 2 Hz (refs. 3, 10, 15, and 18). (See fig. 6b.)

The slope of the z-axis boundary from 1-4 Hz is a compromise between data from several reliable studies. Representative of the spread of the data are results from Janeway (ref. 13), who found "tolerance" to decrease as $1/f$, i.e., inversely proportionally to frequency, and Dieckmann (ref. 9), who found equally low "tolerance" at all frequencies between 1 and 4 Hz. ISO has recommended a compromise slope of $1/\sqrt{f}$, although no specific data exist to support this particular slope. There are indications that the tolerance rises with lowered frequency as found by Janeway, then falls again to the boundary found by

Dieckmann at lower frequencies. The slope above 8 Hz is proportional to frequency, a compromise fit to the data from several studies of the kind illustrated in figure 5.

2. Limit level. The limit for each criterion (e.g., 0.31 g-rms for 8 hours in the z-axis at 4-8 Hz) is a compromise fit to reported laboratory and field data, modified in the case of tolerance (exposure limit) by an arbitrary factor-of-safety of approximately 2. Some confidence can be gained from the fact that long-term occupational exposure to these levels of whole-body vibration has not been recognized for legal or insurance purposes as causing any vibration disease or injury. Work is now in progress in ISO/TC 108/SC4 to develop correction factors that would permit adjusting the limits upward or downward according to specific criteria for a wide range of applications (e.g., building vibrations; or vehicle vibrations affecting crewmen, operators, or passengers).

3. Frequency range. Because of the large variability of human responses to motions below 1 Hz, ISO currently makes no recommendation below that frequency and explicitly discountenances extrapolation of the existing recommendation into that range. The upper limit of 80 Hz encompasses the range where, for example, electric motors, gasoline engines, and air handling equipment vibrate. Because higher frequencies are of little consequence in relation to the intensities of vibrations normally encountered, 80 Hz was deemed to be sufficiently high. The actual cut-off and corner frequencies of the limits are round numbers selected in accordance with the ISO preferred frequencies for acoustical measurements (ref. 19).

4. Exposure time. Based upon experimental data and field experience previously mentioned showing that the human response to vibration changes with the "effective" duration of exposure, the ISO recommended limits have been formulated so as to become more stringent as exposure time increases (figs. 7a and 7b). The time function is again a compromise between the available data. The document (ref. 1) contains a computational procedure (yielding an effective total exposure time) for dealing with cases in which the level of vibration varies substantially during the exposure period.

CONCLUSIONS AND RECOMMENDATIONS

For the following reasons, it is recommended that the proposed ISO limits, with appropriate correction factors when published, be adopted as the human frequency response function of choice for evaluating ride in both aerospace and ground vehicles:

1. The limits embody the collective thinking of many international experts in human response to whole-body vibration and are an acceptable compromise between existing data. The current status of the document as a numbered Draft International Standard commands the respect of many nations and has been or is to be incorporated into their laws, national standards, or draft regulations. Moreover, the guide is the first comprehensive attempt to address duration of exposure, direction of vibration, and criteria of protection.

2. The limits have been adopted as a MIL Standard (MIL-STD-1472A, 1970) and a proposed Air Standardization Coordinating Committee (ASCC) Agreement.

3. In many areas where there is disagreement over these limits or criteria, clarifying research is being conducted and the active working groups of ISO/TC 108/SC4 are committed to modifying the standard as new scientific evidence may indicate is appropriate.

4. The generality of the ISO limits lends itself to ready incorporation as a frequency-weighting function for continually quantifying human vibration exposure, as for example in "ride meters", instruments which yield a weighted measurement of vibration environments (ref. 3) and operate in a fashion similar in principle to sound level meters used to measure weighted sound levels in noise environments. Some ride meters have been built, and the approach should permit extensive, standard comparisons of vehicle ride across a wide variety of transportation systems. (The draft standard includes certain specifications concerning the recommended characteristics of electronic weighting networks for such purposes.)

Continued research will be necessary to increase confidence in these limits or to extend or modify them to suit specific criteria. The following areas are of particular importance:

1. More definitive research in human response to motion in the range of 0.1-1 Hz must be encouraged, ultimately to establish a 95th percentile boundary for passenger ride comfort (defined as the limit up to which 95% of the riding population are, with high probability, unaffected by motion sickness).

2. Additional and better laboratory studies are needed which examine the extent to which data from sinusoidal vibration studies apply where multiple axis, multiple frequency, or random inputs exist, as is generally the case in practice. The human body is biodynamically non-linear (refs. 2 and 3) and therefore the principle of superposition does not necessarily hold. Moreover, it seems plausible, although it has not yet been clearly established, that multi-frequency or multi-axial vibration inputs elicit varying, and perhaps additive, adverse responses.

3. The predictive value of basic "ride" and "vehicle ride" concepts in surface transportation will be enhanced by the development of a set of "standard road spectrum" inputs for operating on the vehicle and human frequency-response functions, in rather the same manner as the aircraft industry utilizes the von Kármán standard gust profile to operate on airplane and pilot or passenger transfer functions to determine a single number representing the "vehicle ride" evaluation (refs. 20 and 21). (A new working group of ISO/TC 108 was set up in 1971 for this purpose.)

4. New avenues must be explored to complement the ISO-type frequency-response function with respect to human performance. For example, promising new research is progressing in the Air Force (ref. 22) to establish "describing function" models for aircrew performance in buffeting environments.

5. Additional data must be collected upon which to base tables of correction factors to adjust recommended levels for a variety of applications, that is, for subsets of the principal criteria (e.g., for different riding populations; for different kinds of task performance with varying error tolerances; or for the presence of other disturbing factors, such as noise).

6. Considerable field and laboratory research is necessary to define dynamic environments and human responses in all 6 degrees of freedom. Very few data yet exist to relate rotational vibrations to various types of human response, although such vibrations commonly occur in practice.

7. The time-dependence of vibration response must be more clearly established and the possibility of performance degradation and injury resulting from chronic exposure must be explored, and appropriate data incorporated into the procedures for evaluating "vehicle ride" on the basis of the ISO recommendations.

8. Psychophysical techniques should be utilized more extensively in the collection of laboratory data on human vibration response. The increased use of psychophysical techniques such as employed by Miwa (ref. 10) and Shoenberger and Harris (ref. 23) is to be encouraged.

While these developments are under way, the following interim recommendations are offered:

1. Use of the word "quality" in reports of the evaluation of ride and vehicle ride should be discouraged.

2. The ISO limits should be adopted as the frequency-response function of choice in design, in vibration control for the protection of man, and in evaluating ride where motion frequencies below 1 Hz are not a significant component of the unintended environment.

3. Regardless of other approaches and methodologies which may be useful in specific programs, ride measurements at the point of input to the man should be made and reported in accordance with the ISO recommended practice. Reports of future investigations of ride and vehicle ride should additionally include data weighted according to the ISO frequency-response function. This will permit the standard, quantitative evaluation and comparison of ride environments and their interrelationships across a wide spectrum of vehicle types, just as the A-scale acoustic frequency weighting permits comparative sound level evaluations in diverse noise environments.

4. As and when appropriate criteria correction tables are developed for inclusion in the ISO guide, these should be adopted and experience with their use made known to ISO/TC 108/SC4, either via contact with members of the working groups or through representation on the corresponding national standardization committees (e.g., ANSI-S3.39 in the USA.) In this connection, constructive comments and suggestions concerning the current recommendation are welcome from any source.

5. It should be borne in mind that the ISO guidelines are in no way intended to be immutable dogma. Like all such recommendations, they offer general guidance only; and the extent of their application to any specific situation in practice is a matter for the engineer or other user to decide in the light of his or her professional judgment.

REFERENCES

1. International Organization for Standardization (ISO), Guide for the Evaluation of Human Exposure to Whole-Body Vibration, Draft International Standard ISO/DIS 2631. Geneva: ISO, 1972. (Copies of this document may be obtained on application to the ISO Central Secretariat, 1, Rue de Varembé, 1211, Geneva 20, Switzerland or to the American National Standards Institute, Inc., 1430 Broadway New York, N.Y. 10018).

2. Goldman, D. E., & von Gierke, H. E., "Effects of Shock and Vibration on Man", In: Shock and Vibration Handbook, Eds Harris, C. M. & Crede, C. E. New York: McGraw-Hill, Vol 3, Ch 44, 1961.

3. Guignard, J. C., "Vibration". In: Aeromedical Aspects of Vibration and Noise, Guignard, J. C. & King, P. F., Paris: NATO/AGARD, AGARDograph 151, 1972, Part One.

4. Speakman, J. D., et al, "Crew Exposure to Vibration in the F-4C Aircraft During Low-Altitude, High Speed Flight", AMRL-TR-70-99, January 1971.

5. Harris, C. M. & Crede, E., (eds), Shock and Vibration Handbook, New York: McGraw-Hill, 1961.

6. Snyder, F. W., Beaupeurt, J. E., Brumaghim, S. J. and Knapp, R. K., "Ten Years of Vibration Research - and Beyond", The Boeing Company, Wichita Division, Paper presented to the 15th Annual ONR Research Seminar, Seattle, Washington, 25 June 1968.

7. Batchelor, G. H., "Determination of Vehicle Riding Properties II", Railway Gazette, 27 July 1962, pp. 97-100.

8. Altman, P. L., & Dittmer, Dorothy S., (eds), Environmental Biology, Bethesda, Md.: Federation of American Societies for Experimental Biology, 1966.

9. Dieckmann, D., "A Study of the Influence of Vibration on Man", Ergonomics, 1, 347-355, 1958.

10. Miwa, T., "Evaluation Methods for Vibration Effect: Part 1, Measurements of Threshold and Equal Sensation Contours of Whole-Body Vertical and Horizontal Vibrations", Ind Health (Japan), 5, 182-205, 1967 (See also later parts in same series: Ibid, 5, 206-212, 1967; 6, 1-10, 11-17 and 18-27, 1968.

11. Getline, G. L., "Vibration Tolerance Levels in Military Aircraft", Washington, D.C.: Office of the Secretary of Defense, Research and Development, Shock and Vibration Bulletin, No 22 (Suppl.), 24-27, 1955.

12. Reiher, H. & Meister, F. J., "The Sensitiveness of the Human Body to Vibrations", Translation from Forschung Ing. -Wes, 2 (11), 381-386, 1931, USAF Air Materiel Command Translation F-TS-616-RE, 1946.

13. Janeway, R. N., "Vehicle Vibration Limits to Fit the Passenger", SAE Journal, Vol 56, pp. 48-49, Aug 1948.

14. Magid, E. B., Coermann, R. R., & Ziegenruecker, G. H., "Human Tolerance to Whole-Body Sinusoidal Vibration, Short-Time, One-Minute and Three-Minute Studies", Aerospace Medicine, 31, 915-924, 1960.

15. Loach, J. C., "A New Method of Assessing the Riding of Vehicles and Some Results Obtained", J. Inst Loco Engrs, 48 (Part 2), 183-20 , 1958.

16. Rosegger, R. and Rosegger, S., "Health Effects of Tractor Driving", Journal of Agricultural Engineering Research, 5, 241-274, 1960.

17. von Gierke, H. E., "On Noise and Vibration Exposure Criteria", Arch Environ Health, 11, 327-339, 1965.

18. Pradko, F. and Lee, R. A., "Vibration Comfort Criteria", New York: Society of Automotive Engineers: SAE Paper 660139, 1966.

19. International Organization for Standardization, Preferred Frequencies for Acoustical Measurements, Recommendation ISO/R.266, Geneva: ISO, 1962.

20. Grande, D. L., "Some Effects of Random Turbulence on Weapon-System Performance", Aerospace Engineering, October 1962, pp. 35-43.

21. Fustenburg, J. W., "Development of Tracking Error Frequency Response Functions and Aircraft Ride Quality Design Criteria for Vertical and Lateral Vibration", ASD-TR-70-18, January 1971.

22. Allen, R., Jex, H. R.; and Magdaleno, R. E., "Vibration Effects on Manual Control Performance", paper presented at the 8th annual NASA-University Conference on Manual Control, University of Michigan, Ann Arbor, Michigan, May 1972.

23. Shoenberger, R. W., & Harris, C. S., "Psychophysical Assessment of Whole-Body Vibration", Human Factors, 13, 41-50, 1971.

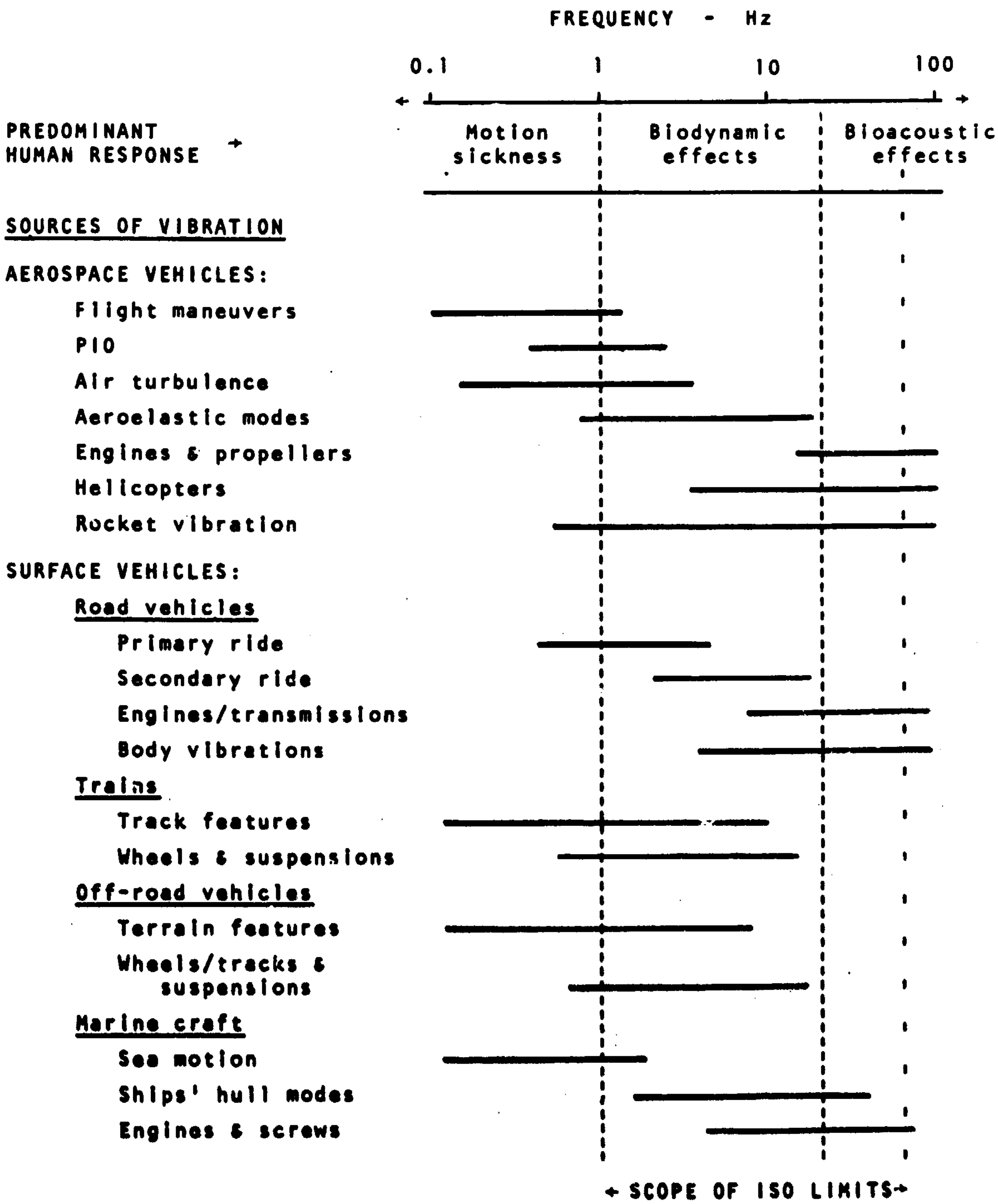


Figure 1.- Approximate frequency ranges of principal sources of vehicle vibration affecting man.

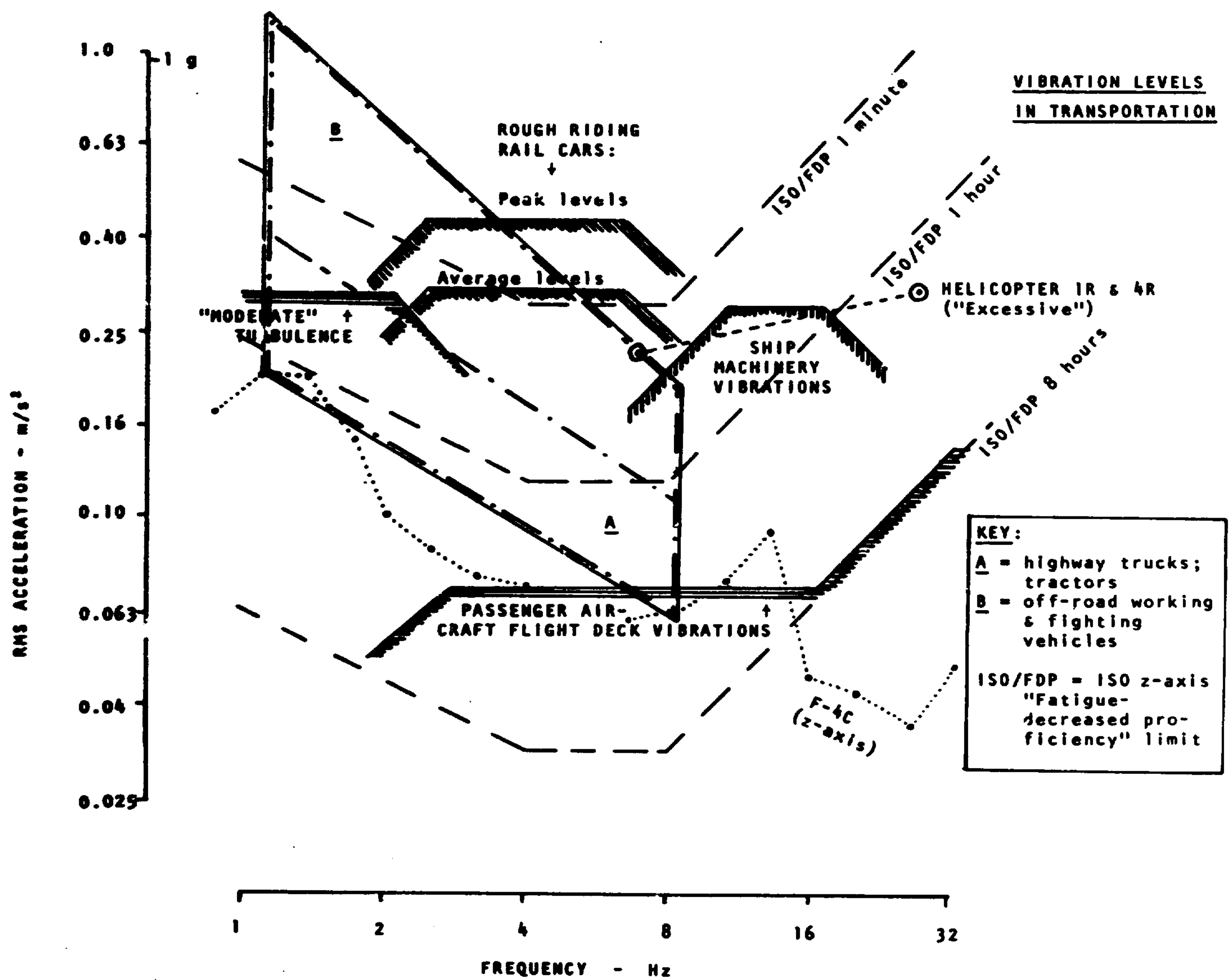


Figure 2.- Approximate envelopes of some representative vehicle vibrations, with selected ISO limits (ref. 1) (see key) for comparison.

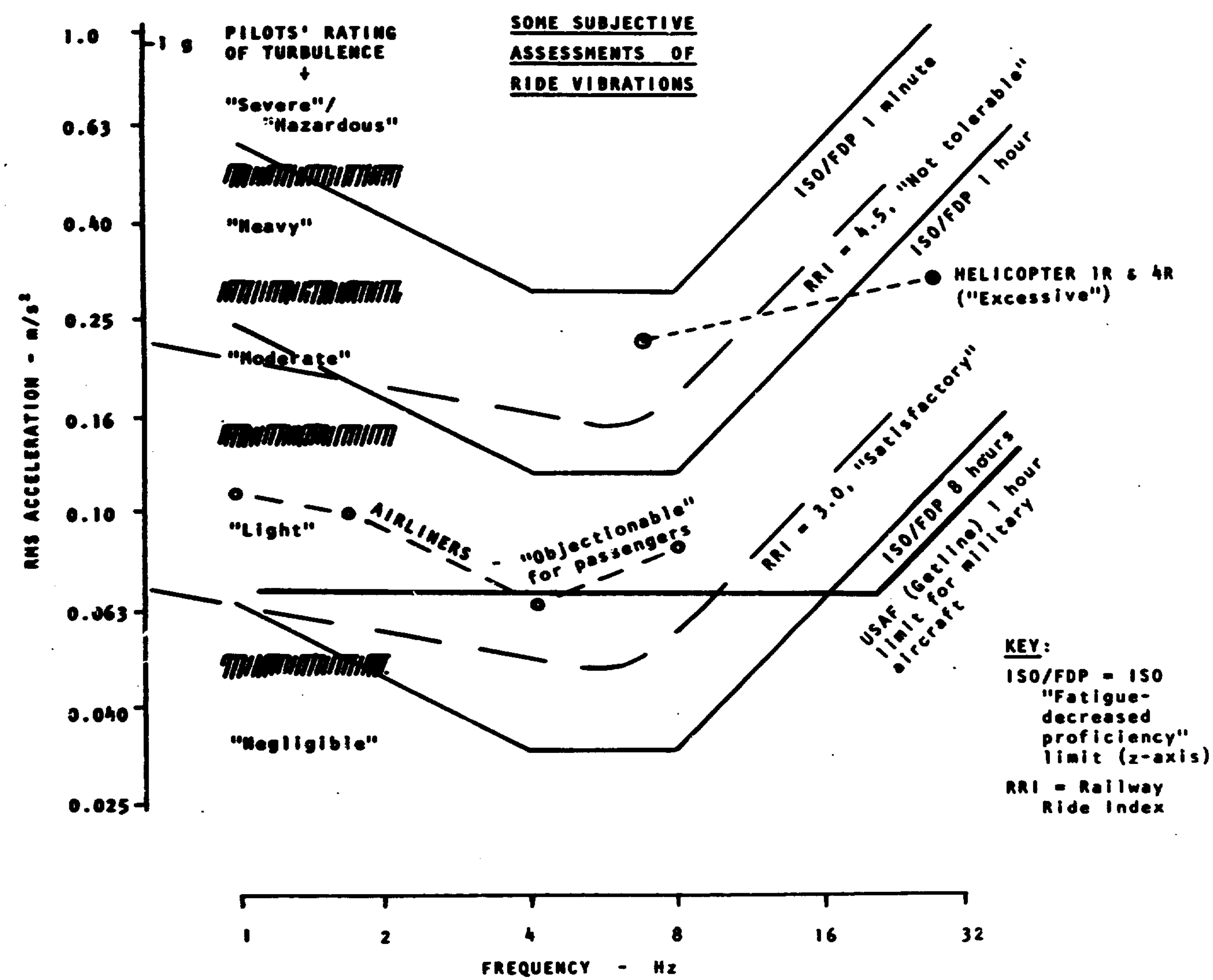


Figure 3.- Some subjective assessments of ride vibrations, with selected ISO limits (ref. 1) (see key) for comparison.

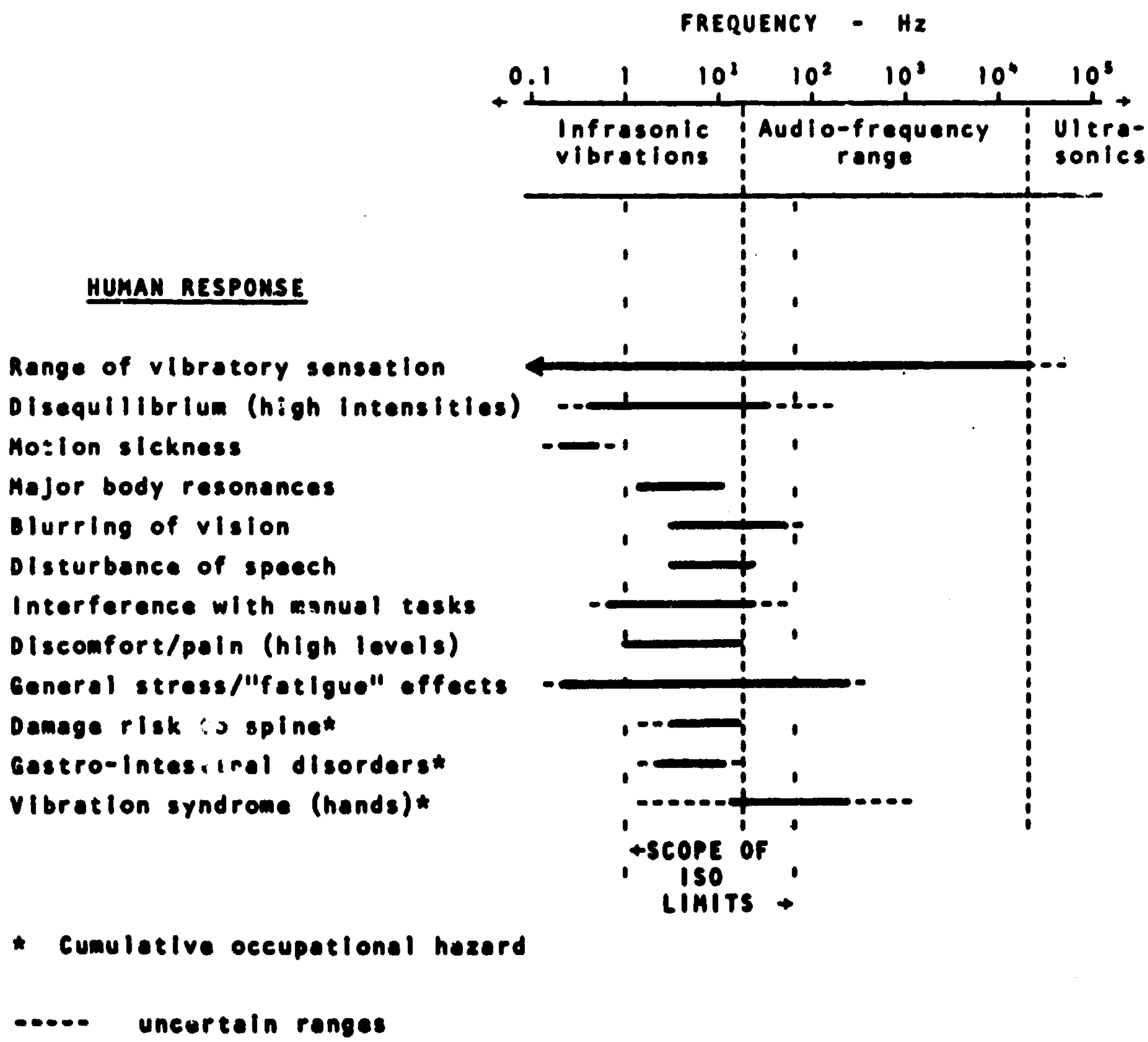
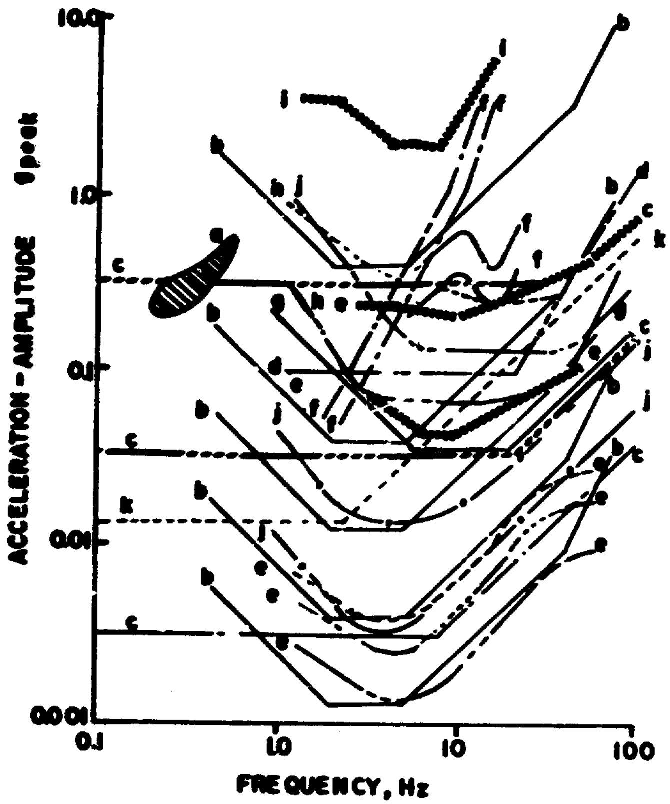


Figure 4.- Approximate frequency ranges of principal effects of mechanical vibration on man.



Key

a. Alexander, S. J., et al. 1945. J. Psychol. 20:31. (Motion Sickness Zone).

b. Boiten, G. S. 1957. Brit. Roy. Aircraft Estab. Library Transl. 695. (Building Vibration Boundaries).

c. Burton, E. F. 1950. Ride and Vibration Data. Ed. 2. Riding Comfort Research Committee, Society of Automotive Engineers, New York, pp. 18-27. (Aircraft Vibration).

d. Getline, G. L. 1955. U.S. Dept. Defense Shock Vibration Bull. 22 (Suppl.). (Military Aircraft Long-Term Limit).

e. Goldman, D. E., and H. E. von Gierke. 1960. Naval Med. Res. Inst. Lecture Rev. Ser. 60-3. (Thresholds of Perception, Discomfort, Intolerability).

f. Harris, C. S., and R. W. Shoenberger. 1964. AMRL Mem. P-73.

g. Janeway, R. N. 1950. Ride and Vibration Data. Ed. 2. Riding Comfort Research Committee, Society of Automotive Engineers, New York. pp. 18-27. (Automotive Vehicles).

h. Linder, G. S. 1962. Aerospace Med. 33:939. (Aircraft Vibration Limits).

i. Magid, E. B., R. R. Coermann, and G. H. Ziegenruecker. 1960. Ibid. 31:915. (Limits of Short-Term Voluntary Tolerance).

j. Notess, C. B. 1963. Cornell Aeron. Lab. Mem. FDM-343. (Aircraft Vibration Limits).

k. Notess, C. B., and P. C. Gregory. 1963. Soc. Automotive Engrs. Paper 679C. (Aircraft Vibration Limit).

After Altman, P. and Dittmer, Dorothy S. (eds), Environmental Biology, Federation of American Societies for Experimental Biology, 1966, pp. 218-220.

Figure 5.- A selection of empirical human vibration thresholds or limits drawn by various authors (cited in ref. 8).

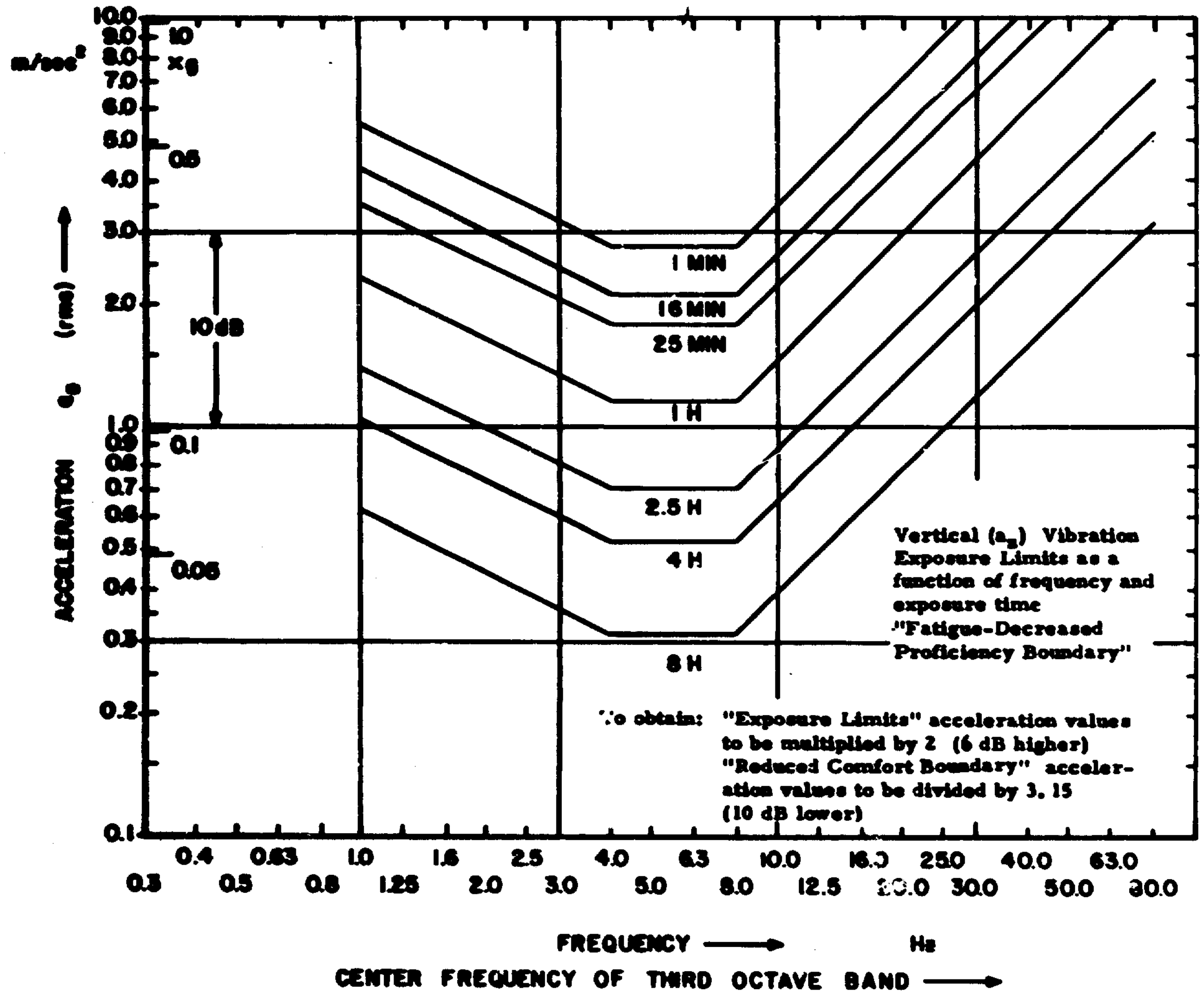


Figure 6a.- The proposed ISO ("Fatigue-decreased proficiency") limits for human vibration exposure: the frequency function for vertical (z-axis) vibration (see ref. 1 for full explanation).

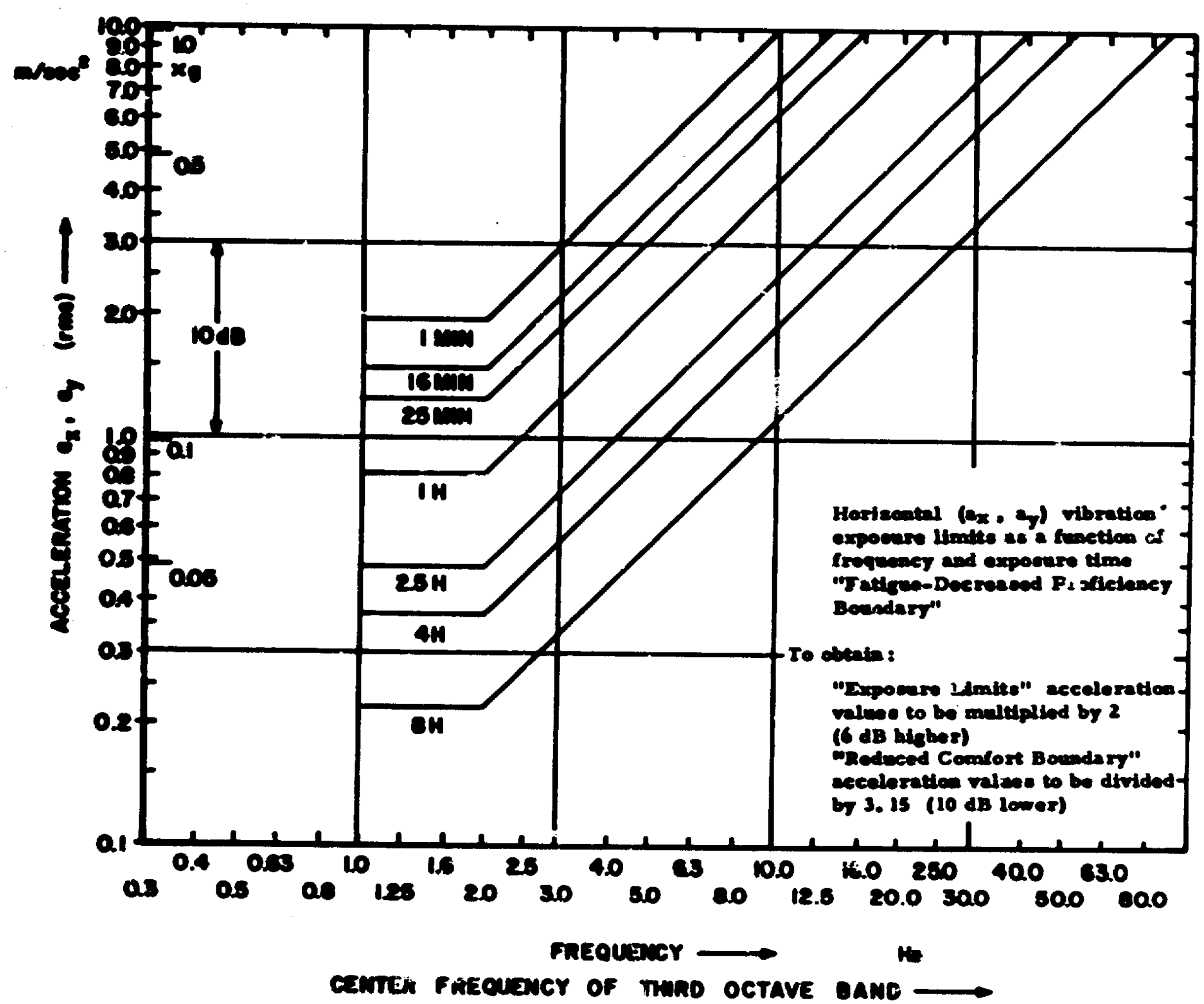


Figure 6b.- The proposed ISO limits for human vibration exposure: the frequency function for horizontal (x- or y-axis) vibration.

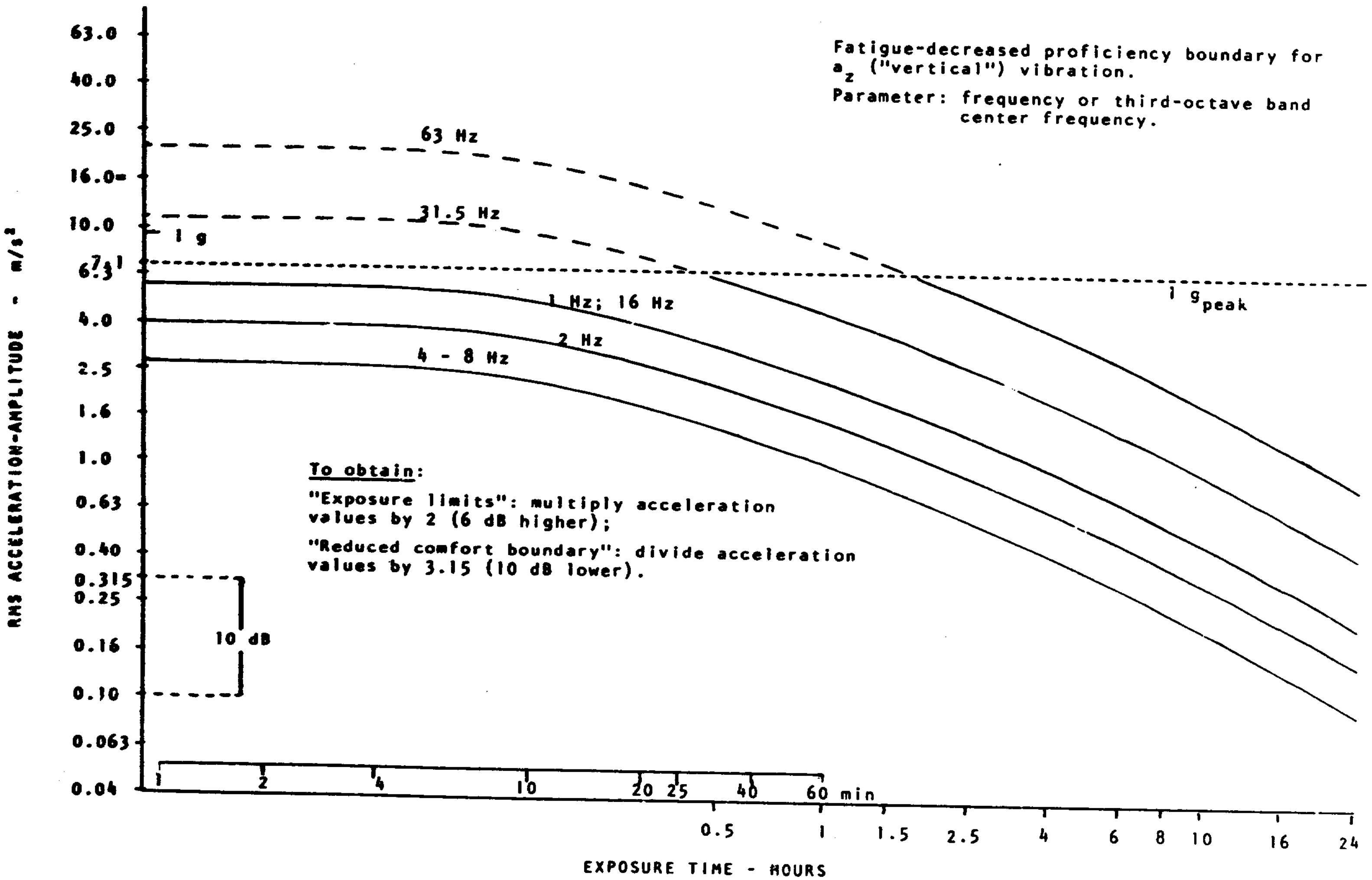


Figure 7a.- The proposed ISO limits for human vibration exposure: the time function for vertical (z-axis) vibration (see ref. 1 for full explanation).

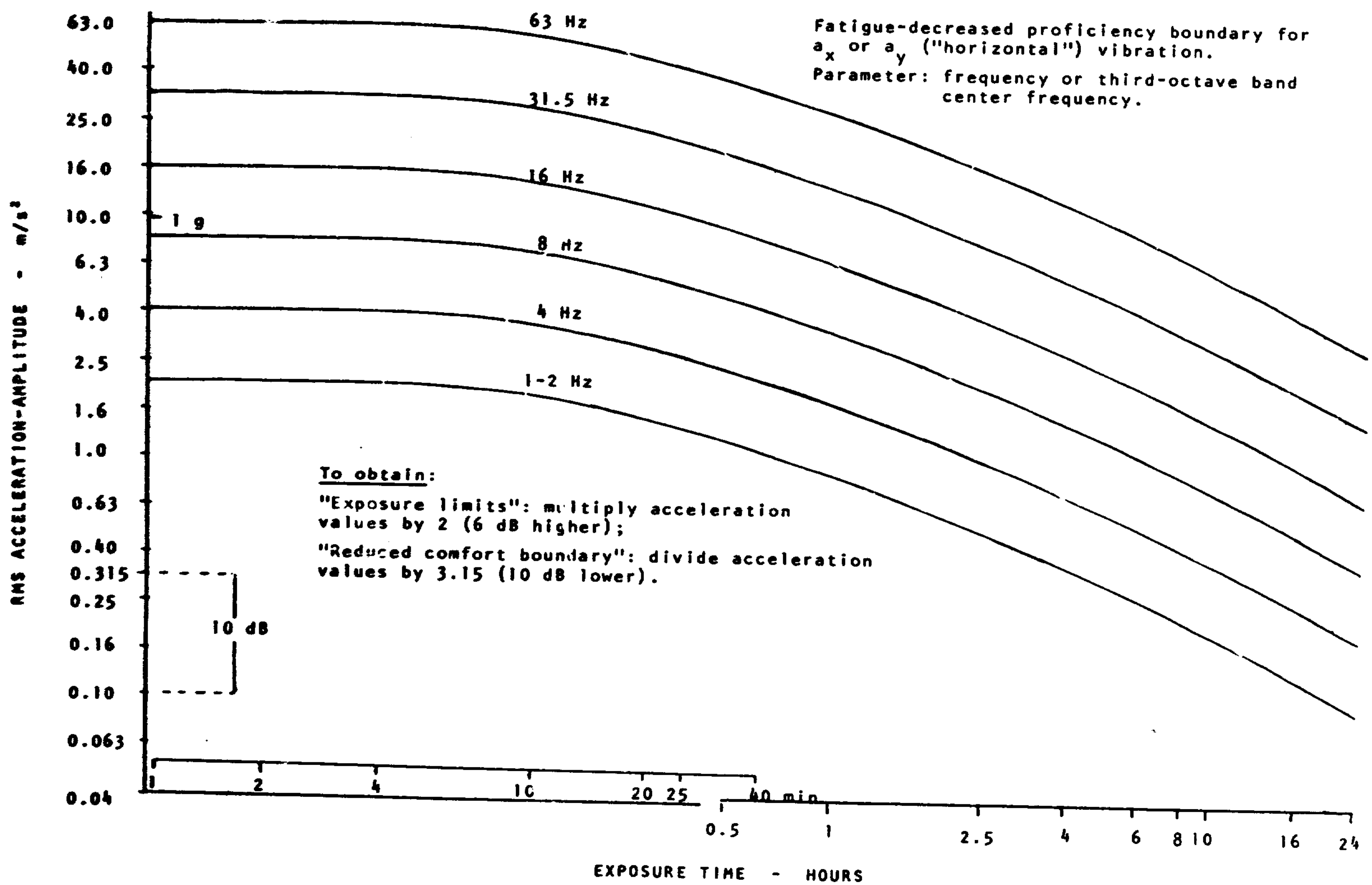


Figure 7b.- The proposed ISO limits for human vibration exposure: the time function for horizontal (x- or y-axis) vibration.

MARINE VEHICLE RIDE QUALITY

by

R. J. Gornstein, W. M. Shultz, & L. D. Stair
Naval Systems Division
The Boeing Company

N73-10022

SUMMARY

A variety of advanced high-speed marine craft has been proposed for the transport of people. Specific vehicles have been tried on a diversity of routes both with success and failure. Claims and counter-claims have been issued. Technical debates have ensued with regard to vehicle performance, reliability, costs, control, stability, propulsion, noise and air pollution, etc. The literature contains numerous reports on these subjects.

With notable exceptions, little has been said about one of the most basic of all considerations where the transport of man is concerned, the effect of vehicle motions on the fare-paying passenger. Generally, the problem is misunderstood and all too often ignored. No universally accepted method has been established to define the water conditions expected along a route, the vehicle motions likely to result, or the reactions of the passengers to those motions. This paper focuses attention on these considerations, compares the ride quality of advanced marine vehicles, and provides a basis for marine vehicle selection in modern water transport systems.

Good harbors and accessible waterways have been vital to the economic growth and community development of almost every major city in the world. The water continues to play a critical role in commerce, but land and air have taken over the transportation of people. Available, inexpensive to maintain, and underused, the waterways can be developed for passenger transit with a minimum of disruption, inconvenience and cost to the community. Ride quality and passenger acceptance are paramount to making it all happen - the keys to any economically viable form of transport.

INTRODUCTION

A fare-paying passenger, whether traveling by land, sea or air, expects safe, dependable, convenient and economical service.

Each mode of transportation has inherent advantages and disadvantages which change in scope as time goes on. For example, the jetliner's speed is offset by terminals located far from the passenger's final destination. In urban areas, the lower vehicle cost of cars and busses is offset by the cost of right-of-way and the problems of community dislocation and congestion.

For centuries water transport was the major mode within many countries, and the only mode of travel between continents. Most of the world's large cities were located to provide easy access to water transportation. In recent years water transportation has declined in relative importance because it has not kept pace with developments and improvements enjoyed by land and air transport systems. Water transport systems have remained slow, uncomfortable and subject to the vagaries of weather.

With the advent of modern technology this need no longer be true. Advanced marine vehicles have been designed to provide competitive speeds with a quality ride, and have achieved a broad passenger acceptance. This has been demonstrated in Russia where over 1,000 hydrofoil craft are engaged in river travel today. Technology is in hand to provide the same or better ride quality at still higher speeds in the open waters of the United States.

Current problems of population growth, traffic congestion and pollution demand that we again take a hard look at the number of potential benefits water passenger transit has to offer. Think of what this would mean to the crowded city of today, and the congested city of tomorrow.

Sixty percent of the population of this country lives adjacent to water, and nine of our fifteen largest cities are coastal, all having main waterways that are generally underused and underdeveloped in relation to other transit rights-of-way. These water freeways are available with a minimum of property condemnation or community disruption. Water rights-of-way are inexpensive to maintain and flexible in meeting changing conditions.

In theory, at least, water passenger transit systems appear to have much to offer modern society and community development. The key question is, -- can marine vehicles be made available that will meet the demands of comfort, dependability and high speed within ecological constraints and be a good neighbor to other users of the waterways and those living on the shore? If so, then can they be economically viable since there are already too many transit systems that are losing money at an ever-increasing rate. (Reported as 1,079 systems that lost a total of $332 million in 1970.)

MAN -- THE DETERMINANT

The most critical factor in economic viability for any transportation system is passenger acceptance. No system is worth much if the people it is intended to serve won't use it. This concern is especially true for water systems, where it is contended that many past systems were not acceptable to people and were discontinued for that very reason.

RIDE QUALITY

Human reaction to motion is primarily subjective, and for the most part, has defied rigorous formulization and quantification. Defining the level of ride quality acceptable to passengers on a day-to-day basis is a weak link in the progression of marine transportation. Each type of marine vehicle provides a unique motion environment in a particular sea. Knowledge of the effects on passenger comfort due to motion spectrality and intensity is necessary to intelligently select candidate vehicles for operation on specific routes. Improvements in vehicle design aimed at providing a better ride await a clear understanding of passenger requirements.

Some of the recent work in the field of human reaction research, while not directed specifically at marine applications, is revealing in the sense that it offers insight into the problems of what is important in providing passenger acceptable ride quality. It is the consensus that ship vertical or heave motions (aptly named) are the primary cause of sea-sickness and severe discomfort. (Ref. 1) The sea-sickness and comfort boundaries shown in Figure 1 were derived from the data existing in the references. Due to the limited amount of information available the boundaries presented should be considered to be tentative rather than definitive. People appear to be more sensitive to a particular level of motion during a period of increasing motion intensity and less sensitive during a period of decreasing motion intensity. Motion sickness has been found to be most predominate (30 to 50 percent of test subjects became ill) when oscillation was less than .8 hertz and vertical acceleration ranged from .1 to .17 g's rms. (Ref. 2 thru17)

ROUGH WATER -- THE CULPRIT

Does the water ever really get rough in places like New York Harbor, San Francisco Bay, Puget Sound, Honolulu, etc? Does it happen enough of the time to worry about? Is it going to affect the ride of any reasonably sized craft in a significant manner? This is the next key problem in evaluating marine systems.

VEHICLE BEHAVIOR

Today's marine designer has a decided edge over those of yesterday. He can predict with confidence the characteristics of the sea in which his vessel will operate. He can likewise simulate the response of his design to that sea and shape the vessel response through application of modern control theory. If only he knew what shape he needed to have before the passengers started to board on the maiden voyage.

Marine vehicles come in a wide assortment of sizes, shapes and types. It is primarily the type that is of interest here. There are conventional craft, surface effect vehicles and hydrofoils. Within each type there are different kinds to further compound and confuse all but the most knowledgeable observer. Conventional craft include all normal displacement craft that depend on the bouyancy of the water for support, and include catamarans and planing craft which obtain some dynamic lift as the craft increases speed. Surface effect ships employ cushions of air to provide lift. Hydrofoils depend on dynamic foil lift, and are either surface piercing or the fully submerged type.

With only one exception, the fully submerged hydrofoil, these vehicles are surface followers. These surface following vehicles can provide good ride quality in relatively calm conditions. The fully submerged hydrofoil can provide excellent ride quality in rough water environments.

Figure 2 presents vertical motion transfer functions which were developed from data in References 11 thru 16. The upper two curves are for a 200-ton, 140-foot long conventional ship operating in a head sea at 22 and 35 knots. The middle curves are for a typical 60-ton surface piercing hydrofoil operating in a head sea at 35 knots, and a 175-ton surface effect ship in the same sea at 33 knots. The lower curve is for a fully submerged hydrofoil operating in a head sea at 45 knots.

Figure 3 presents acceleration characteristics determined by combining the conventional ship transfer functions with the four different wave spectra from Figure 4. As can be seen, a reduction in speed from 35 to 22 knots does reduce the acceleration levels.

Figure 5 presents vertical acceleration responses obtained from the 175-ton surface effect ship transfer function of Figure 3, with the wave spectra of Figure 4. One paper on surface effect ship operation in the English Channel (Ref. 17) reports that over 10 percent of the passengers carried were seasick when operating in observed wave heights of five feet and higher at speeds less than 33 knots. The associated vertical accelerations in these waves were from 0.13 to 1.15 g's rms. No frequency response data was presented, and therefore this data is shown as a band on Figure 5.

Figure 6 presents the acceleration characteristics for the hydrofoil vehicles. The surface piercing hydrofoil at 35 knots provides a ride comfort approximately comparable to the 200-ton conventional ship at 22 knots. The addition of control systems to surface piercing hydrofoils (as is currently being undertaken by some manufacturers) shows promise of as much as 50 percent reduction in vertical acceleration. The fully submerged hydrofoil data is based on computer simulations correlated with four years of operating experience with similar hydrofoil vehicles.

RIDE REQUIREMENTS

The most difficult task is to determine sea transportation ride quality requirements. To define the level of motion that would be acceptable to any specific group of passengers being transported over the sea, we would ideally need to know the reaction of that group to specific motion environments. Obviously, the ride quality that would be acceptable to a group of pilots or astronauts might not be acceptable to a group of ladies from the B'nai B'rith of Topeka, Kansas.

Over the past 50 years a limited number of tests have been conducted with the goal of determining the effects of motion on people.

Without exception, the results show a great variability of human reactions. Many physiological and psychological factors interact to affect people's comfort from day to day and from group to group. Some of the factors which need to be specifically investigated and others for which qualitative information is needed are listed below:

1. Direction of motion with respect to the body
2. Wave form or spectrum of the motion
3. Uni- or multi-directional motions
4. Duration of the motion
5. Environmental conditions such as temperature, humidity, ventilation, odors, noise level, etc.
6. Activity of the individuals during the tests such as drinking, reading, writing, etc.
7. Characteristics of the test subjects: Age, sex, height, weight, previous motion experience, etc.

In 1968, the SST Technical Staff undertook a program of tests and evaluations to develop aircraft passenger ride acceptance criteria and to define a ride quality analysis method. Comparisons were made between the expected SST ride qualities and those of current commercial airplanes. The results are presented in Reference 5. Although these tests were aimed primarily at determining passenger acceptance of the SST ride under turbulent air conditions, some of the results were of interest from the standpoint of marine transportation, specifically the results of tests using narrow band random motions with spectra similar to those observed for marine vehicles operating in waves.

None of the motion experiments was conducted with more than one person at a time. Individuals within a group may react differently to the test environment when not under exclusive scrutiny by the observers. A group mutually engaged in some activity may react contrary to what would be expected based on individual test reactions.

In general, the individuals in a test population were males between 20 and 40 years of age from various backgrounds. The number of people tested in a typical experiment usually varied from 2 to 15.

CONCLUDING REMARKS

It is hoped that this paper will stimulate researchers to conduct additional tests of variables, types and numbers of passengers in a frequency and g spectrum which encompasses marine travel so that future marine designers can improve their systems and expand the roll of marine transportation to the benefit of future travelers.

REFERENCES

1. Shaw, C.C.; "On the Dynamics of Motion Sickness in a Seaway", Science Monthly Vol. 78, 1954, pp. 110-116.

2. Working Group 7; "Guide for the Evaluation of Human Exposure to Whole-Body Vibration", International Organization for Standardization ISO/TC 108/WG 7 (Secretariat -19), June 1969.

3. Grey, L.H.; "Personnel Subsystem Development Plan", The Boeing Company D6-11039-1, August 1965.

4. Brumaghim, S.H.; "Effects of Low Frequency Cyclic Oscillations on Passenger Ride Comfort", The Boeing Company D3-3026, March 1969.

5. Brumaghim, S.H.; et al; "SST Passenger Ride Quality Criteria Analysis Development and Validation Testing Results", The Boeing Company D3-7600-7, February 1969.

6. "Ride and Vibration Data Manual", SAE J6a, October 1965.

7. Bender, E. and Collins, A.; "Effects of Vibration on Human Performance: A Literature Review", Bolt, Beranek and Newman, Inc. Report No. 1767, February 1969.

8. Michel, W.; "Sea Spectra Simplified", SNAME Marine Technology Vol 5 No. 1, January 1968.

9. Marine Advisers, Inc.; "Characteristics of Deep-Water Waves in the Oahu Area for a Typical Year", March 1964.

10. Boeing Test Data on Puget Sound 1968-1970.

11. Abkowitz, M.A.; et al, "Recent Developments in Seakeeping Research and Its Application to Design", SNAME Annual Meeting Paper No. 5, November 1966.

12. Vossers, G.; "Fundamentals of the Behavior of Ships in Waves, Part V", International Shipbuilding Progress, Vol. 9, No. 92, April 1962.

13. Kaplan, Paul; Bentson, James; Sargent, Theodore P.; "Study of Surface Effects of Ship SES Craft Loads and Motions", Report No. 71-84B, Oceanics Co., August 1971.

14. Hamlin, N. and Compton, R.; " Assessment of Seakeepability", SNAME Marine Technology Vol. 3 No. 4, October 1966.

15. Von Schertel, H.; "Design and Operating Problems of Commercial Hydrofoils" Supramar A. G., Lucerne, Switzerland, 1962.

16. Schmitke, R.; " A Computer Simulation of the Performance and Dynamics of HMCS Bras D'Or (FHE-400)", Canadian Aeronautics and Space Journal, March 1971.

17. Wheeler R.; "The Development Phase of the Mountbatten Class (SR.N4) Hovercraft, AIAA Paper No. 69-410, May 1969.

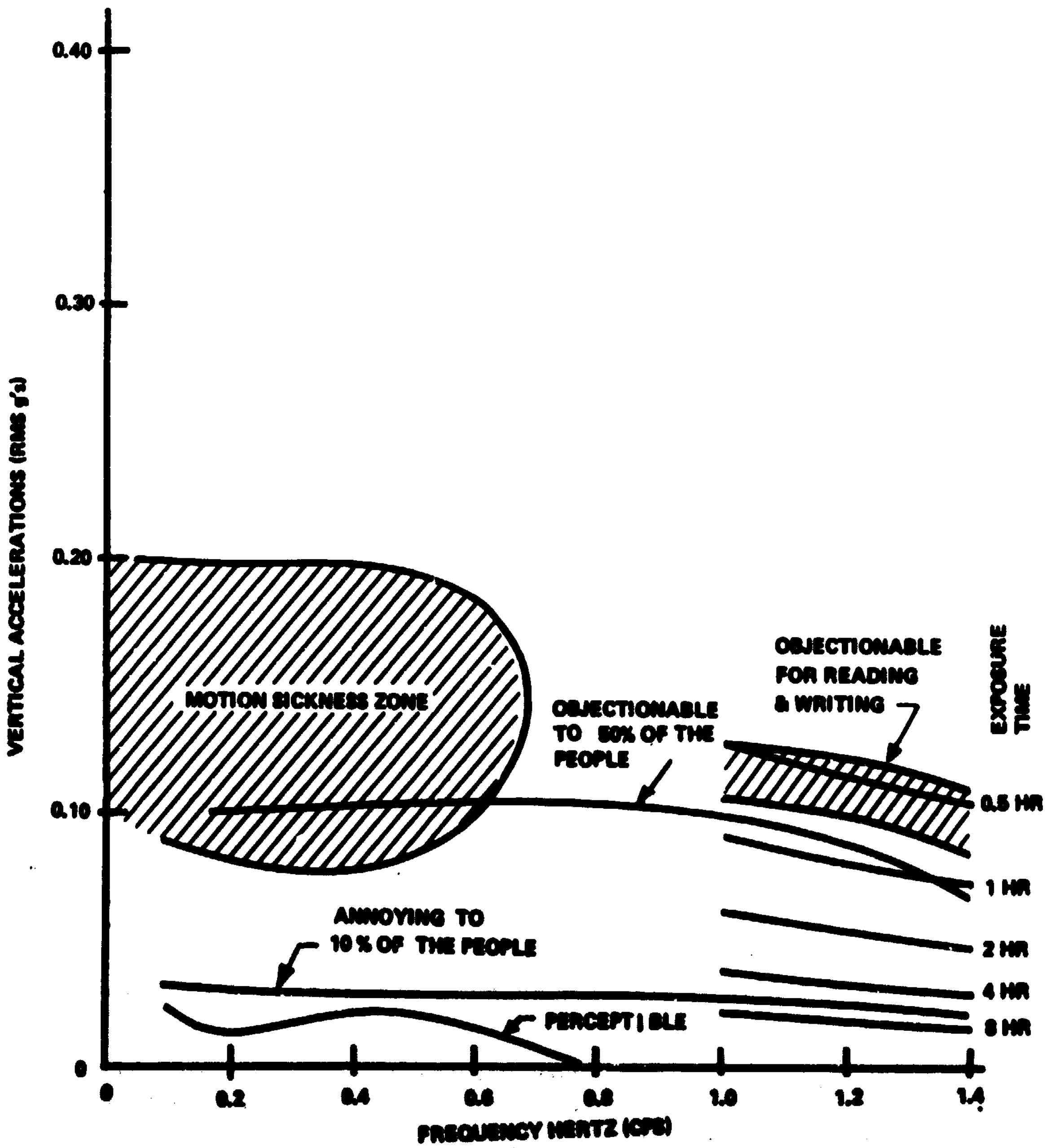


Figure 1.- Tentative passenger comfort boundaries.

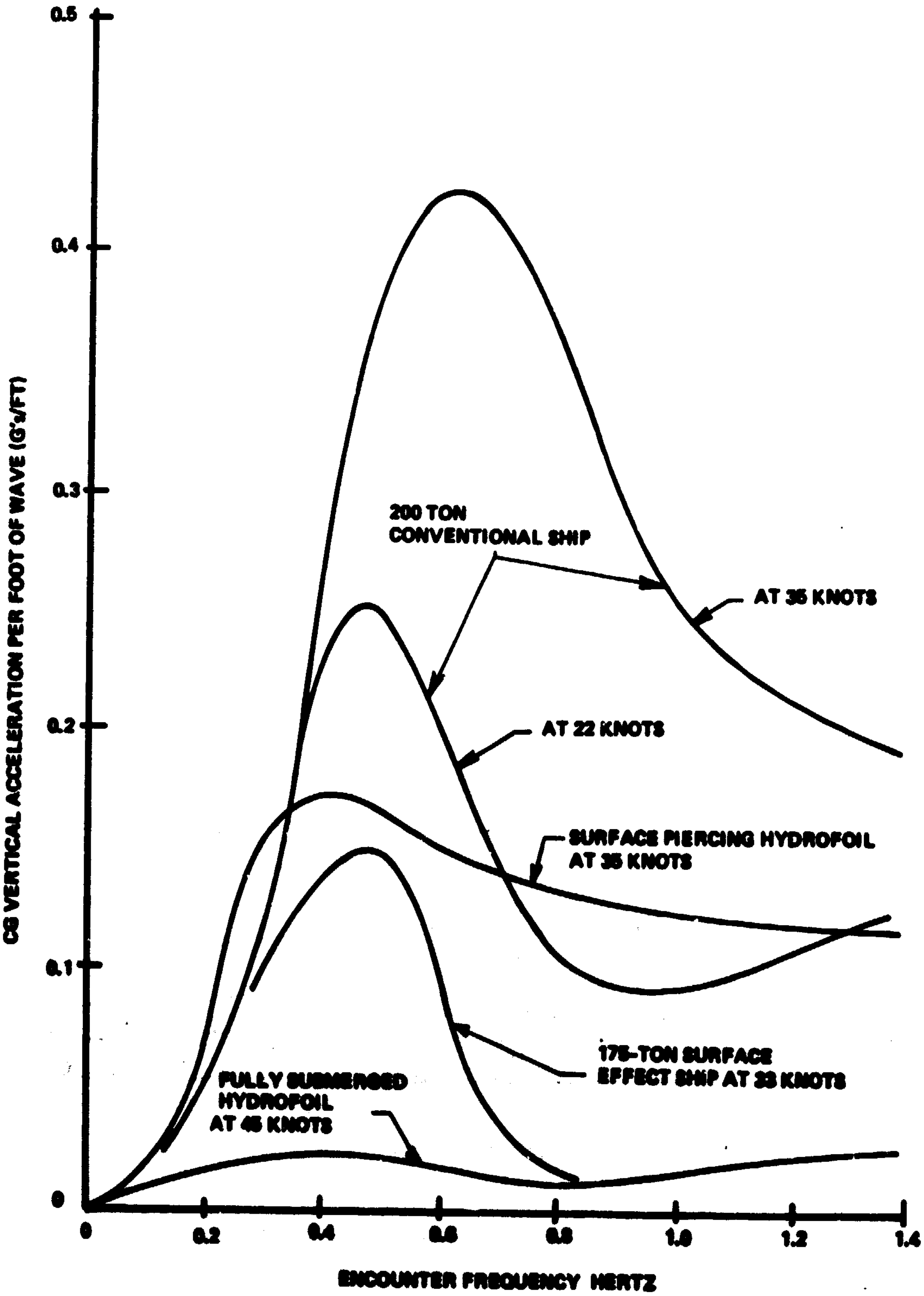


Figure 2.- Vertical acceleration transfer functions.

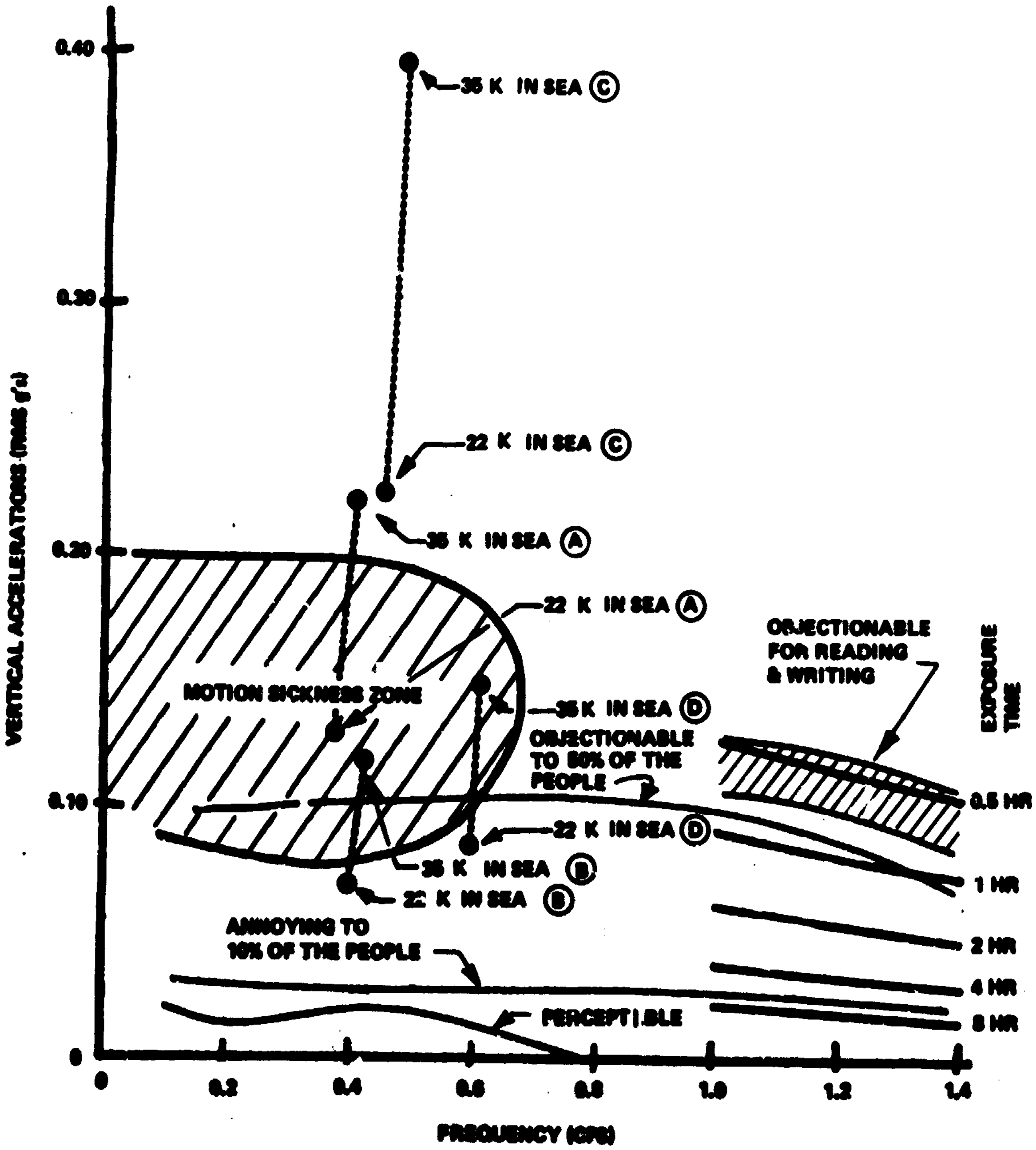


Figure 3.- 200-ton conventional boat.

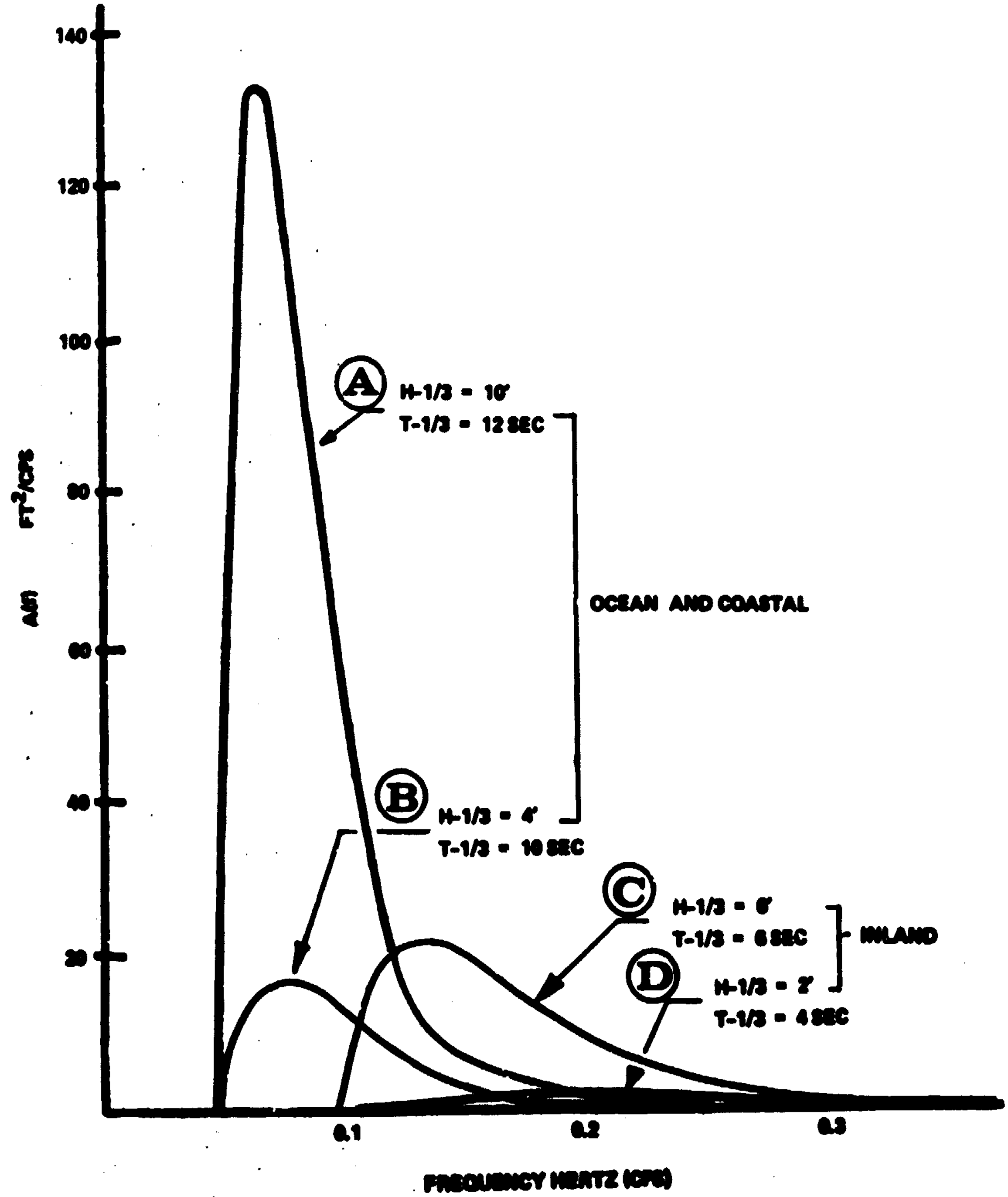


Figure 4.- Fixed point wave amplitude spectra.

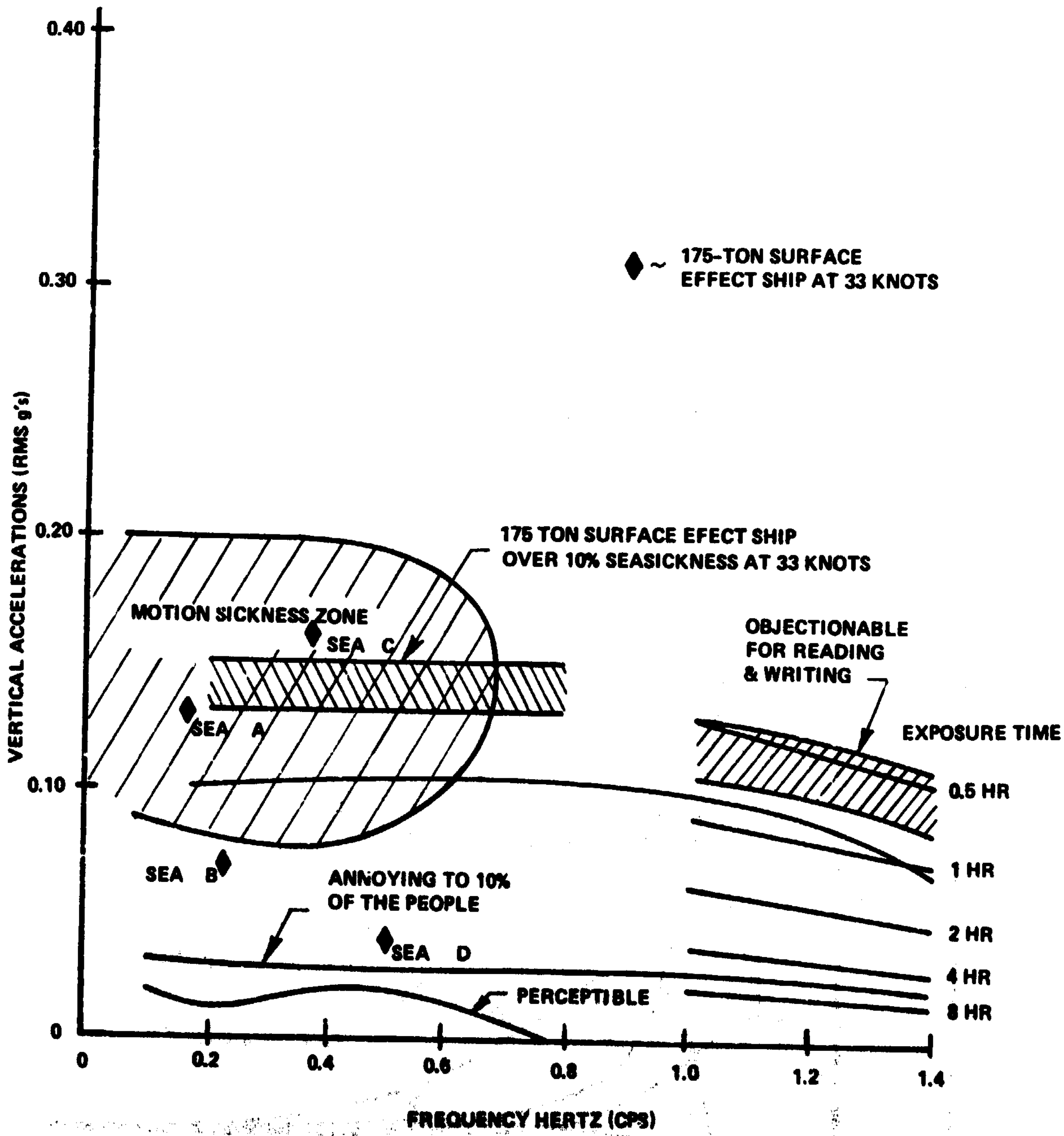


Figure 5.- Surface effect vehicles.

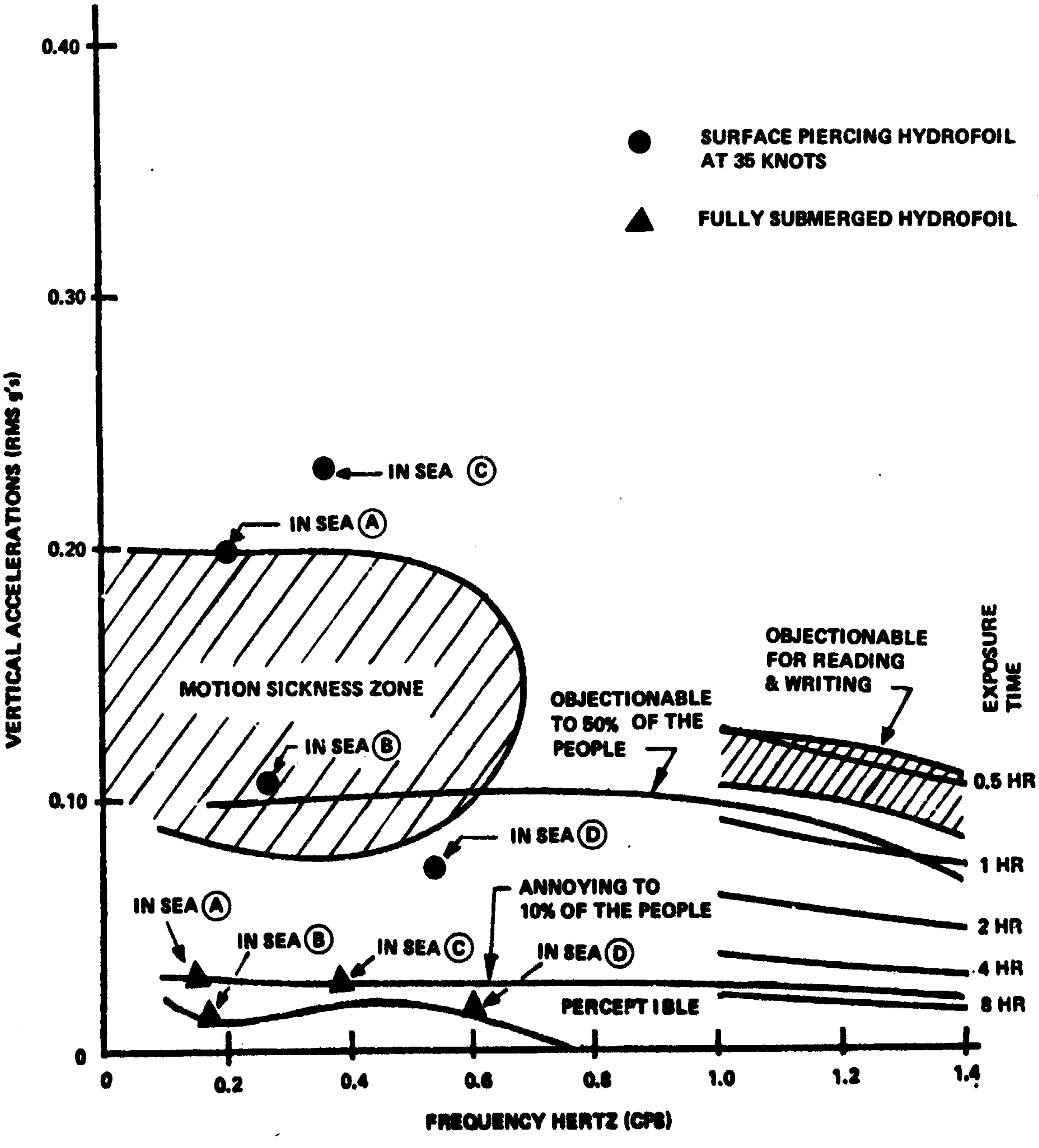


Figure 6.- Hydrofoils.

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INVESTIGATION OF TRAVELER ACCEPTANCE FACTORS IN SHORT-HAUL AIR CARRIER OPERATIONS*

A.R. Kuhlthau† and Ira D. Jacobson††

Center for Application of Science and Engineering to
Public Affairs
University of Virginia

N73-10023

INTRODUCTION AND BACKGROUND

The ability to mathematically model human reaction to variables involved in transportation systems offers a very desirable tool for the prediction of passenger acceptance of proposed systems and for establishing acceptance criteria for both the system and hardware designers. To provide useful practical results the model must accommodate all essential inputs from all parties involved, i.e., the passenger, the general public, and the industries which will build the equipment and facilities required and offer the services which result from their use.

Although this paper will be limited to a discussion of some of the techniques, activities, and results related to defining certain specific inputs to the model, it is important to place them in their proper perspective and so a very brief review of the overall approach should be of value.

Figure 1 shows a general schematic diagram of the problem solution plan which has been adopted. The industry component has been neglected in this initial formulation on the grounds that to a first approximation economic factors will dominate industrial acceptance and that the appropriate cost factors will be defined by the passenger and public studies.

The solution plan also assumes that the reactions of the traveling and non-traveling public are generally independent and can be assessed in parallel. This is also obviously valid only to a first approximation and cross-talk between the two channels must definitely be accounted for in subsequent iterations.

Since this paper is concerned solely with passenger acceptance, let us look at this channel in more detail. Without any attempt to be exhaustive, the general content of the various inputs to the passenger model will include such items as the following:

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†Professor, Aerospace Engineering

††Assistant Professor, Aerospace Engineering

Inputs due to Vehicle

motion of all types .... effect of amplitude, velocity, acceleration, frequency, etc.

cabin environment ...... temperature, humidity, noise, seat accommodation

cabin service, aesthetics, limitations, etc.

visual cues

Inputs due to Systems Characteristics

safety	convenience
reliability	comfort
time savings	aesthetics
cost	service

Inputs due to Passenger Characteristics

motivation for the trip

personal traits that influence likes and dislikes

relative importance of various system characteristics

general attributes of standard of living

Inputs due to Passenger Preconditioning

impressions based on marketing and promotion

impressions based on previous trip experiences

experiences related to current trip

terminal location	handling in terminal
ground transportation	handling in aircraft on ground
parking	

Although the ride quality aspects are nominally contained in the category of vehicle inputs, it should be clear that the human reaction output will be strongly influenced by the conditions existing in the other input classes. This fact has important implications in the design of experiments for determining reaction to such variables as motion, temperature, noise, etc. Because of this influence of one input on another, inadequate documentation of the conditions under which large quantities of human response data have been obtained makes these data of little value to model development.

Another important feature of the model results from the fact that no specific system can be evaluated in isolation. When the final decision as to acceptability is made by the passenger, it will always be in comparison with the similar types of attributes of alternative systems. This also has a profound influence on the acquisition and evaluation of data obtained from passengers or travelers. Thus in effect we are concerned with modal split demand analysis. For example, the usual presentation of demand models results in a form typified by:

$$D_n = K\, \$_n^{\alpha}\, T_n^{\beta}$$

where

- D = Demand for travel mode n; i.e. percentage of total number traveling between two points who use mode n
- $\$$ = Cost
- T = Time
- K = Empirical coefficient
- α, β = Elasticities

The key to the ability of such an approach yielding a reliable result rests with the coefficient K. It is the only term in the formulation which can account for the many factors of human acceptance described above. The total acceptance modeling concept should result in a much more detailed expression for D_n of a form

$$D_n = f(C, T, S, R, E, \$)$$

where

- $C \rightarrow$ Comfort = f(motion, noise, temperature, pressure....)
- $T \rightarrow$ Time = f(connect time, trip time, delay time....)
- $S \rightarrow$ Safety = f(mechanical reliability, accident record, risks as sensed by passenger....)
- $R \rightarrow$ Reliability = f(weather, breakdown frequency, space availability....)
- $E \rightarrow$ Convenience = f(schedules, locations, routes....)
- $\$ \rightarrow$ Cost = f(connect cost, mode cost, ancilary costs....)

where the effect of passenger preconditioning can also be included.

Two final comments are in order concerning the University of Virginia concept. First, it is apparent that if the approach is successful for STOL or short-haul air transportation systems, then by proper characterization of the inputs to the model, it should be applicable to any type of transportation system, be it land, sea, or air. Secondly, a considerable amount of the methodology and techniques perfected for application in the transportation field should be sufficiently general to form a firm base for a quantitative approach to human acceptance in a wide variety of problem areas.

ATTITUDE SURVEY

In order to define the inputs to the passenger acceptance model it is first necessary to assess the relative importance of the various aspects of the transportation system as they relate to the satisfaction of the passenger or potential passenger. It was hoped that the general areas included would order themselves in some hierarchy of values which would be relatively invariant across subjects, allowing a predictive model of the prospective passenger to be developed. This possibility did indeed emerge from the study.

Although a considerable body of literature exists concerning travel habits of passengers, it is not properly oriented for the current studies. In the case of inter-urban air transportation it is mostly demographic in nature (see reference 1)with very little data on attitudes. Factors affecting modal choice in urban transportation have received serious study (see reference 2), but the situation here is quite different from the inter-urban case. Consequently, it was felt desirable to obtain information relating to the inputs defined earlier by direct contact with the particular user group likely to be most concerned with short-haul or STOL air transportation.

Basically, two questionnaires were utilized for this study - one a ground-based questionnaire probing attitudes, the other a flight questionnaire which in addition to surveying attitudes was concerned with subjective reaction to the flight environment. This will be discussed below. Table I shows some of the demographic features for the subjects responding to each of these questionnaires. Although the ground-based version was administered to a subject group of predominately professionals, a wide variety of occupations from secretary to airline pilot was represented in the flight administered version. The data for the general public were taken from reference 1.

TABLE I

	Percent Traveling for		
Response Group	Business	Personal	Other
General Public (High Density Market)	74	23	3
UVA Ground-Based Questionnaire	79	21	-
General Public (Low Density Market)	40	34	26
UVA Flight Questionnaire	22	12	66*

*Paid Subjects

Response Group	Percent Whose Age 25	25-34	35-44	45-54	55
General Public (High Density Market)	14	20	27	22	17
UVA Ground-Based Questionnaire	11	19	28	27	15
General Public (Low Density Market)	28	18	22	18	14
UVA Flight Questionnaire	28	26	16	23	7

It is apparent from a study of Table I that the respondents to the ground-based questionnaire very closely approximated the typical profile which emerges from studies of the general public in a high density market. Similarly, discounting the perturbation imposed by the necessity to use a high percentage of paid subjects in the flight questionnaire program, there is a marked similarity between this group and the general public involved in a low density market.

The factors determining satisfaction with air travel are shown in figure 2. It is important to note that the rank order of the variables remained essentially unchanged when broken down by ground based or flight administration as shown. In addition they remained relatively invariant for most other sub-divisions (e.g. male versus female) with the noted exception of the effect on the ranking of cost with purpose of trip. When the major trip purpose was personal (i.e. personally funded) cost became third in the rank order.

In addition to investigating the overall aspects of passenger satisfaction, the importance of the aircraft environmental variables on passenger comfort and the most likely in-flight activities (for short-haul flights) were studied. The results are shown in figures 3 and 4. Subjecting the data to a factor analysis leads to some interesting conclusions (see reference 3).

FACTOR ANALYSIS

Follow-up interviews were conducted during which several psychological tests were conducted, and an in-depth analysis of these along with the questionnaire data was carried out. The results indicated that the variables associated with traveler's degree of satisfaction with his air travel experience can be distinguished on the basis of four principal dimensions:

Dimension 1 - A safety dimension

This includes reliability.

Dimension 2 - A cost-benefit dimension

It is interesting to note that cost alone is not the prime quantity involved here; convenience and time saving must be considered in trade-off with cost.

Dimension 3 - A "luxury" dimension

This dimension includes a mix of comfort, convenience, on board services, and aesthetics.

Dimension 4 - An in-flight activity dimension

This characterizes the passenger's preference for how he will spend his time in flight and is strongly influenced by comfort.

Thus the customary variables associated with travel are not unique to a given dimension, but generally appear more than once, and often in a different context.

Based upon this analysis it is proposed that a demand model of passenger usage should be a function of the four basic dimensions, not just the economic and time variables usually considered.

MODELING

Although the ultimate goal of the modeling effort is to determine a relationship which quantizes the passenger acceptance of the system (demand model), a first step of which is described above, the present modeling work is focused on a subvariable in the problem. As seen from figures 2 and 3, the comfort of the passenger is as important a variable as the convenience, time, and cost of the system; and the ride quality (motion) is an important parameter along with temperature, seat comfort, noise, lighting, pressure changes, and presence of smoke in determining comfort. Thus an experimental program was undertaken to provide data for a first generation model of comfort. This program consisted of a series of flights by a selected subject group on a regularly scheduled commercial airline with associated equipment to measure both the environmental variables and the subjective response of a group of subjects.

A total of 100 flight segments were flown aboard three different aircraft --YS-11, F-227, B-737-- for a variety of turbulence conditions and over a variety of terrain (both flat and mountainous). There were either one or two subjects per flight segment and a minimum of six flight segments were obtained for each of nine subjects. The response of the subjects was scheduled by time and involved a subjective evaluation of comfort every two or four minutes during flight in response to the motion environment.

In addition to the six motion variables consisting of three linear accelerations and three angular accelerations, the temperature and noise level were monitored. The motion variables were recorded on NASA provided equipment shown in figure 5 consisting of angular accelerometers, and a recording system. The measuring equipment was placed on the cabin floor directly in front of the subject's seat location. The motion data was recorded on a standard FM tape recorder and later reduced for analysis using a standard time series analysis program (see reference 4). The temperature and noise level were manually recorded. A typical trace of the recorded motion data in shown in figure 6. The comfort response is based on a five-point scale from 1 - very comfortable to 5 - very uncomfortable.

Two models have been developed based on these data and a third proposed. At present they are a function of only the motion variables since the other comfort parameters were either substantially constant or not measurable for the aircraft used. The first model is an extension of the work done by Van Deusen (see reference 5). The comfort, C, of the passenger is related to the RMS accelerations and their cross correlations by

$$C = C_o + \sum_{j=1}^{6} \alpha_j \bar{a}_j^{\nu_j} + \sum_{j=1}^{6} \sum_{i=j+1}^{6} \beta_{ij} \bar{b}_{ij}^{\mu_{ij}}$$

where

$$\bar{a}_j = \sqrt{\frac{1}{T} \int_0^T a_j^2(t)\, dt}$$

are RMS accelerations in the vertical, transverse, longitudinal, pitch, roll, and yaw directions and

$$\bar{b}_{ij} = \sqrt{\frac{1}{T} \int_0^T a_i(t)\, a_j(t)\, dt} \qquad i \neq j$$

are the cross correlations of each variable with all others. The α_j's and β_{ij}'s are weighting factors and the ν_j's and μ_{ij}'s are scaling exponents. A physical interpretation of the model is to consider the α's and β's as sensitivities of the human subject to the different directions of acceleration and the scaling exponents as representative of the nonlinearity of the human sensor. For the data obtained to date this equation has the form:*

$$C = 1.8 + 11.5\bar{a}_{vert.} + 5.0\bar{a}_{trans.} + 1.0\bar{a}_{long.} + .25\bar{a}_{pitch} + .4\bar{a}_{roll} + 1.9\bar{a}_{yaw}$$

*This model is based on a preliminary data evaluation and in the more general case can be expected to be nonlinear and contain cross correlation terms. The amount of data evaluated to date restricted the number of determined coefficients. Thus the model presented is one which contains only a linear form of the comfort equation.

where the linear accelerations have the units of "g's" and the angular accelerations, rad/sec^2. This model was obtained using a composite of a least squares fit of the data and isocorrelation curves of the variables. A measure of the goodness of fit is indicated by the number of points whose predicted comfort rating differs from the actual by more than one, which for this model is approximately 10 percent.

In order to interpret this model it is necessary to note the following. First, since all the field data were taken during normal flight conditions, there was no control over the accelerations. Thus the process of going to the limit of a single degree of freedom is not appropriate except perhaps for the most dominant term. Second, the range of values for each of the accelerations varied considerably and is shown in Table II.

TABLE II

Acceleration	Range	Median
Vertical	$0 \rightarrow .10$ "g's"	.06 "g's"
Transverse	$0 \rightarrow .14$ "g's"	.013 "g's"
Longitudinal	$0 \rightarrow .14$ "g's"	.012 "g's"
Pitch	$0 \rightarrow 1.6$ rad/sec^2	.07 rad/sec^2
Roll	$0 \rightarrow 1.6$ rad/sec^2	.20 rad/sec^2
Yaw	$0 \rightarrow 1.0$ rad/sec^2	.04 rad/sec^2

With these in mind, it can be seen that the vertical acceleration is the predominant factor with transverse and yaw accelerations also relatively important. It can be expected that the inclusion of cross correlations will allow for a more precise evaluation of the role each variable plays. It is recommended that a value of 3.5 for C be the acceptable limit for most commercial flight applications.

The second model - patterned after Rustenberg (see reference 6), has the form

$$C = C_o + \sum_{i=1}^{6} \sum_{j=1}^{4} \gamma_{ij} \int_{\delta_{j-1}}^{\delta_j} f^{\tau_j} \phi_i(f)df$$

where

γ_{ij}	are weighting factors
f	the frequency
$\phi_i(f)$	the power spectrum in each of the six acceleration variables
$\delta_{j-1} \rightarrow \delta_j$	the frequency range
τ_j	the dependence on frequency in the frequency range

The δ's and τ's are assumed as in Rustenberg's development to be given by a "human response function". Here we assume the following form patterned after the response curves given in reference 7.

$0 \le f \le 2.0$	cps	$\tau = 0$
$2 < f \le 5.0$	cps	$\tau = .6$
$5 < f \le 20$	cps	$\tau = 0$
$20 < f$		$\tau = -1$

In the present model the "human response function" is considered constant for each direction; this will be relaxed for future models and the relationship established from the data.

The "best fit" of the data for this model is given by*

$$C = 1.8 + 10.6\int f^{\tau}\,\phi_V(f)df + 2.0\int f^{\tau}\,\phi_T(f)df + .1\int f^{\tau}\,\phi_L(f)df$$
$$+ .7\int f^{\tau}\,\phi_P(f)df + .3\int f^{\tau}\,\phi_R(f)df + .15\int f^{\tau}\,\phi_Y(f)df$$

where the subscripts V,T,L,P,R,Y represent the vertical, transverse, longitudinal, pitch, roll, and yaw directions, respectively. Here it is again seen that the vertical acceleration is the dominant one. The number of points exceeding the actual comfort response by more than one is 11 percent.

The third model postulated takes into account both of the above approaches. It relates the comfort to the RMS values of acceleration in discrete octave bands.

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*As before the amount of data dictated the use of only a limited number of terms.

$$C = C_o + \sum_{i=1}^{6} \sum_{\Delta f=1}^{N} K_{i,\Delta f} \bar{a}_{i,\Delta f}^{\epsilon_{i,\Delta f}} + \sum_{i=1}^{6} \sum_{j=i+1}^{6} \sum_{\Delta f=1}^{N} \Lambda_{i,j,\Delta f} \bar{b}_{i,j,\Delta f}^{\eta_{i,j,\Delta f}}$$

where as before the K's and Λ's are weighting factors, ε's and η's non-linearities, $\bar{a}$ the RMS value for each degree of freedom i, and $\bar{b}$ the correlation coefficient for each pair of directions are subdivided into octave bands, Δf. Insufficient data have been obtained to date to evaluate this model.

FUTURE ACTIVITIES

At the present time continuing efforts are underway in both traveler attitude analysis and data accumulation for model development. In the former area, the procedures and techniques used in the study of the group of academic professionals reported in reference 3 are being extended to a larger and more diverse group. This includes government and industrial personnel having training and job functions ranging from science and engineering through sales and management. These individuals can normally be expected to travel frequently in the conduct of their business. Also to be sampled at the same locations are employees whose job assignments do not usually involve travel. The survey is taking place in the Richmond, Hampton Roads, and Northern Virginia areas. As previously, all participants complete a basic questionnaire and then a restricted number of follow-up interviews are conducted with volunteer candidates.

The results of the attitude analysis cited earlier clearly indicate the importance of broadening the data base for model development. Also the ranges of motion encountered in our first program were limited by the selection of aircraft and flight profiles available. Finally, it was not possible to obtain any responses from the paying passengers and Civil Aeronautics Board regulations caused undesirable restrictions on the number of test subjects available.

Taking all of these factors into consideration a decision was made to work with the commuter airlines in the next phase. The Allegheny commuter arrangement is ideally suited to our needs. With their cooperation we have initiated a test program with Ransome Airlines, which operates an Allegheny Commuter Service between Philadelphia-Trenton and Philadelphia-Washington, and with Atlantic City Airlines operating a similar service connecting New York and Philadelphia with Atlantic City and Cape May. The aircraft used include the Volpar Beech 18, Nord 262, and de Havilland Twin Otter. The routes are such that there is definite competition with other air and/or ground modes (rail, bus, car).

One member of the University of Virginia research team flies on selected flights as a regular paying passenger (to assure a place on high density flights). Whenever space is available, additional research team members fly without charge. These special experimental subjects produce quantitative response data keyed to recorded measurement of the aircraft motion, temperature, and noise. At the same time the team members distribute questionnaires to all passengers prior to take-off and collect them upon deplaning. The opinion of the pilot as to ride quality is also obtained. This program represents an important step in the development of passenger models in that it is the first time that it has been possible to correlate quantitative measurements of flight parameters directly with the response of regular commercial passengers.

CONCLUSIONS

The initial steps have been taken in the development of a mathematical model to predict and evaluate human acceptance of transportation systems. The inputs and results to date are appropriate to a short-haul service, either STOL or otherwise and serving either a high density or a low density market.

The desires and preferences of a typical traveling group of business and professional persons have been surveyed. Safety, reliability, time savings, comfort, convenience and cost were determined to be the most important attributes of a transportation system.

In addition, a program of data acquisition from experimental test subjects on regularly scheduled short-haul airline flights was undertaken. Since the questionnaire survey also indicated that motion, temperature, and noise were important components of comfort, these variables were measured and correlated with the subject quantitative rating of the ride comfort.

Three mathematical models were presented with the data used to determine preliminary forms of a comfort equation for two of them. They indicate that vertical motion is the predominant factor affecting satisfaction with the ride, with yaw and transverse motion also important. A guideline for acceptability has also been established. As more of the data is reduced, it will be possible to introduce more sophistication into the models and also look for cross correlations between the variables.

Additional flight experiments are planned which will introduce factors related to convenience, time savings, and cost into the model. Also for the first time measures of satisfaction will be obtained from the regular passenger in flight.

It is interesting to note that a general analysis of the results of the ground-based survey of typical passengers shows that the variables related to air transportation group very nicely into four major "dimensions". These are safety, cost-benefit, luxury, and in-flight activity dimensions.

The subject group for these surveys is being expanded widely, and if the validity of this concept holds, it should serve as a highly useful tool for the development of models, especially the design of experiments to provide data for the models.

REFERENCES

1. Jacobson, Ira D.: Characteristics of the Air Traveler - A Selective Review. University of Virginia, Center for the Application of Science and Engineering to Public Affairs, STOL Program Memorandum Report 403204, June 1972.

2. Solomon, K.M., Solomon, J., and Silien, J.S.: Passenger Psychological Dynamics. Report No. 3, New York, The Journal of Urban Transportation Corporation, June 1968.

3. Jacobson, Ira D., and Martinez, John.: The Comfort/Satisfaction of Air Travelers--Basis for a Descriptive Model. University of Virginia, Center for the Application of Science and Engineering to Public Affairs, STOL Program Memorandum Report 403203, March 1972.

4. Ward, Robert C.: Dynamic Data Analysis Techniques Used in the Langley Time Series Analysis Computer Program. NASA TM X-2160, February 1971.

5. Van Deusen, B.D.: A Study of the Vehicle Ride Dynamics Aspect of Ground Mobility, Volume II: Human Response to Vehicle Vibration. Chrysler Corporation under Contract DA 22-079-eng-403, March 1965.

6. Rustenberg, J.W.: A Technique for the Evaluation of Aircraft Ride Quality. Aero Systems Division, Wright Patterson Air Force Base, Ohio, ASDTR 6818, June 1968.

7. Jacobson, Ira D.: Criteria for Ride Quality - Motion. University of Virginia, Center for the Application of Science and Engineering to Public Affairs, STOL Program Memorandum Report 40302, February 1972.

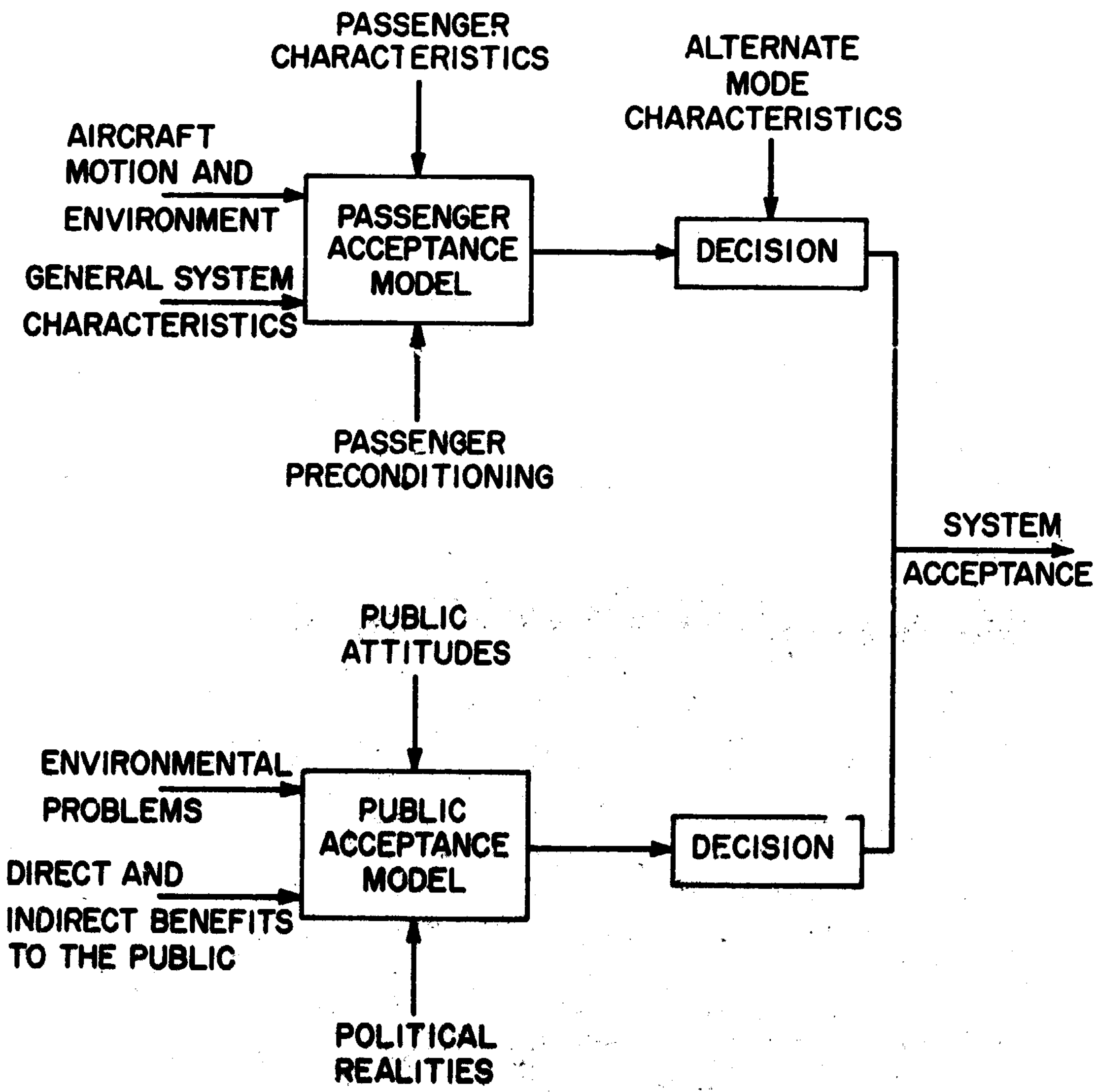


Figure 1.- Problem solution plan.

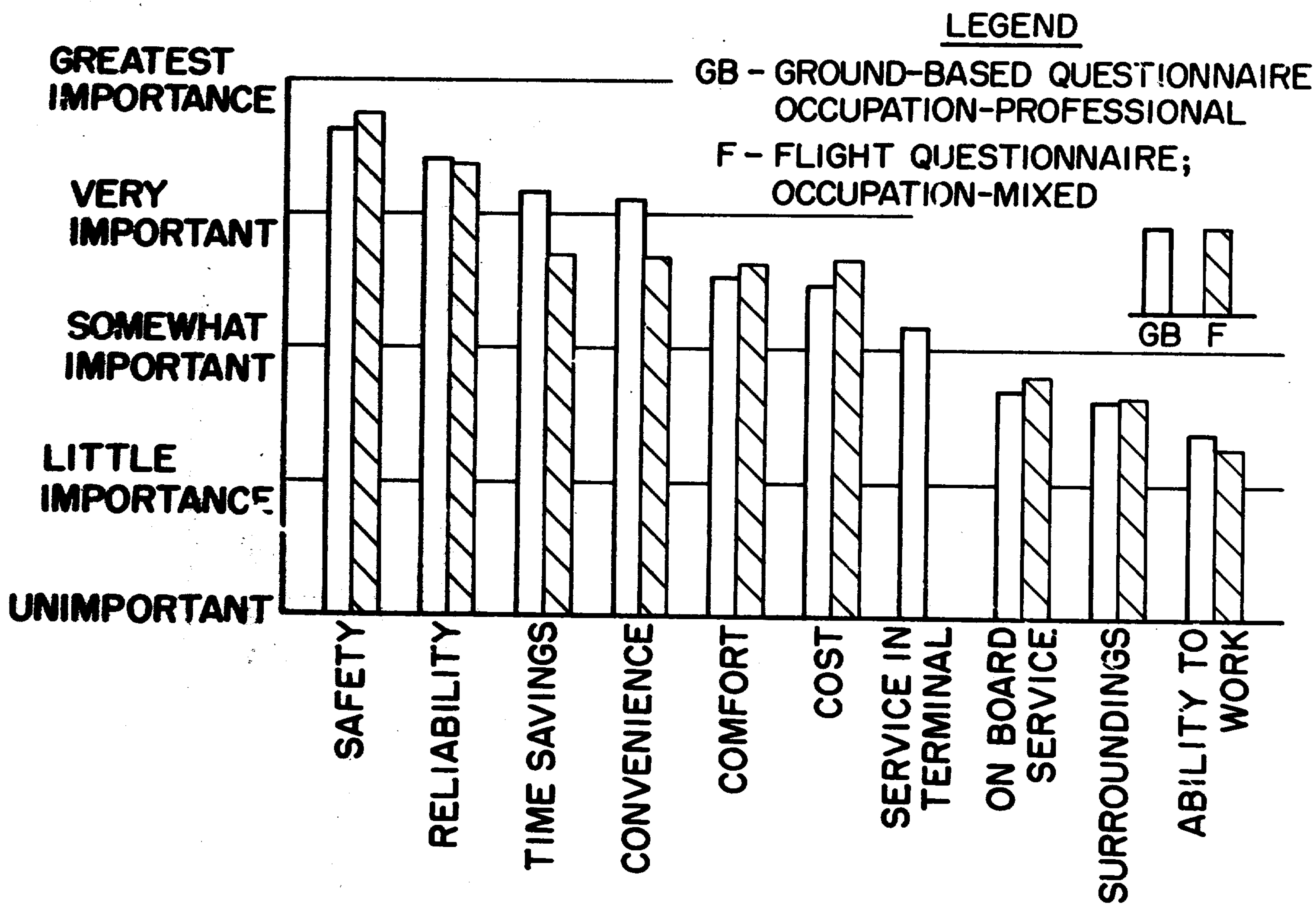


Figure 2.- Factors important in determining passenger air travel satisfaction.

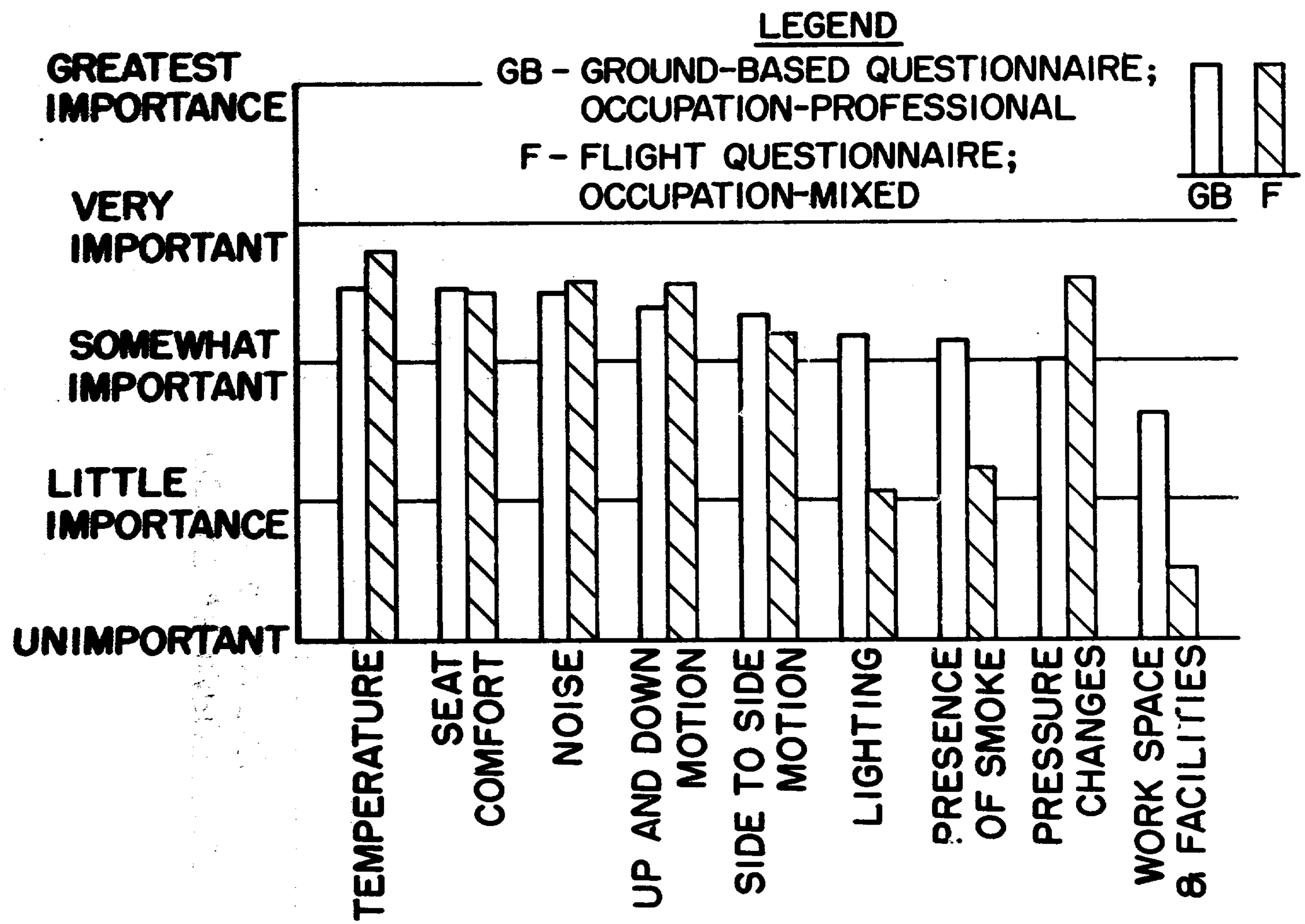


Figure 3.- Factors important in determining passenger comfort on aircraft.

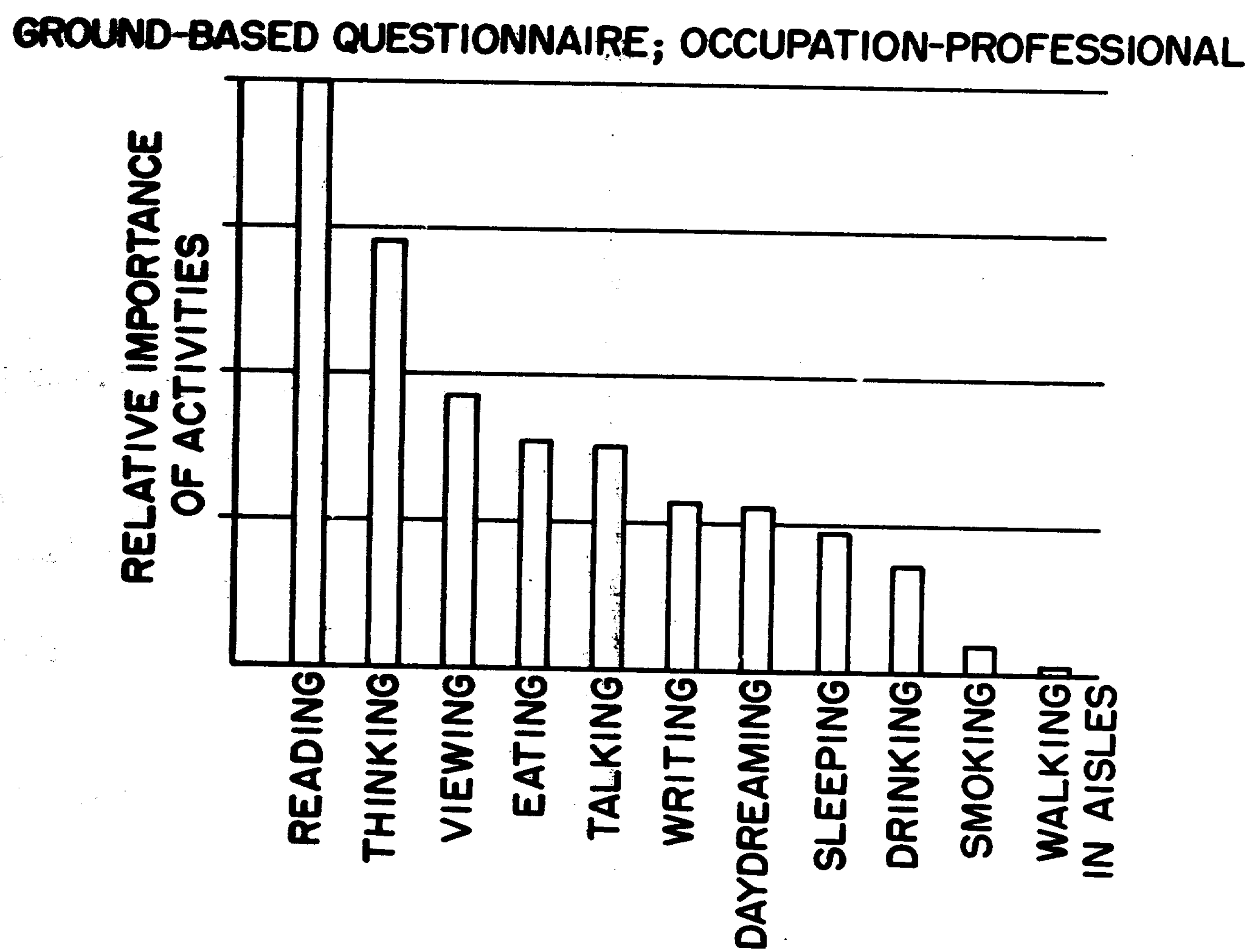


Figure 4.- Relative importance of in-flight activities on short-haul air trips.

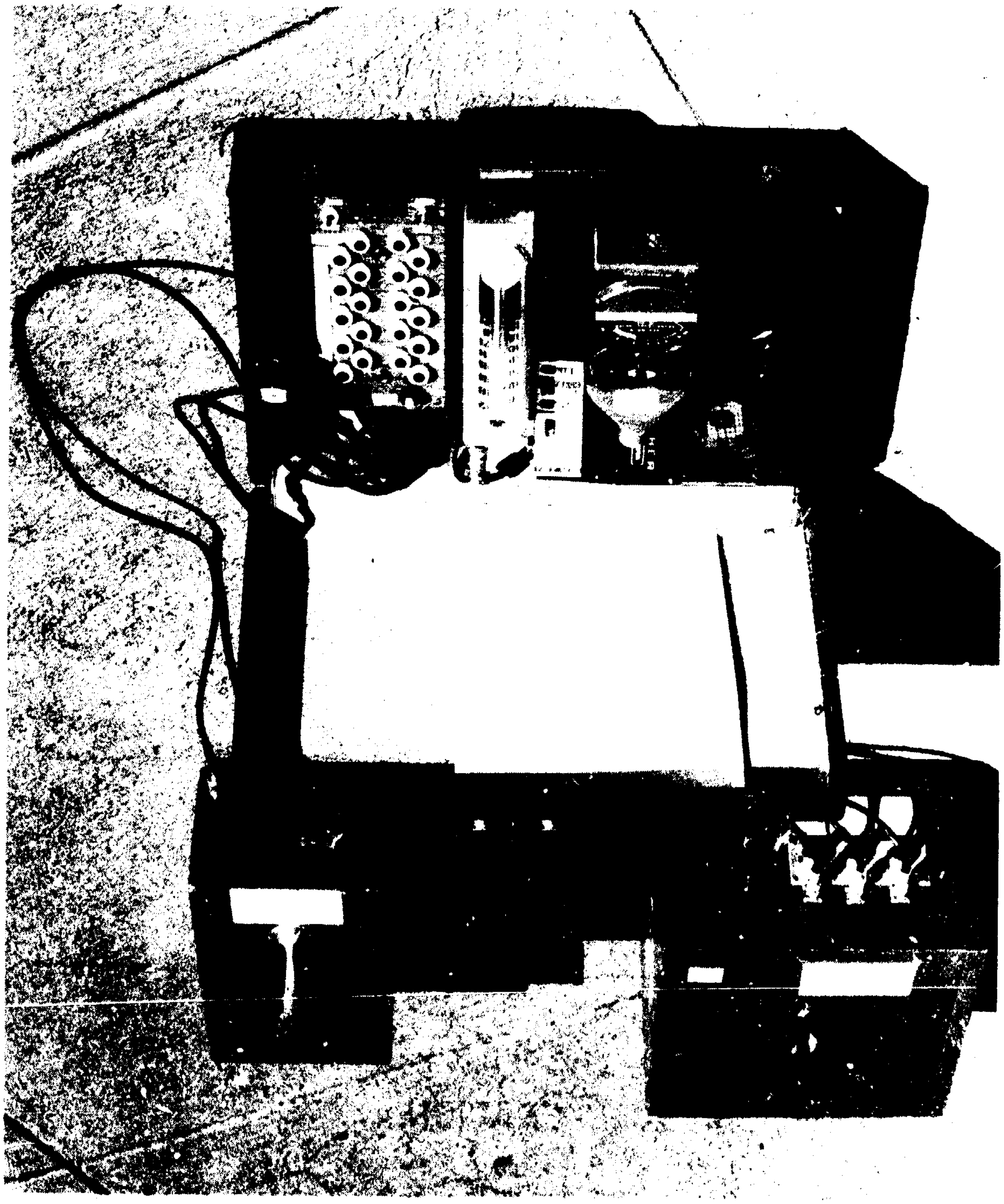


Figure 5.- Data measurement and recording equipment.

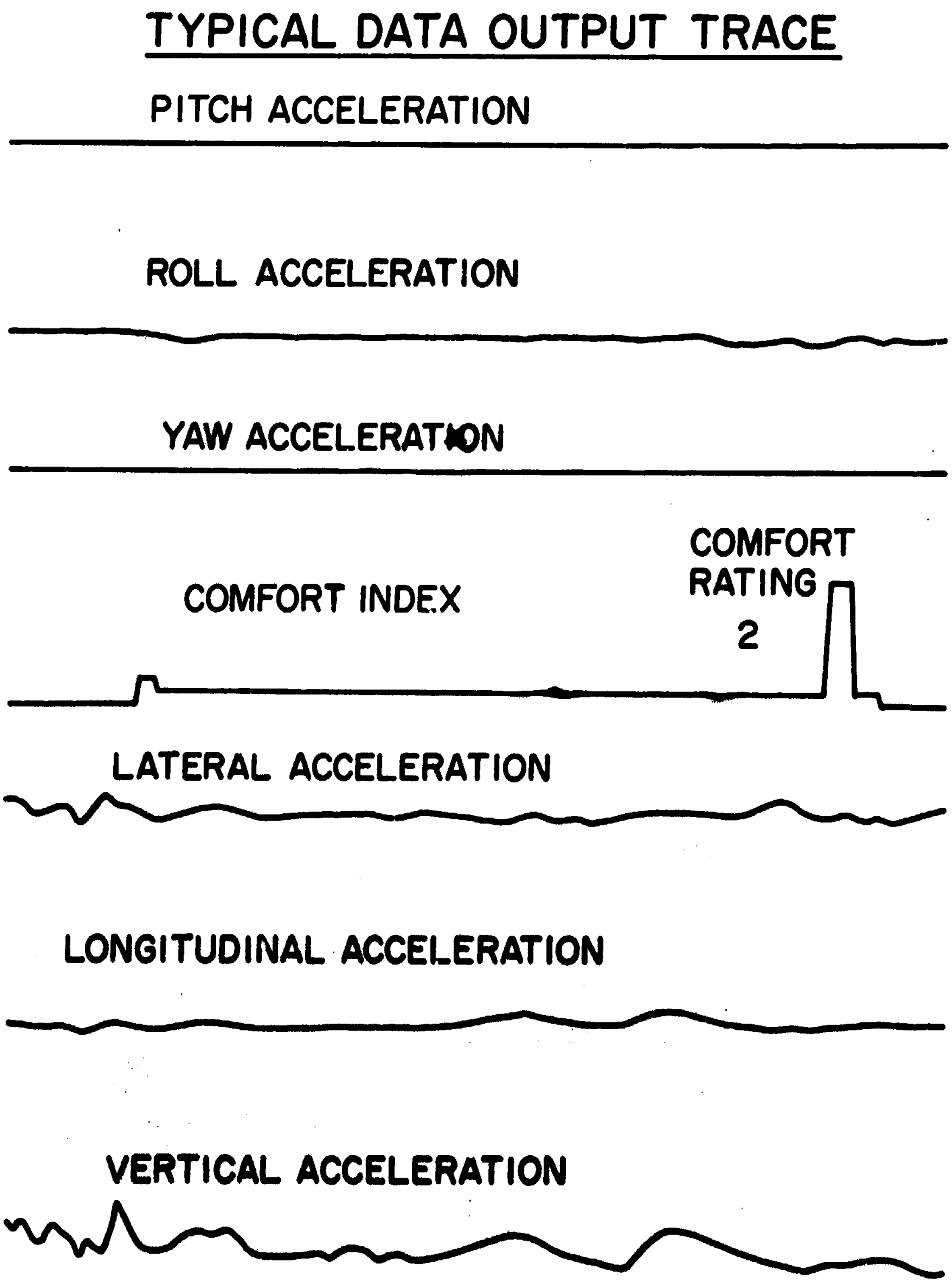


Figure 6.- Accelerometer/subjective response output trace.

RIDE-QUALITY RESEARCH ACTIVITIES AT

NASA LANGLEY RESEARCH CENTER

By Andrew B. Connor, Hugh P. Bergeron, and W. Elliott Schoonover, Jr.
NASA Langley Research Center

12

INTRODUCTION

N73-10024

This paper will briefly outline ride-quality research presently underway at the NASA Langley Research Center. The objective of this research is to establish a definition of vehicle design criteria based on passenger acceptability. More specifically, criteria are sought which describe those vehicle performance characteristics which will insure passenger comfort. Emphasis on passenger comfort is somewhat new in that the bulk of ride-quality research in the past centered on improvement of crew performance.

Figure 1 illustrates how Langley personnel in the disciplines of vehicle environmental dynamics, structural dynamics (rigid body and elastic), and electromechanical measurement techniques combine their talents in defining the passenger environments of various types of vehicles. At the same time (and in the case of field testing, in the same tests) human factors experts quantify passenger subjective response to these environments. Findings in these two areas are then integrated to establish the characteristics of those environments found to be most acceptable to passengers, that is, to define ride-quality design criteria.

Ride-quality research activity at Langley complements similar efforts at the NASA Flight Research Center. Through comparison of ride-quality flight data obtained at the two centers using aircraft with different passenger environments and further correlation with data obtained aboard Langley ground-based simulators, a broad, yet in-depth, investigation of the various factors affecting passenger comfort is possible. Langley's ride-quality research is also coordinated with and frequently conducted in conjunction with research sponsored by the Department of Transportation through the Federal Aviation Administration, the Federal Railway Administration, and the Office of Research, Development and Demonstration. In addition, contact is maintained with the USAF Aerospace Medical Laboratory at Wright-Patterson Air Force Base and the Naval Aerospace Medical Institute in Pensacola, Florida. Langley sponsors significant research related to ride quality through contracts or grants with universities as well as commercial research laboratories.

RIDE-QUALITY CRITERIA

Below the limit of perception motion presents no problem; levels above the limit of incipient nausea, pain, or possible injury are excessive and are not being investigated at Langley. The vast region between these two boundaries is an area in which essentially no generally agreed-upon definitions of passenger/crew acceptability exist.

The engineering approach to ride quality is to achieve passenger-acceptable levels of motion, vibration, and noise at the minimum cost in terms of vehicle weight, complexity, and investment. In other words, one should not buy more treatment than he needs. There is no need to invest in heavy, complicated, costly vibration-suppression devices to insure a perfectly smooth ride if the passenger finds that an occasional gentle motion is tolerable. For all vehicles, equipment weight cuts into payload revenue, complexity increases maintenance expense, and these with increased investment cost add up to higher fares for the passenger. The question, then, is where to draw appropriate acceptability ride-quality boundaries.

FIELD TESTING

Ride-quality research began at Langley about 5 years ago with a request from the Department of Transportation for passenger compartment vibration surveys on the Metroliner train operated between New York City and Washington, D.C. Similar passenger environment surveys have since been made aboard a variety of vehicles, so that Langley has now compiled within its data bank motion surveys of more than 30 different vehicles. As shown in figure 2, these vehicles include aircraft, high- and low-speed surface craft, and several research and development craft which have yet to be proved economical passenger-carrying vehicles. These data not only document conditions as they exist within each vehicle but also can provide input signals to motion simulators within the laboratory where human response to those conditions can be investigated through carefully controlled and repeatable tests. Also shown in the center of figure 2 is one of the portable instrumentation systems developed at Langley for measuring and recording passenger environments. References 1 to 8 describe much of the Langley in-house research pertaining to ride quality conducted during the last several years.

Under an NASA grant, the University of Virginia has flown a number of test subjects in pairs aboard regularly scheduled commercial airline flights. Both the six-degree-of-freedom motions of the aircraft and the subjective reactions are recorded on tape. The University is now analyzing these data to determine what correlation, if any, exists between passenger comfort and various types and degrees of vehicle motion. In future flight testing, such passenger environmental variables as cabin pressure, temperature, and noise level will also be recorded.

Old Dominion University, under NASA contract, is investigating the dependency of subjective reaction to passenger environments on subject characteristics, such as age, sex, occupation, etc. As many as 30 test subjects recruited from the community according to test requirements are seated aboard a commercial bus and driven over a prescribed course at prescribed speeds. The six-degree-of-freedom motion of the bus and periodic reactions from all the test subjects are recorded simultaneously, and statistical analyses are employed to determine correlations. The low cost of a commercial bus as a test vehicle permits the testing of a very large subject population.

Under contract to NASA, Princeton University is studying human response to vehicle motion through flight tests aboard a variable-stability light airplane capable of carefully controlled motions about five degrees of freedom. (Side-force generators were not available.) In these flight tests two test pilots, alternately serving as passenger subject, rated the comfort of the ride as the airplane was flown through preprogramed and repeatable maneuvers. These tests are complete, and a formal report on the results is plann-.

Tentative plans at Langley call for a sequence of flight tests with eight passenger test subjects simultaneously aboard a larger variable-stability airplane to obtain data which can be correlated with those obtained from tests with ground-based motion simulators. Subjects who are tested in simulators will also fly aboard the variable-stability airplane and will experience the same motions in both instances. The two sets of subjective reactions will then be compared for a statistically significant number of test subjects. The objective is to "validate" the results and procedures of ground testing. The flight tests will also amplify ground-based test results in that sustained motions which are impossible to achieve on the ground can be produced in the air.

Another flight test program of significance to Langley deals with ride-quality factors specifically associated with helicopters. These factors will be identified and studied as part of a program to develop technology for designing helicopter airliners acceptable to passengers as well as to airline operators. As illustrated by the left side of figure 3, which shows the program in flow-diagram form, a helicopter will be modified by addition of an air-conditioned passenger compartment and of acoustic, vibration, and motion reduction features sufficient to provide a passenger-acceptable ride in smooth air at moderate speeds and in straight and level flight or in gentle maneuvers. Flight experiments will then be made to study subjective reaction to the environmental factors (e.g., noise, vibration, motion, steady acceleration, and/or visual cues) which could be expected to accompany real-world operations where high cruising speeds and high-performance terminal-area maneuvers are experienced. Comparison studies with ground-based simulators will be carried out where considered appropriate.

The U.S. Naval Aerospace Medical Institute (NAMI), under NASA contract, has extensively researched the underlying causes of motion sickness (refs. 9, 10, and 11). NAMI also contributes to Langley ride-quality research by "calibrating" each of our test subjects with regard to his individual susceptibility to motion sickness. This background information is very important in the interpretation of data "scatter" common to results of tests involving human response to motion stimuli.

By using a total-systems approach, a new portable environmental measuring system optimized with regard to size, weight, reliability, and simplicity of operation is being designed under NASA contract. The system will be small enough to fit under a not-so-big commuter airline seat, light and compact enough to be carried by one man, and essentially foolproof in operation to permit use by essentially untrained subjects chosen from the general public.

LABORATORY TESTING

The number of passenger ride-quality environment variables mentioned earlier can best be analyzed and interrelated by appropriate ground-based testing where greater control of test conditions is possible. The cost per hour of simulator testing is significantly less than that of flight testing. Ride-quality testing requires a simulation which covers the complete range of test variables and which, at the same time, maintains the realism of the actual environment. It is practically impossible to construct any one simulator to perform this task. However, several simulators do exist at Langley which can be used to examine specific regions of the motion environment under carefully controlled conditions.

As shown in figure 4, the Langley simulators have three areas of motion capability. Low-frequency large-amplitude motion can be produced by the real-time dynamics simulator (RDS), medium-frequency medium-amplitude motion can be produced by the visual-motion simulator (VMS), and high-frequency low-amplitude motion can be produced by the passenger ride-quality apparatus (PRQA). Figures 5, 6, and 7 present the motion envelope for each of the three simulators in terms of acceleration plotted against frequency for maximum simulator loading. The limiting velocities and displacements are also shown.

Tests will be performed in the three Langley simulators to determine human subjective reactions to motion stimuli spanning a range of frequency and acceleration levels. Particular attention will be devoted to those types of motion shown through field testing to be significant to ride comfort. Testing will initially center upon the effects of single-degree-of-freedom motion, then expand into multiple-degree-of-freedom motion, and finally simulate actual vehicle motions as measured and recorded in the field. The wide range of motions available in the three simulators will be used to determine in detail and under controlled conditions the types of motion which are most significant to passenger comfort and, for each motion or combination of motions, the boundary between comfort and discomfort. With this approach, overall passenger evaluation of ride comfort will be made predictable as a function of quantified human reactions to the individual motion components of the passenger environment. The statistical passenger ride comfort model thus derived can then be applied to any proposed transportation vehicle to determine the degree of ride smoothing necessary to satisfy, with regard to comfort, an adequate percentage of its passengers.

DATA REDUCTION AND ANALYSIS

The Langley Research Center has extensive facilities for analog-to-digital data transcription as well as digital computer capability for statistical analyses. A time-series-analysis program maintained on data cell converts input digital data to histograms, power-spectral densities, auto- and cross-correlations, etc., depending on user requirements. Such output data can be tabulated and/or machine plotted. A new time-series-analysis program tailored more directly to ride-quality research requirements and incorporating newer more efficient analysis techniques is being written in-house for this purpose. Through a study contract, Langley is examining the possible application of acoustic analytical techniques to the reduction of ride-quality data and to the formulation of ride-quality criteria. This approach is being investigated because of the similarity between the phenomena involved; that is, both areas of research concern human response to time-dependent vibratory physical stimuli. It is possible that useful ride comfort indices analogous to the effective perceived noise level (EPNdB) of acoustics can be derived.

CONCLUDING REMARKS

Vehicle ride quality, although a relatively young research discipline, is commanding considerable and increasing attention at the Langley Research Center. With overall coordination by the V/STOL Aircraft Program Office, specialists in the fields of vehicle environmental dynamics, structural dynamics, and human factors are together investigating what constitutes a comfortable ride in a variety of vehicles. This research is conducted both in-house and through contracts and grants and both in the field (often in a commercial environment) and in the laboratory under closely controlled conditions. The ultimate goal is ride-quality criteria in a form useful to the vehicle designer.

REFERENCES

1. Clevenson, Sherman A.; Martin, Dennis J.; and Dibble, Andrew C.: Low-Frequency Portable Vibration Measuring and Recording System. Shock Vib. Bull., Bull. 40, Pt. 7, U. S. Dep. Def., Dec. 1969, pp. 45-50.

2. Catherines, John J.: Measured Vibration Ride Environments of a STOL Aircraft and a High-Speed Train. Shock Vib. Bull., Bull. 40, Pt. 6, U. S. Dep. Def., Dec. 1969, pp. 91-97.

3. Catherines, John J.; and Clevenson, Sherman A.: Measurement and Analysis of Vibration Ride Environments. Preprint No. SW-70-21, Amer. Helicopter Soc., Nov. 1970.

4. Clevenson, Sherman A.; and Catherines, John J.: Measurement and Analysis of Vibration in Transportation Systems. Vol. 26 of AAS Science and Technology Series, F. W. Forbes and P. Dergarabedian, eds., Amer. Astronaut. Soc., c.1971, pp. 197-202.

5. Conner, D. William: Ride Quality - An Increasingly Important Factor in Transportation Systems. Paper presented at 1971 International IEEE Conference on Systems, Networks, and Computers (Oaxtepec, Mexico), Jan. 1971.

6. Clevenson, Sherman A.; and Ullman, Kenneth B.: A Technique for Evaluating Track Condition Using Railcar Vibrations. AIAA Paper No. 71-384, Apr. 1971.

7. Clevenson, Sherman A.; Snyder, William J.; and Catherines, John J.: Preliminary Study of Effects of Vibration on Aircraft Ride Quality. NASA Aircraft Safety and Operating Problems - Vol. I, NASA SP-270, 1971, pp. 335-345.

8. Catherines, John J.; Clevenson, Sherman A.; and Scholl, Harland F.: A Method for the Measurement and Analysis of Ride Vibrations of Transportation Systems. NASA TN D-6785, 1972.

9. Guedry, Fred E., Jr.: Conflicting Sensory Orientation Cues as a Factor in Motion Sickness. Fourth Symposium on the Role of the Vestibular Organs in Space Exploration, NASA SP-187, 1970, pp. 45-51.

10. Miller, Earl F., II; and Graybiel, Ashton: Motion Sickness Produced by Head Movement as a Function of Rotational Velocity. NAMI-1101, U. S. Navy, Mar. 5, 1970. (Available as NASA CR-109891.)

11. Oosterveld, Wilhelmus J.; Graybiel, Ashton; and Cramer, D. Bryant: The Influence of Vision on Susceptibility to Acute Motion Sickness Studied Under Quantifiable Stimulus-Response Conditions. NAMRL-1149, U. S. Navy, Nov. 17, 1971. (Available as NASA CR-125546.)

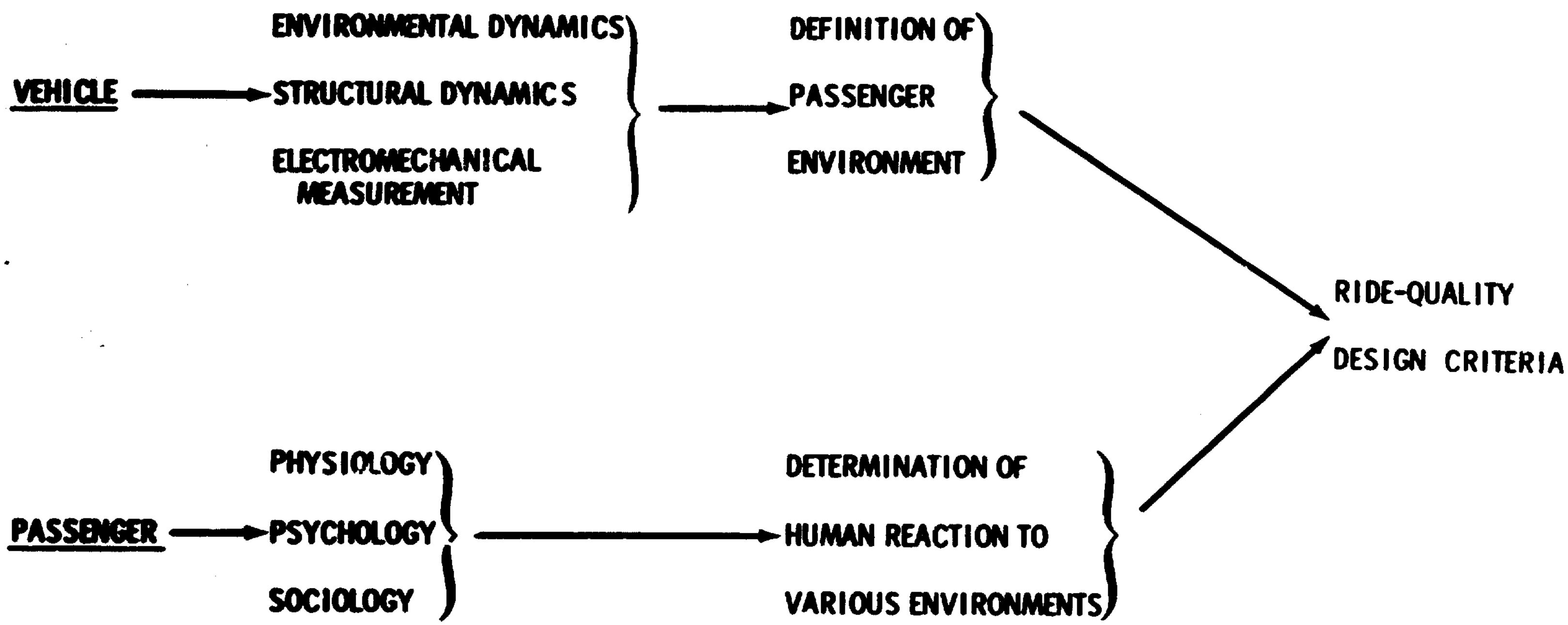


Figure 1.- Langley interdisciplinary approach to the formulation of ride-quality design criteria.

Figure 2.- Vehicles tested in field surveys.

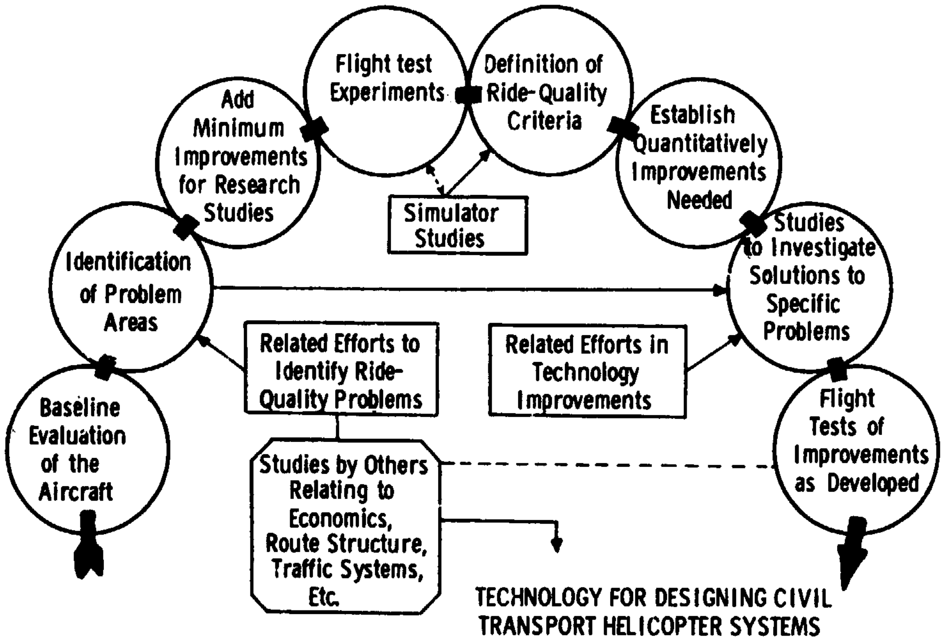
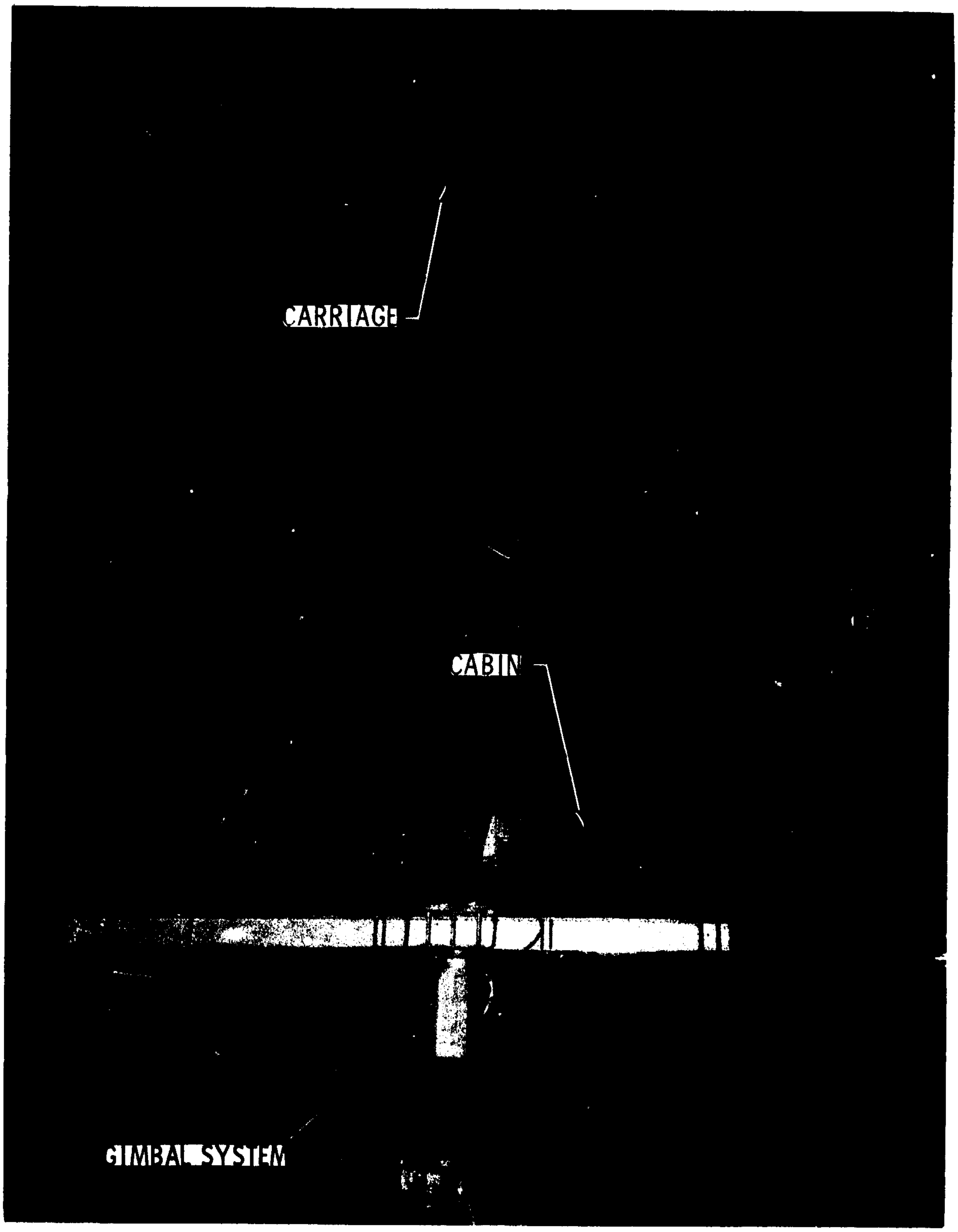


Figure 3.- Civil transport helicopters ride-control technology development plan.

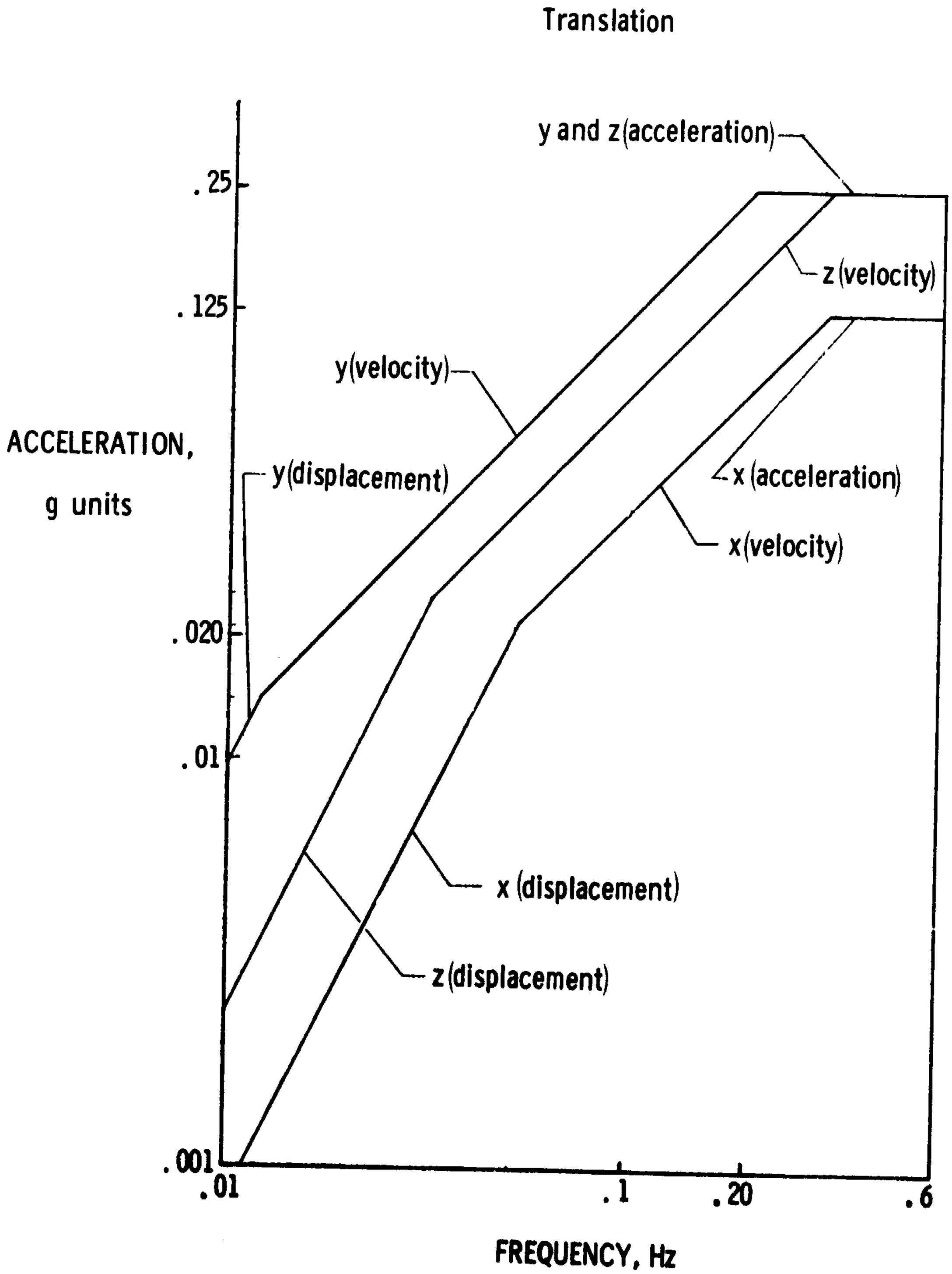
Facility	Frequency range	Number of subjects	Degrees of freedom	Translation (one axis)			Rotation (one axis)			Possible adverse passenger reaction
				Disp., cm	Vel., cm/sec	Accel., cm/sec²	Disp., rad	Vel., rad/sec	Accel., rad/sec²	
Real-time dynamics simulator	Low	2	6	±2286	±183	±0.64	2π	±1.0	±1.0	Motion sickness
Visual-motion simulator	Medium	4	6	±91	±61	±2.03	±0.38	±0.26	±0.87	
Passenger ride-quality apparatus	High	4 to 6	3	±8	±61	±1.27	±0.1	±0.77	±6.25	Vibratory pain

Figure 4.- Langley motion simulation capability.



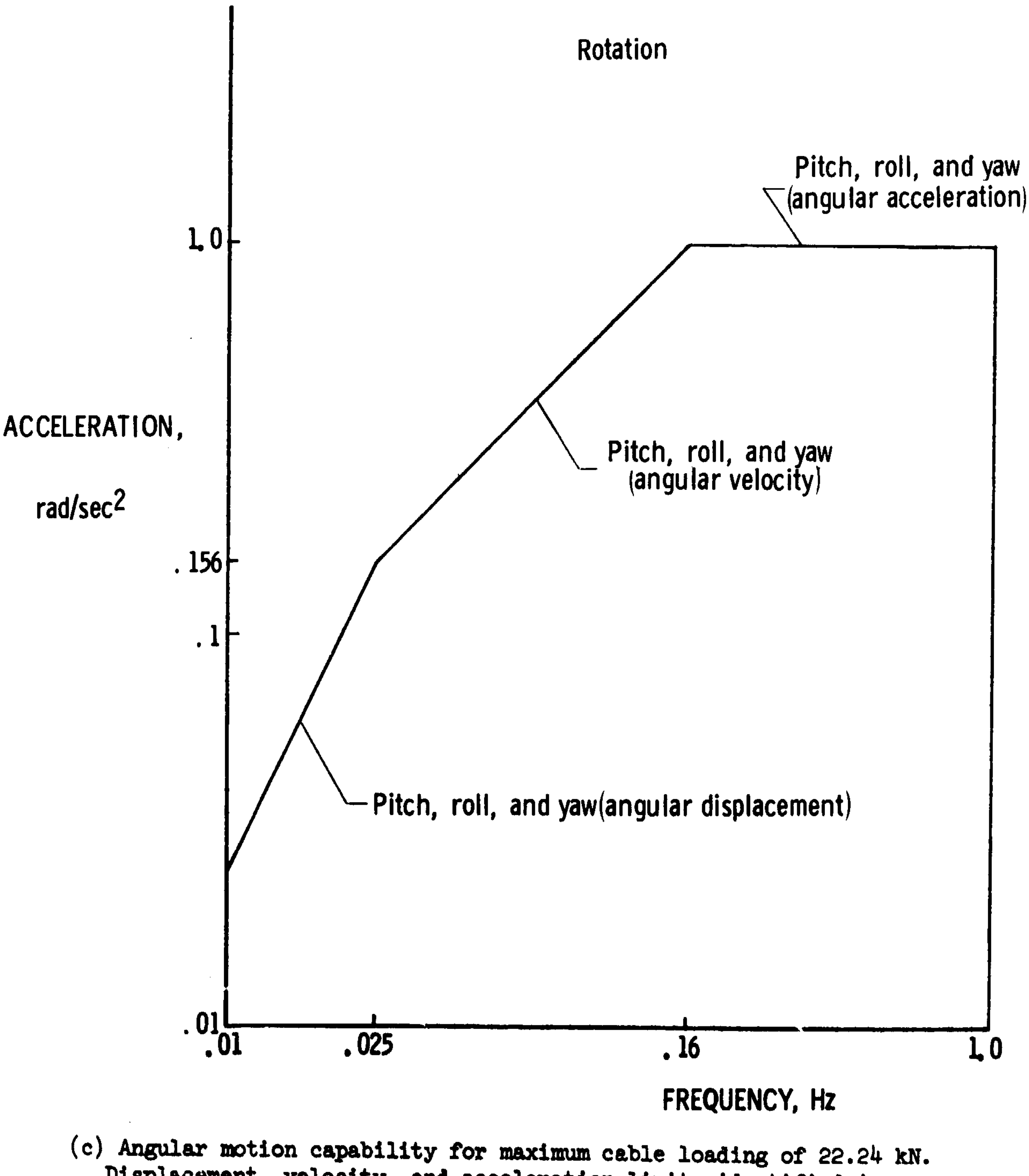
(a) Laboratory installation.

Figure 5.- Langley real-time dynamics simulator (RDS).



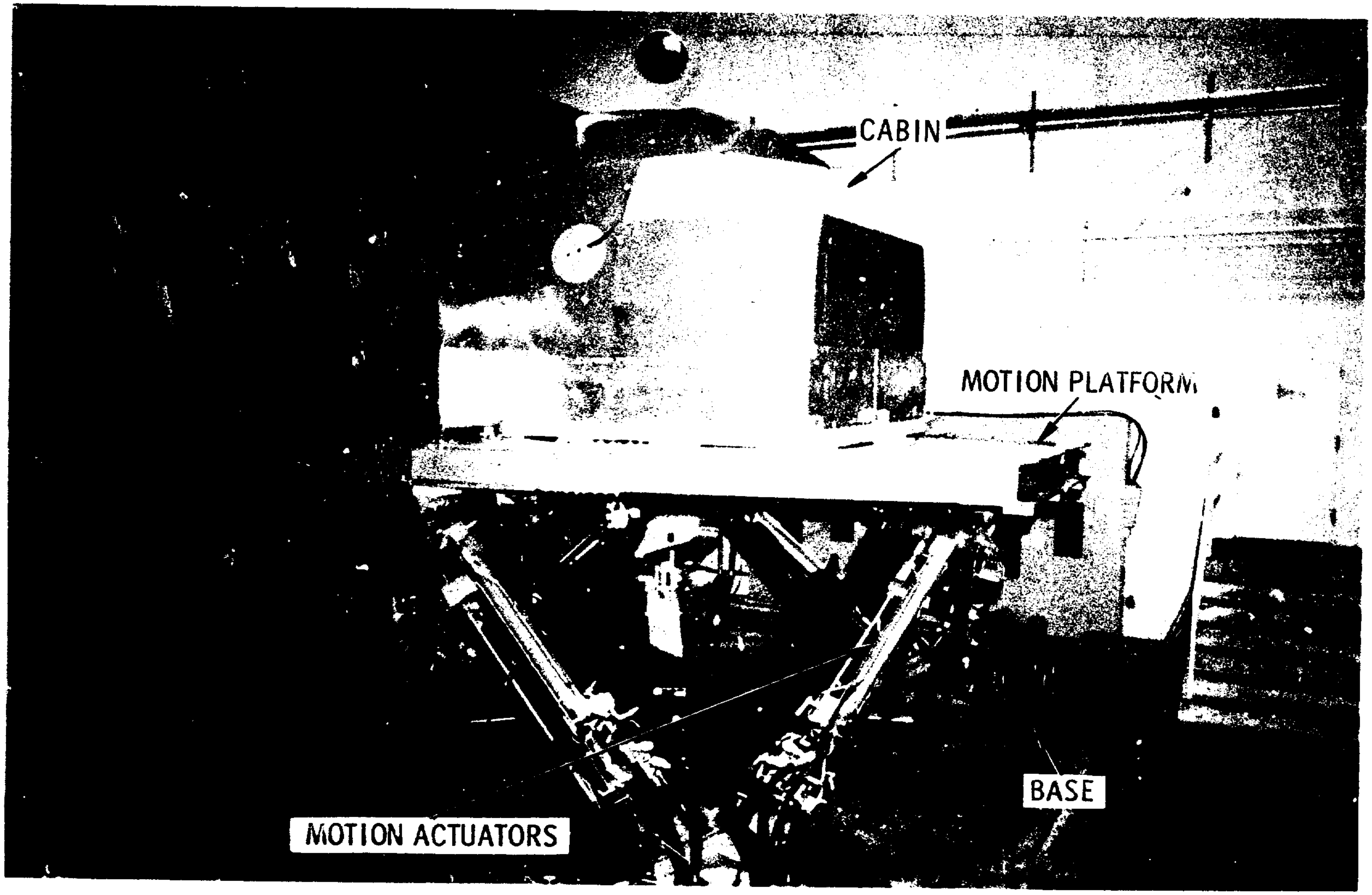
(b) Linear motion capability for maximum cable loading of 22.24 kN. Displacement, velocity, and acceleration limits identified in parentheses.

Figure 5.- Continued.



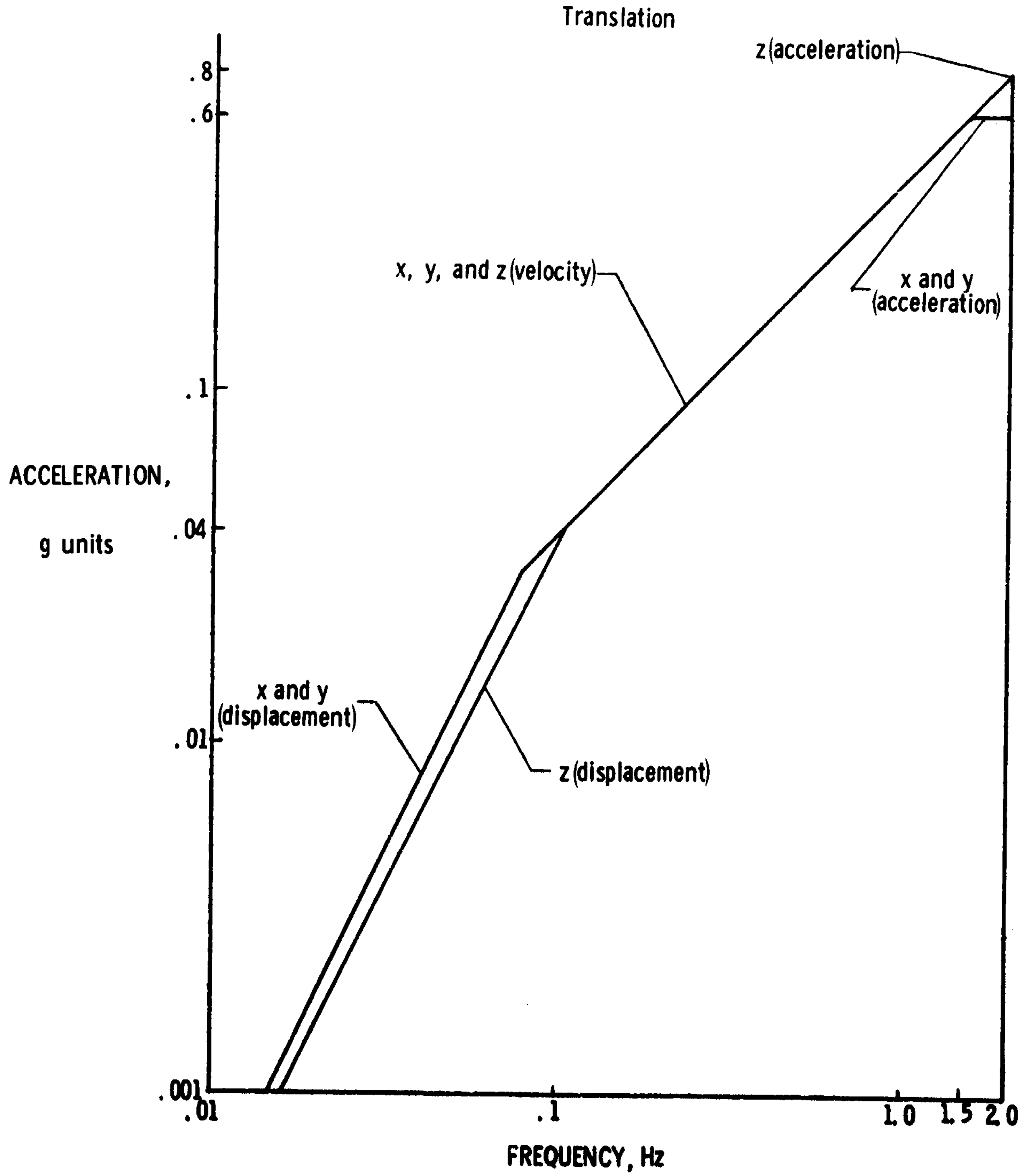
(c) Angular motion capability for maximum cable loading of 22.24 kN. Displacement, velocity, and acceleration limits identified in parentheses.

Figure 5.- Concluded.



(a) Simulator installation.

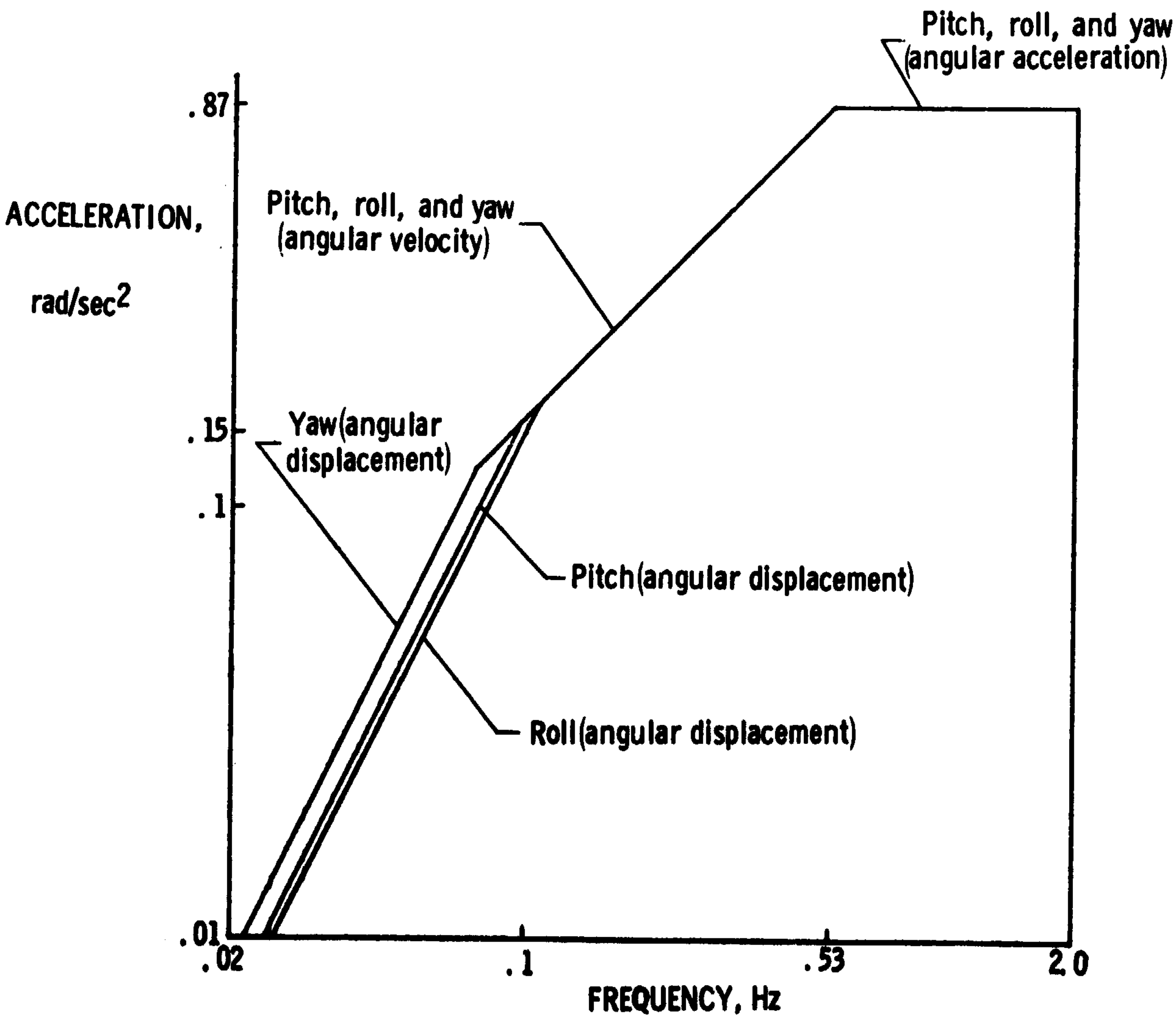
Figure 6.- Langley visual-motion simulator (VMS).



(b) Linear motion capability for maximum payload weight of 88.96 kN. Displacement, velocity, and acceleration limits identified in parentheses.

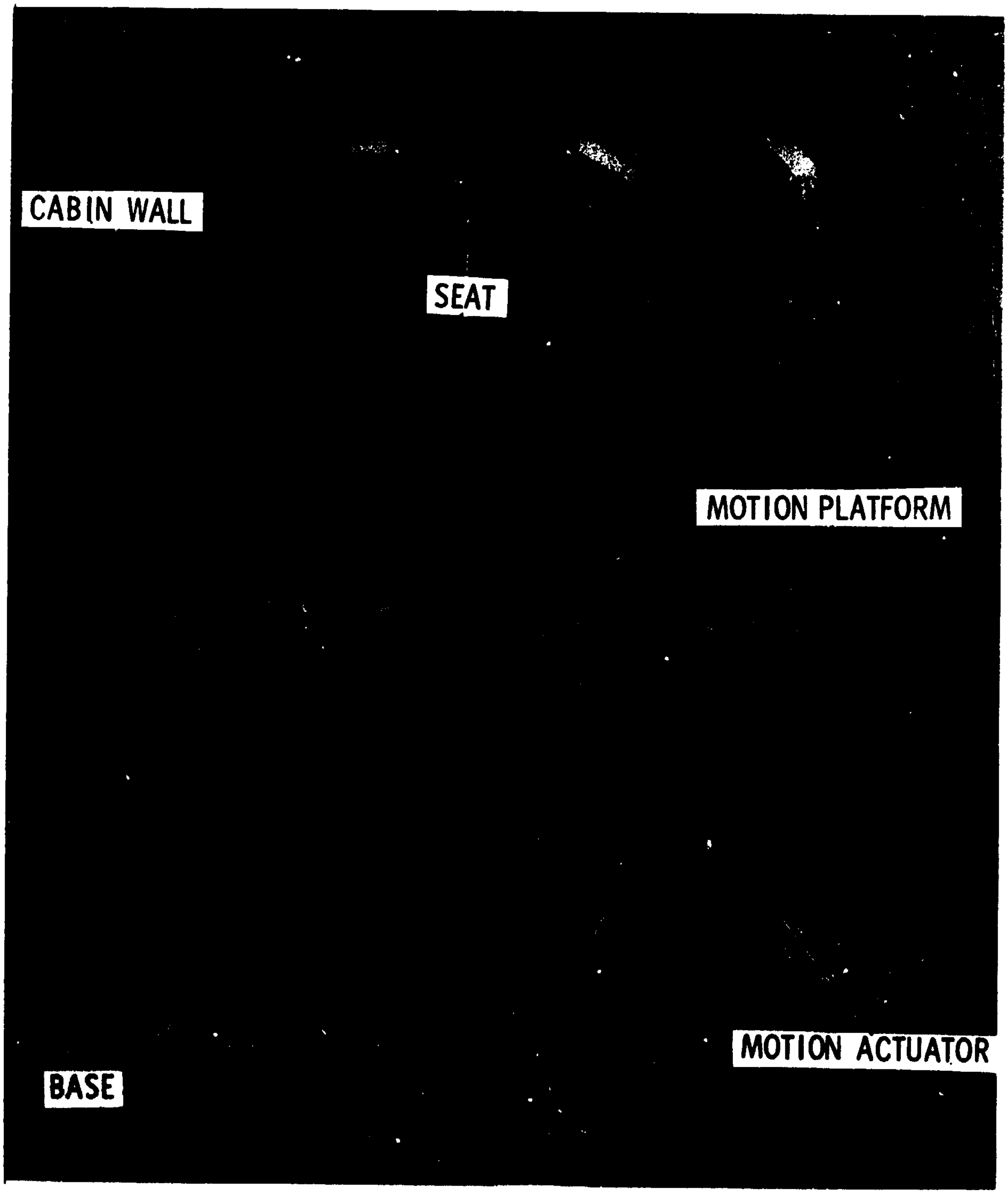
Figure 6.- Continued.

Rotation



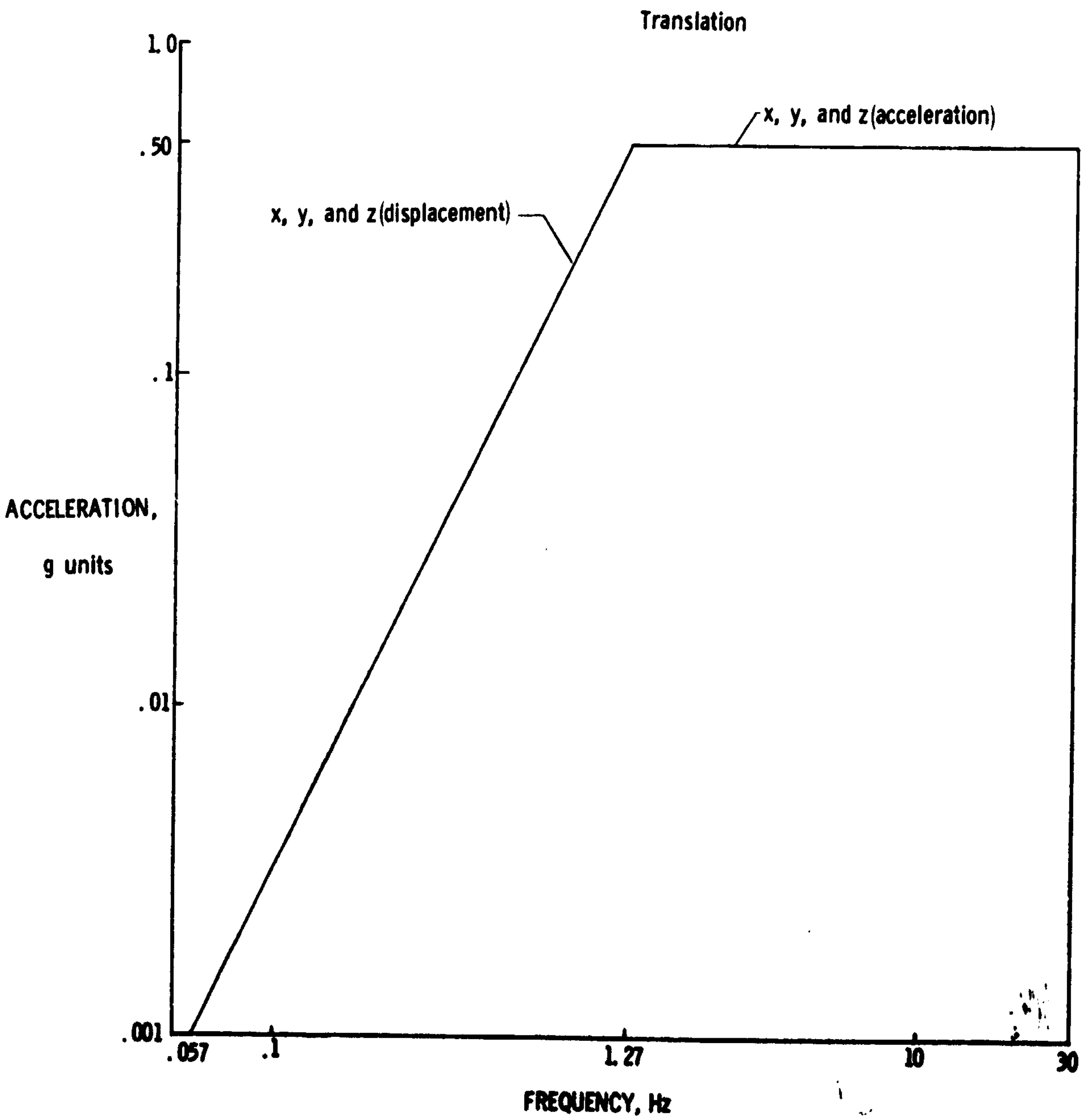
(c) Angular motion capability for maximum payload weight of 88.96 kN. Displacement, velocity, and acceleration limits identified in parentheses.

Figure 6.- Concluded.



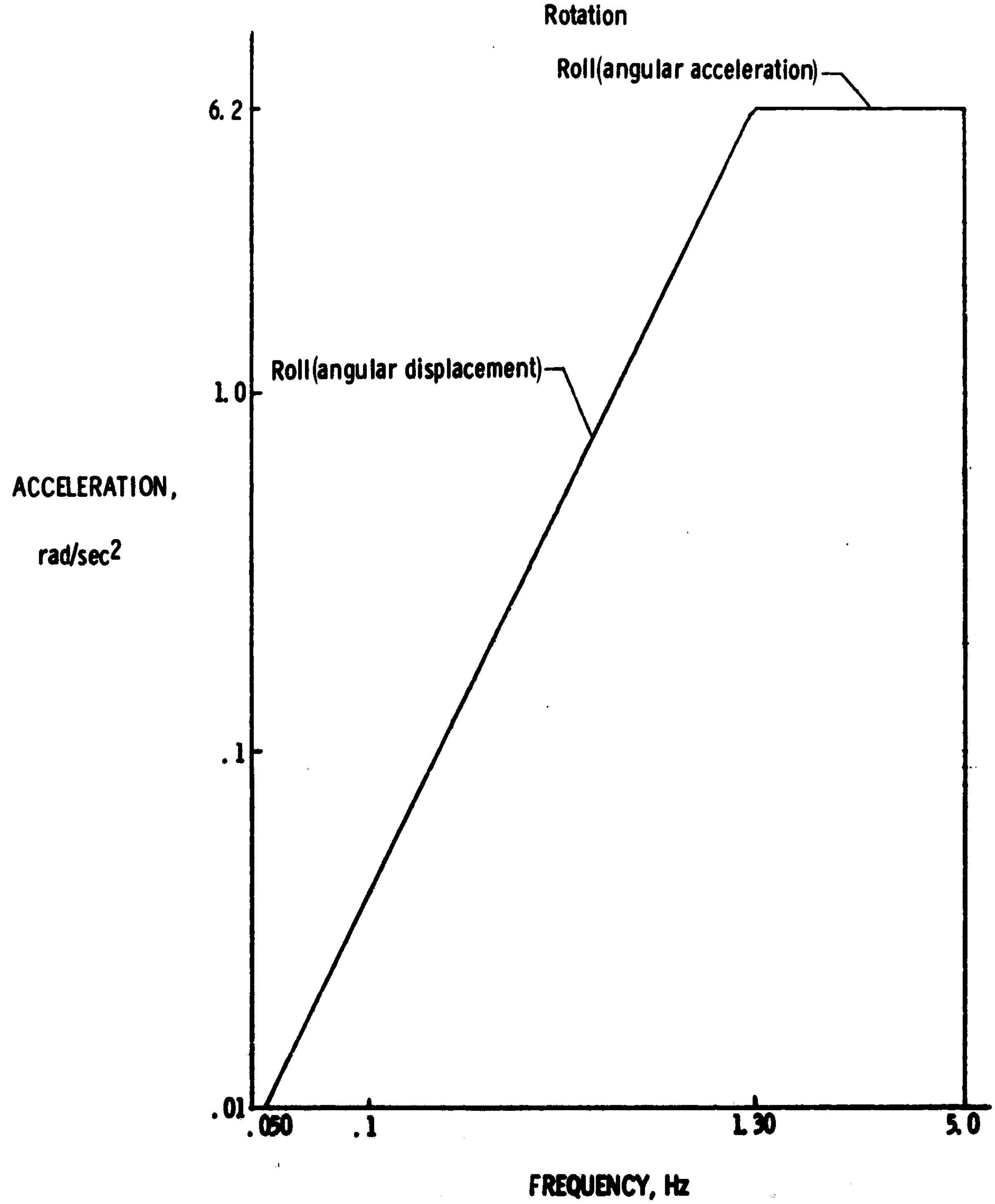
(a) Demonstration model.

Figure 7.- Langley passenger ride-quality apparatus (PRQA).



(b) Linear motion capability for maximum payload weight of 22.24 kN. Displacement, velocity, and acceleration limits identified in parentheses.

Figure 7.- Continued.



(c) Angular motion capability for maximum payload weight of 22.24 kN. Displacement, velocity, and acceleration limits identified in parentheses.

Figure 7.- Concluded.

NASA RIDE-QUALITY PROGRAM AT THE

FLIGHT RESEARCH CENTER

By Shu W. Gee and Thomas D. Wolf

NASA Flight Research Center

N73-10025

INTRODUCTION

A major NASA program is the development of technology leading to the design of short-takeoff-and-landing (STOL) aircraft for use in high-density short-haul airline operations. Since the primary objective of STOL aircraft operation is moving people, their well-being and comfort must be considered in the early stages of design. However, at present, the technology for ride quality design suffers from lack of criteria, lack of ground and flight test experimental data, and lack of basic information. These deficiencies exist because aircraft designers have concentrated primarily on solving the technical problems associated with the performance and economics of their designs and less on passenger riding comfort. The justification for this emphasis was the stage length of conventional jet airline operations, in which most flight is at altitudes above atmospheric turbulence. With STOL and short-haul commuter aircraft, the stage length consists of flight at lower altitudes, longer exposure to the vehicle accelerations associated with turbulence, maneuvering flight, and steep departures and approaches. These flight conditions, coupled with the lower wing loading of STOL aircraft, have caused increasing concern about passenger ride quality.

Both industry and government agencies have studied human reaction to vehicle accelerations. The results shown in figure 1 represent some of the work that has been done to identify the threshold of objectionable accelerations. Like most of the other work, this study was made with a highly sophisticated simulator, and the data are limited by the capabilities of the simulator. Accelerations encountered in flight extend beyond the range of any existing simulator; thus human response to extremely low frequency acceleration must be studied in flight. It is at these low frequencies that motion sickness may occur. To meet the need for flight test data and data in the low frequency range (below 0.2 hertz), a flight test program on passenger ride quality is being developed at the NASA Flight Research Center.

PROGRAM OBJECTIVES

The primary objective of this program is to accumulate flight test data on aircraft ride quality in terms of vehicle motion and acceleration and human responses. An additional objective is to correlate these data and to formulate data into ride quality criteria. To meet these objectives the existing simulation data must be verified in actual flight, and the existing test data expanded to include very low frequency flight data.

TEST EQUIPMENT

The NASA Flight Research Center's variable-stability, general-purpose airborne simulator (GPAS) airplane (fig. 2) will be used as the test vehicle. It is a modified Lockheed JetStar, which is a medium-sized, four-engine jet transport. The unique capabilities of the GPAS are well suited to ride quality research. Recently installed side force generators and direct lift control systems permit controlled motions about one aircraft axis while holding the other axis steady. Programed model following and tape playback can be performed through the onboard simulation equipment. Flight tests will be limited to frequencies below 5 hertz to stay within the structural limits of the airplane.

Two standard JetStar passenger seats will be used for ride quality evaluation, one at the center of gravity of the airplane and the other just behind the rear bulkhead of the pilot's compartment. The latter location will also contain instrumentation for biomedical monitoring.

The data acquisition system on the GPAS is a pulse-code modulation system capable of multiplexing 140 channels of data for telemetry or for onboard tape recording. Ride quality and aircraft information will be recorded on this system. A separate analog tape system will be used to record the biomedical information. The same time code generator supplies time information to both tape systems to permit the correlation of data.

TEST PROCEDURE

First, subject passengers will be selected from a pool of Flight Research Center volunteers. A control panel for selecting and recording one of three ratings will be located near each passenger seat. The rating scale will be explained in detail to each passenger. As the test is conducted, the subjects will evaluate the ride, and their ratings will be recorded. At the conclusion of each flight test, they will fill out a questionnaire.

The side force generator and direct lift control systems will be excited to induce motion about the desired aircraft axes. Initially, a frequency will be selected and the acceleration will be increased until the worst rating is obtained. The test will then be stopped. Rest periods will be provided between test runs.

The following data will be recorded during each test: passenger ride quality rating, three-axis accelerations at the passenger location, aircraft attitude and attitude rates, airspeed, altitude, rate of climb, cabin temperature, an event marker, time code, heart rate, and blood pressure. Samples of 17-ketosteroid excretion will be taken before and after each flight. As the program progresses, the data recorded will be expanded.

DATA PROCESSING

Data will be analyzed after each flight by using the Flight Research Center's central computing facilities. A block diagram of the data processing requirements is shown in figure 3. The aircraft recording system tape and the biomedical tape will be merged into one time-correlated tape. Basic ride quality data will be processed in the form of acceleration spectra power or root mean square (RMS) acceleration versus hertz for each ride quality rating. These flight test results will be compared with existing ride quality data. Biomedical data will be processed with existing computer programs. The results will be analyzed for possible correlation with ride quality ratings.

PROGRAM SCHEDULE

A program schedule is shown in figure 4. The initial flight test program, as described earlier, is intended to be a starting point. Therefore it has intentionally been kept simple and flexible. Some areas of the flight testing are expected to expand as information and experience are obtained.

At present a group of Center volunteers is available and the aircraft instrumentation is ready. Biomedical instrumentation is being checked out, and flights are being made to check the aircraft systems. Flight testing for ride quality is planned to start in the latter part of August. The first 3 months of flight testing will be to obtain only ride qualities data. Later, other programs will be conducted along with the ride qualities program.

'OBJECTIONABLE' THRESHOLD DATA FROM A BOEING, WICHITA, STUDY

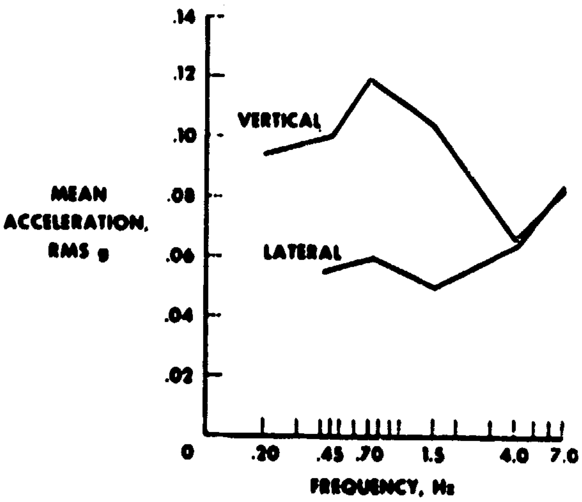


Figure 1

NASA GENERAL PURPOSE AIRBORNE SIMULATOR (GPAS)

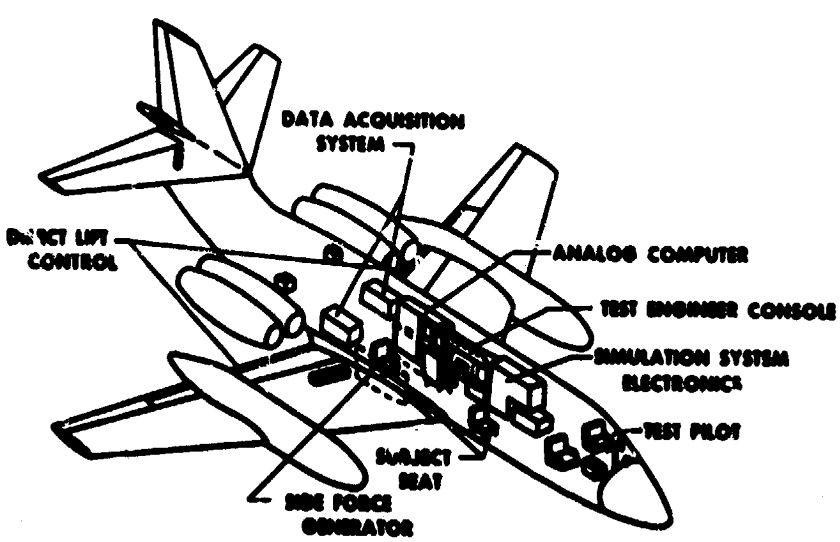


Figure 2

DATA PROCESSING BLOCK DIAGRAM

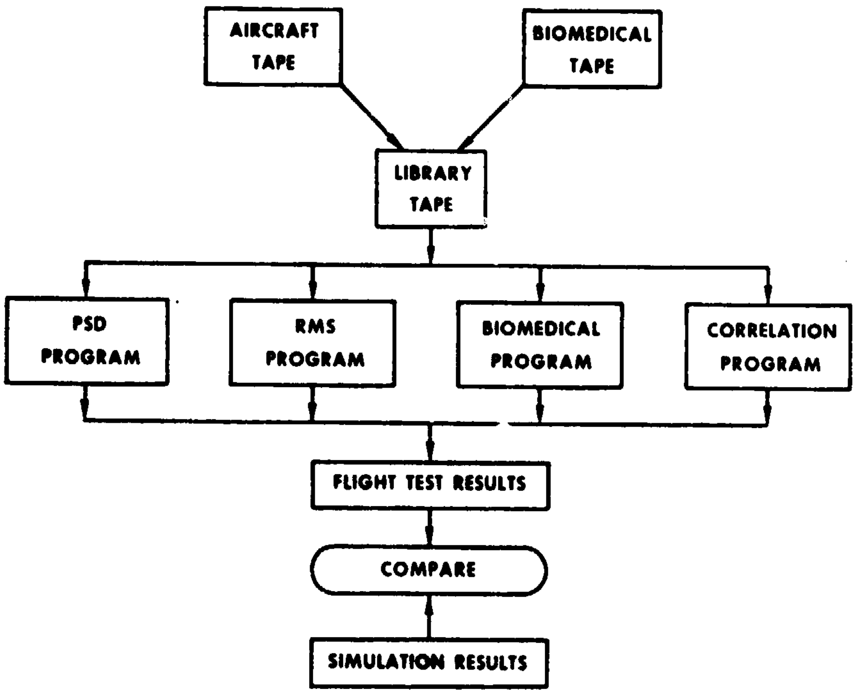


Figure 3

RIDE QUALITY FLIGHT PROGRAM SCHEDULE

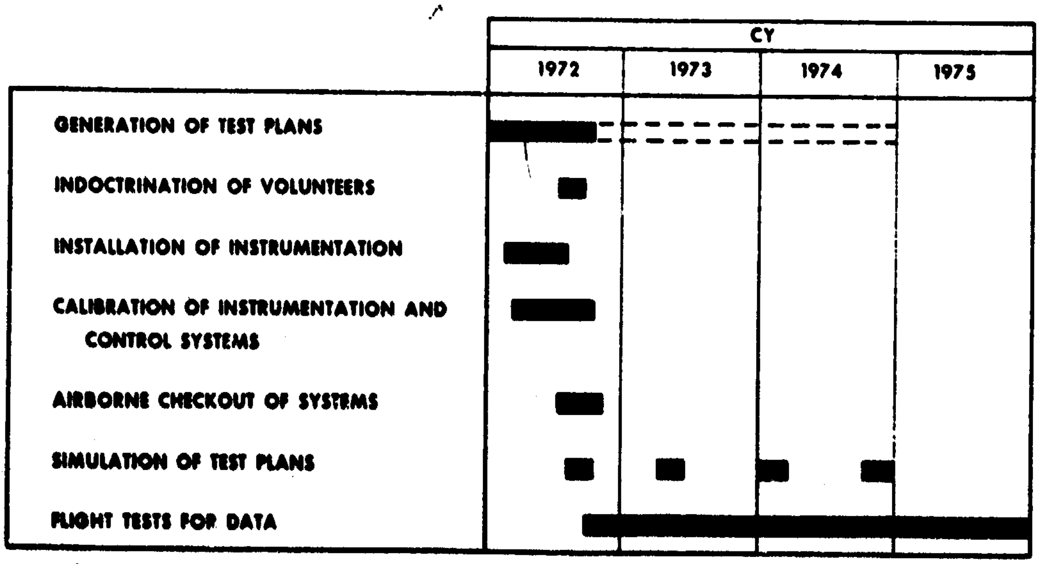


Figure 4