2-up-mix
-p-

NASA TECHNICAL MEMORANDUM

NASA TM X- 71922

COPY NO.

NASA TM X- 71922

RIDE QUALITY - AN EXPLORATORY STUDY AND CRITERIA DEVELOPMENT

Ralph W. Stone, Jr.

February 1974

(NASA-TM-X-71922) RIDE QUALITY - AN EXPLORATORY STUDY AND CRITERIA DEVELOPMENT (NASA) 34 p HC $4.75 CSCL 05E

N74-20731

Unclas

G3/05 35322

This informal documentation medium is used to provide accelerated or special release of technical information to selected users. The contents may not meet NASA formal editing and publication standards, may be revised, or may be incorporated in another publication.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

LANGLEY RESEARCH CENTER, HAMPTON, VIRGINIA 23665

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TM X-71922		
4. Title and Subtitle RIDE QUALITY - AN EXPLORATORY SIMULATOR STUDY AND CRITERIA DEVELOPMENT		5. Report Date February 1974 6. Performing Organization Code
7. Author(s) Ralph W. Stone, Jr.		8. Performing Organization Report No. L-9296 10. Work Unit No. 504-29-12-05
9. Performing Organization Name and Address NASA Langley Research Center Hampton, VA 23665		11. Contract or Grant No. 13. Type of Report and Period Covered Technical Memorandum
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

The Langley six degree of freedom visual motion simulator has been used to measure subjective response ratings of the ride quality of eight segments of flight, representative of a wide variation in comfort estimates. The results indicate that the use of simulators for this purpose appears promising. A preliminary approach for the development of criteria for ride quality ratings based on psychophysical precepts is included.

17. Key Words (Suggested by Author(s)) (STAR category underlined)	18. Distribution Statement
Ride quality, simulations, response modeling Star Category 05	Unclassified - Unlimited

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	34	$4.75

*Available from The National Technical Information Service, Springfield, Virginia 22151
STIF/NASA Scientific and Technical Information Facility, P.O. Box 33, College Park, MD 20740

RIDE QUALITY - AN EXPLORATORY SIMULATOR STUDY AND CRITERIA DEVELOPMENT

By Ralph W. Stone, Jr.

SUMMARY

An exploratory simulator study of the motion aspects of ride quality has been performed on the Langley Six-Degree of Freedom Visual Motion Simulator. A simulator test composed of eight segments similar to segments measured in actual airline operations was used. The results indicate that the use of simulators for this purpose appears promising. The results further show that experienced and inexperienced subjects do not differ appreciably in ride quality estimations. A preliminary ride quality criteria based on the psychophysical precept of the variation of sensory response with the logarithm of stimuli has been developed from these results.

INTRODUCTION

The Civil Aviation Research and Development Policy Study (ref. (1)) indicated the problems of noise and congestion and the need for short haul transportation which, as air travel progresses, will lead to conditions of flight at lower altitudes and requiring more acute maneuvering than is experienced by current jet aircraft. Such conditions will tend to make the quality of the ride less acceptable than it now is. In order to design for the ride quality problem, it is necessary first to understand and define conditions that are acceptable to the air traveler and then to develop aircraft and/or aircraft systems that will achieve passenger acceptance and use. Ride quality, as evidenced from reference (2), is normally construed to be the result of a collection of factors. These factors include the cabin environment (temperature, humidity, air circulation, smoke, etc.); the passenger psychophysical condition, including his attitude toward flying; the cabin accouterments (seats, seat spacing, head room, etc.); and the motion environment. The NASA has undertaken a program of study (ref. (2)) to examine ride quality and to establish criteria, particularly as regards the motion environment. As a part of this program, simulator studies are being made to identify the critical aspects of the motion environment and to establish their influence on subjective responses to the quality of ride. This paper is concerned primarily with the motion environment and contains some exploratory experiments using the Langley Visual Motion Simulator to study six degrees of freedom of motion similar to those experienced in flight (ref. (3)). A technique for criteria development is also presented.

SYMBOLS

$\bar{a}_x$	RMS longitudinal acceleration, g's
$\bar{a}_y$	RMS transverse acceleration, g's
$\bar{a}_z$	RMS vertical acceleration, g's
$\bar{\omega}_p$	RMS rolling velocity, rad/sec
$\bar{\omega}_q$	RMS pitching velocity, rad/sec
$\bar{\omega}_r$	RMS yawing velocity, rad/sec
K	constant
R_s	subjective ride quality response rating
R_{c_1}	calculated ride quality response rating (linear model)
R_{c_2}	calculated ride quality response rating (nonlinear model)
S	actual stimulus, g's and rad/sec
S_T	effective threshold of stimulus, g's and rad/sec
$\bar{S}$	effective stimulus $\left(\frac{S}{S_T}\right)^K$

<u>Subscripts</u>

i	general denoting any degree of freedom
max	maximum, identifying the stimulus having the largest effective stimulus value, $\bar{S}$, for any specific flight segment

TESTS AND TEST CONDITIONS

A major thrust in NASA's ride quality program is to experience actual scheduled airline flights, measure the motion environment encountered during the flights and periodically measure subjective responses to this motion environment (e.g., see refs. (3), (4), and (5)). Motion environmental conditions used in the current simulator study were derived from such flight studies.

The specific motion environments experienced in the various flights discussed in reference (3) were examined and eight flight segments, 2 minutes long, were selected. The subjective ride quality responses recorded during these flight segments ranged from very comfortable to very uncomfortable.

These responses were for a period of about 30 seconds in the middle of the 2-minute segments. The eight segments of flight were assembled on a 16-minute tape. For the segments of flight used, the three linear accelerations and the three angular accelerations were measured. The operation of the simulator requires angular velocity, rather than angular acceleration. Accordingly, the angular flight data were integrated and biases were removed. The six motion components were then filtered below 1/2 Hz, as the simulator cannot duplicate complete maneuvering and above 10 Hz, as the simulator has greatly reduced response at such frequencies. This tape then was used as the input to drive the control mechanisms of the Langley Visual Motion Simulator, shown in figure 1. Input signals from a computer or magnetic tape drive six hydraulically operated legs to create the simulator motion. The simulator is termed a synergistic motion device, as movement of all six legs is required for movement in any one or all degrees of freedom. The existence of motion in any one degree of freedom therefore affects the motion of the legs available for any or all other degrees of freedom. The motion limits of the simulator, for each independent degree of freedom, are shown in table I. Because of the acceleration, velocity, and displacement limits of the simulator, washout procedures are applied to the input signals to prevent reaching these limits. This washout and the simulator limitations are effective filters to the input data.

This effective filtering causes the motions of the simulator to be generally smaller than those of the input signals. Figure 2 shows a comparison of time histories of input motions and simulator motions. The nature of the motion is reasonably reproduced. The simulator is further described in reference (6). The software and compensation methods used for this simulator are described in references (7) and (8).

The simulator motion was measured by three linear accelerometers and three rate gyros. These were mounted in a package and installed on the floor of the simulator near the seats. The accelerations and rates, along with the subjective responses, were recorded on magnetic tape which was subsequently analyzed. As the simulator is driven by signals from a magnetic tape, the motions, as recorded in the simulator cabin, are repeatable from simulator test to test. The RMS values of the magnitudes of the six elements of motion measured in the simulator for the eighth test segments are shown on table II. The vertical accelerations are relatively small and generally smaller than those experienced in real flight. The other components are more nearly comparable with flight values. These conditions are caused primarily by the limitations and washout previously discussed. The power spectrum of these segments, covering the region of 1 to 10 Hz, are shown in figure 3.

The simulator cabin in which the subjects rode represents the cockpit of a transport aircraft, and not a passenger compartment. The interior of the cockpit is shown in figure 4. The seats are standard airline pilot seats, and the area for each subject was more spacious than that available in a standard passenger area. The controls and instruments were inoperative and no effort was made to disguise the cockpit appearance. The subjects were merely passive, as are normal passengers. The windows of the cockpit were covered and, therefore, no out-the-window visual cues were available.

The subjective ride quality response ratings were obtained by the subjects pressing one of five switches. These switches were mounted on a box which was passed back and forth between the subjects for their ratings. The signals resulting from the switch actions were recorded on magnetic tape.

TEST SUBJECTS

The subjective responses from the simulator tests were made by 10 subjects. Two subjects rode the simulator during each test and 12 tests, each lasting 16 minutes, were made. The subjects were divided into two groups, one consisting of persons who had been subjects on actual flight tests for ride quality research and the other group, persons who had not been subjects in actual flight tests for ride quality research. These subjects are hereinafter termed experienced and inexperienced subjects. Two of the subjects were women. The subjects range in age from 24 to 55 years. Their age distribution, as compared to that of the general air traveler (ref. (9)), is shown in figure 5. Except for the youngest, who was a graduate student, the subjects were professionals and research-oriented persons in academic or government research. All subjects had flown six or more times prior to the simulator study and all liked flying. Two subjects rode on each simulator test, as was noted previously; one experienced and the other inexperienced. The experienced subject supervised the operational aspects of data recording. The subjective ratings were obtained by switch pressing, as noted previously. The subjects were instructed not to observe their coriders when making subjective response.

RESULTS AND DISCUSSION

In previous studies performed by the University of Virginia (see refs. (3)-(5)), a five-point rating scale has been used to establish subjective responses to the motion environment experienced on scheduled airlines. The five-point scale has been a compromise of test and subject requirements. Although evidently coarse, this scale has proven very appropriate for ride quality studies. In flight tests the five-point scale (refs. (3), (4), and (5)) is augmented by demographic data, airplane cabin characteristics including its internal environment, the motion environment, and so forth. The five-point scale was used in the current research and consists of the following ratings:

Rating number	Subjective judgment
1	Very comfortable
2	Comfortable
3	Acceptable
4	Uncomfortable
5	Very uncomfortable

Subjective Responses

The subjective response ratings obtained for all the simulator tests are shown on table III. A total of 12 tests were made on the simulator in a 2-day period with the 10 subjects randomly taking rides. No subject rode on consecutive tests. There were 24 ratings for each of the test segments. The standard deviation is approximately three-fourths of a rating point for all flight segments (see table III). This implies that, based on the five-point rating scale, the judgment of comfort or discomfort is equally difficult.

The response ratings of the experienced and inexperienced subjects for the simulator tests are compared on table IV. The most obvious difference between these groups is that the standard deviations for the experienced group are smaller (nearly one-half as large) as those of the inexperienced group. This smaller scatter in the responses of the experienced subjects indicates that experience in ride quality studies sharpens the ability to estimate one's sense of comfort. The specific average response ratings of the two groups are quite similar. The experienced group rated the test segments slightly less comfortable than did the inexperienced group. This implies that ride quality subjective responses probably are not appreciably biased by ride quality test experienced.

Criteria Development

Criteria for vibratory motions have long been of concern to man. The current program of the International Organization for Standardization (ISO) to establish international standards (ref. (10)) is a major effort in this regard. This work is generally founded on measured human responses to single degree of freedom motions and generally at discrete frequencies. The material of reference (2) indicates a concern for the conditions of multiple degrees of freedom with random magnitudes and frequencies, as is experienced in real airplane flights. Mathematical models or criteria based on responses to multiple degrees of freedom with random magnitudes and frequencies are, therefore, desired.

The University of Virginia has developed a linear model by regression analysis using the various subjective responses and motions measured in actual airline flights (see refs. (3), (4), and (5)). This model has the form

$$R_{c_1} = K_1 + K_2\,\bar{a}_x + K_3\,\bar{a}_y + K_4\,\bar{a}_z + K_5\,\bar{\omega}_p + K_6\,\bar{\omega}_q + K_7\,\bar{\omega}_r \qquad (1)$$

The value of the constants in this model are evolving with the accumulation of measured data. Some recent put unpublished values of the constants are $K_1 = 2.0$, $K_2 = 1.0$, $K_3 = 7.5$, $K_4 = 11.5$, $K_5 = 0.12$, $K_6 = 0$, and $K_7 = 0.1$. The results of applying this model and these constants to the current simulator data are shown in figure 6. These results show that this model does not represent well the limited and specific data of the current simulator test. This is in part, at least, because the value of K_1 allows no values of R_{c_1}

less than 2, and because of the large value of K_4 for the vertical accelerations. As noted previously, the vertical accelerations were relatively small on the simulator tests. Clearly, a linear model could be developed for the specific set of data of this report. However, it would not represent the general flight results for which equation (1) was developed. The results of the current simulator tests are legitimate subjective responses to real motions. It is felt that a general model should reasonably fit all data.

Accordingly, an examination was made to establish a psychophysiological basis for a mathematical model for ride quality response. Such a model has been developed and is presented in the appendix. The model so developed is nonlinear and is generally based on the "Weber-Fechner Law" which states that the intensity of a response varies as the logarithm of the stimulus. The general psychophysical law discussed in references (11) and (12) further indicates that the logarithms are modified by a multiplying factor or power. As developed in the appendix, the response to a single degree of freedom of motion is expressed as

$$R_{c_{2_i}} = 1 + \log_{10}(\bar{S}_i) \tag{2}$$

The model for multiple degrees of freedom was based on empirical judgments and is expressed as

$$R_{c_2} = 1 + \log_{10}\bar{S}_{max} + K_1(\log_{10}\bar{S}_{max})^{K_2}\left[\Sigma(\log_{10}\bar{S}_i)^{K_3} - (\log_{10}\bar{S}_{max})^{K_3}\right] \tag{3}$$

This represents a nonlinear subjective ride comfort response rating.

This model criterion was developed from and applied to the simulator data presented herein. Values of K_2 and K_3 of 4 and K_1 of 0.000176 were established. The calculated responses (R_{c_2}) based on equation (3) are compared with actual subjective responses in figure 7. The root mean square deviation of the calculated responses (R_{c_2}) from the average subjective response ratings (R_s) is 0.148 of a response rating unit. Clearly, this criteria must be applied to much more data than for the simulator data of this report, but the current results appear promising.

As noted in the appendix, the influence of frequency on human response to motion is not included in this model. It is widely recognized that human response to motion varies appreciably with the frequency of the stimulus (see, for example, ref. (10)). The power spectrum of the motion environment shown on figure 3 indicates that much of the energy of the motions encountered in the simulator is at relatively low frequency, probably leading to the relative accuracy of the calculated responses (R_{c_2}) shown in figure 7. A refined criteria would treat each stimuli for a few or several frequency bands, depending on the spectra and human sensitivity to frequency.

The results of this paper suggest that representative motions are produced by the Visual Motion Simulator and that its use for ride quality studies is promising.

FUTURE RESEARCH

The results presented indicate that ride quality evaluations would be enhanced by specific tests to examine the influence of motion in individual degrees of freedom and their combinations. Improved evaluations of the subjective threshold values and the slopes of the subjective response ratings with specific stimuli need to be established. This must be done through a range of stimulus magnitudes and with power spectra of random frequencies representative of real airplane motions. The suggested tests using combined stimuli will examine the principals wherein responses to combined stimuli are subjectively evaluated.

The studies of references (3) to (5) and of this paper are based on the RMS values of the magnitudes of the motion components. Other measures of the motion such as peak counts and absorbed power also need examination. The effects of time of exposure to motion and of the sequences of events in such exposures also need examination. The influences of demographic, social, economic, and motivational differences in subjects are also of concern.

CONCLUDING REMARKS

An exploratory study to examine the influence of combined motions on human acceptance of the quality of airplane rides has been performed on the Langley six degree of freedom motion simulator. The results indicate that the use of simulators appears promising for this purpose. The subjective ride quality response ratings for the simulator tests show that subjects experienced in ride quality evaluation give average subjective ratings about the same as those of subjects inexperienced in ride quality evaluation, indicating that experience does not bias subjective response ratings. The standard deviations of the experienced subjects' ratings, however, were appreciably smaller than those of the inexperienced subjects, indicating that experience in ride quality evaluation primarily sharpens one's ability to estimate his sense of comfort. The results further show that the standard deviation of subjective response ratings for all subjects remained approximately constant over the range of ratings experienced. This indicates equal difficulty in assessing one's state of comfort whether one is comfortable or uncomfortable.

A preliminary ride quality response rating model based on the psychophysical precept of the variation of sensory response with the logarithm of stimuli has been developed from the data of this study. The rating model uses the RMS magnitudes of the motion components. The variations of the calculated response rating from the average subjective response ratings are appreciably smaller than the standard deviations of the subjective response ratings. The model precept appears promising and should be refined. The effects of frequency, peak counts, absorbed power, and duration of exposure also require consideration.

APPENDIX

DEVELOPMENT OF A PRELIMINARY RIDE QUALITY RESPONSE RATING MODEL

A ride quality response model should relate to the sensory-neural processes that are involved in human responses to motion. Therefore, the laws of psychophysical response expressed by the Weber-Fechner Law and the power law (e.g., see refs. (11) and (12)) were considered to be applicable hypothesis upon which to build a ride quality response model.

This model expresses response as follows:

$$\text{Response} = K_1 + K_2 \log_{10} (\text{Stimulus}) \tag{A-1}$$

or

$$\text{Response} = K_1 + \log_{10} (\text{Stimulus})^{K_2} \tag{A-2}$$

which indicates that the intensity of a response varies as a function of the logarithm of the stimulus.

Human response to noise is a significant demonstration of this law. The response is generally related, however, to the logarithm of the ratio of the noise pressure to a standard noise pressure with a constant representing the response at standard pressure. Thus the stimulus is effectively a nondimensional ratio of the stimulus to a standard or baseline stimulus.

The response process expressed by equations (A-1) or (A-2) are common to the human sensory-neural system. Vibration and oscillatory motions, as encountered in moving vehicles, stimulates the vestibular system in this fashion (ref. (11)). The proprioceptive senses are stimulated by motions and are assumed to respond in the same manner.

Motions in aircraft consist of six degrees of freedom, three linear and three angular. The vestibular, proprioceptive, and visual senses are stimulated by all six degrees of freedom and it is assumed that the sensory system responds to each degree of freedom in accordance with the law expressed in equations (A-1) or (A-2).

For ride quality assessment, the response must be related through the constants K_1 and K_2 to the response scale of concern. In the case of this paper, they must relate to the five-point scale ranging from very comfortable to very uncomfortable. Hence, if other scales are used, as a 7 or 10-point scale, the constants must be adjusted. It is assumed that a subjective rating of one (very comfortable) represents a threshold condition where the subject just becomes aware of the stimulation of his sensory system. This does not necessarily imply that these thresholds are the normally measured thresholds attributed, for example, to the vestibular system, although a strong correlation with these probably exists. The response system, therefore, is not considered to be bipolar about the middle point (the acceptable response rating) but merely a progressive response starting from the threshold. The concept of this paper thus ranges from a condition of no motion, or rather of subliminal motion, to a condition of extreme motion where great discomfort exists. The neural system functions in this manner, increasing its activity with increasing stimulus.

A response to a single degree of freedom motion would then be represented as follows:

$$R_{c_i} = 1 + \log_{10}\left(\frac{S_i}{S_{T_i}}\right)^{K_i} \tag{A-3}$$

Herein, the concept of effective stimulus is established where the effective stimulus

$$\bar{S}_i = \left(\frac{S_i}{S_{T_i}}\right)^{K_i} \tag{A-4}$$

such that

$$R_{c_i} = 1 + \log_{10}(\bar{S}_i) \tag{A-5}$$

In these expressions, S_i is the specific stimulus; S_{T_i} is the previously discussed threshold stimulus, and the exponent K_i is the rate of change of the subjective response with the $\log_{10}$ of the specific stimulus. $\bar{S}_i$, as noted above, is considered an effective stimulus to the neural system. $\bar{S}_i$ is proportional to the actual neural response caused by a given single degree of freedom stimulus. These differ for each motion component. The constant, one, in equations (A-3) and (A-5) represents the very comfortable response to a threshold stimulus.

For the preliminary criteria presented herein, values of S_{T_i} and K_i for the six degrees of freedom were emperically established from the results of the simulator tests presented. The values so established were obtained from observation of the variations of subjective response ratings with the logarithms of individual specific stimuli. Figure 8 is an example of these variations. It must be recalled that the response ratings are for all six degrees of freedom and not just the specific degree of freedom shown. A straight line emperically drawn through the centroid of the data was used to establish S_T, its intersection with the response rating of one. An adjustable straight line, intersecting S_T and bounding all data above it, was used to establish the value of the slope K. Ideally, response rating data with the subjects exposed to each specific degree of freedom should be used to establish S_T and K. For such data only a single straight line through its centroid would have been used.

The values of S_{T_i} and K_i established by this procedure are listed on table V. They are thresholds for the RMS values of the motion components shown on table II and figure 2.

The next and more complex aspect of this preliminary criteria is how these separate responses are combined to represent the total response to two or more degrees of freedom. The values represented by equation (A-3) or (A-5), although representing responses to different degrees of freedom and sources of stimulation, represent responses of equal weight. A calculated response rating of four, for example, in any degree of freedom is equivalent to a rating of four in any other degree of freedom, causing equal senses of discomfort.

The process of assimilating the results of stimulation of more than one sensory modality and from more than one source of stimulation is not well understood. It is assumed that this process is one where correlations are made between the modalities and sources of stimulation to establish the degree of normalacy of a given set of stimulations. Such a process is probably learned. It is assumed that if a normal coexistance between stimuli exists, then the general overall response may be a little different than the response to any single degree of freedom. From this, it is further assumed that the response to the maximum effective stimulus, is the dominant response in the total response for two or more effective stimuli.

If normal coexistance of sensations from multiple stimulations does not exist, then some neural process must upgrade the response to the maximum effective stimulus based on the degree that normalacy does not exist. In the extreme, it is known that a conflict in sensory cues indicative of a great or complete lack of normalacy, can cause extreme responses, including vomiting (ref. (13)). Discomfort is simply a lesser response than is motion sickness.

The process involved when several sensory modalities are involved is one probably occurring through the reticular formation of central nervous system. This then is an intermodality process where the processing element is accepting, correlating, and assessing all neural responses from the original multiple stimuli.

In examining the subjective responses of the simulator data and the effective stimuli calculated on the basis of equation (A-5), it was apparent that the subjective responses, although keyed to the maximum effective stimulus, became progressively larger than the maximum effective stimulus with the increasing magnitude of the maximum effective stimulus and with the increasing magnitude of all other stimuli. From these observations the following expression for a criteria involving all degrees of freedom was developed.

$$R_{c_2} = 1 + \log_{10} \bar{S}_{max} + K_1(\log_{10}\bar{S}_{max})^{K_2}\left[\Sigma(\log_{10}\bar{S}_i)^{K_3} - (\log_{10}\bar{S}_{max})^{K_3}\right] \qquad (A-6)$$

This is a highly nonlinear ride comfort response in contrast to current linear models. Examination of the results of the simulator response rating and the effective stimulations has lead to preliminary values for the constants of equation (A-6). These values are $K_1 = 0.000176$, and $K_2 = K_3 = 4$. These are the values applied in the body of this report.

As stated in equations (A-3) and (A-6), the effect of frequency of motions on response is not considered. This model can be refined to estimate response ratings for specific bands of frequency by considering effective stimuli, not only for each degree of freedom, but for specific bands of frequency for each degree of freedom. Further study is required of this frequency effect, and the process whereby all such effective stimuli are evaluated to obtain a single response.

REFERENCES

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

2. NASA TM X-2620. Symposium on Vehicle Ride Quality Held at Langley Research Center, Hampton, Virginia, July 6-7, 1972, October 1972.

3. Kahlthau, A. R.; and Jacobson, Ira P.: Analysis of Passenger Acceptance of Commercial Flights Having Characteristics Similar to STOL. Presented at CASI Flight Test Symposium, Ottowa, Canáda, March 7, 1973.

4. Kuhlthau, A. R.; and Jacobson, Ira D.: Investigation of Traveler Acceptance Factors in Short-Haul Carrier Operations. NASA TM X-2620, pp. 211-228, Symposium on Vehicle Ride Quality, October 1972.

5. Jacobson, Ira D.; and Kulthau, A. R.: Mathematical Modeling to Determine Criteria for Evaluating Human Acceptance of Transportation Systems. STOL Program Technical Report 403204, June 1972.

6. Connor, Andrew B.; Bergeron, Hugh P.; and Schoonover, W. Elliott: Ride Quality Research Activities at NASA Langley Research Center. NASA TM X-2620, pp. 229-246. Symposium on Vehicle Ride Quality held at Langley Research Center, Hampton, Virginia, July 6-7, 1972, October 1972.

7. Parrish, Russell V.; Dieudonne, James E.; Martin, Dennis J.; and Copeland, James L.: Compensation Based on Iinearized Analysis for a Six-Degree-of-Freedom Motion Base. NASA TN D-7350, 1973.

8. Parrish, Russell V.; Dieudonne, James E.; and Martin, Dennis J.: Motion Software for a Synergistic Six-Degree-of-Freedom Motion Base. NASA TN D-7350, 1973.

9. Wendell, Lee; and Jacobson, Ira D.: Characteristics of the Air Traveler - A Selective Review STOL Program Memorandum Report 403204, June 1972.

10. International Organization for Standardization, International Standard ISO/DIS 2631. Guide for the Evaluation of Human Exposure to Whole-Body Vibration. 1972.

11. Larson, Carl Alfred. Otolith Receptors: A Mathematical Description of Their Function. Ph. D. Thesis Biomedical Engineering and Science, Drexel Inst. of Technology, 1973.

12. Stevens, S. S.: Neural Events and the Psychophysical Law. Science, Vol. 170, pp. 1043-1050, 1970.

13. Graybiel, Ashton: Some of the Mechanisms Underlying Motion Sickness. NASA TM X-2620, pp. 155-174. Symposium on Vehicle Ride Quality held at Langley Research Center, Hampton, Virginia, July 6-7, 1972, October 1972.

TABLE I.- PERFORMANCE LIMITS FOR SINGLE-DEGREE-OF-FREEDOM

OPERATION OF THE LANGLEY SIX-DEGREE-OF-FREEDOM MOTION SIMULATOR

Degree of Freedom	Performance limits		
	Position	Velocity	Acceleration
Longitudinal	Forward 1.245 m Aft 1.219 m	±0.610 m/sec	±0.6 g
Transverse	Left 1.219 m Right 1.219 m	±0.610 m/sec	±0.6 g
Vertical	Up 0.991 m Down 0.762 m	±0.610 m/sec	±0.8 g
Pitch	+ 30° - 20°	±0.262 rad/sec	±0.873 rad/sec^2
Roll	± 22°	±0.262 rad/sec	±0.873 rad/sec^2
Yaw	± 32°	±0.262 rad/sec	±0.873 rad/sec^2

TABLE II.- SIMULATOR AND FLIGHT MOTION ENVIRONMENTS

(RMS Values for "Flight" Segment Period)

Motion element \ Test segment	1	2	3	4	5	6	7	8
Simulator								
Angular velocities, rad/sec								
Pitch	0.00134	0.00669	0.000764	0.0116	0.00992	0.00192	0.000771	0.00625
Roll	.00112	.0318	.00133	.0251	.0107	.0159	.00247	.0309
Yaw	.000879	.0152	.000866	.0154	.00932	.00173	.00233	.0120
Linear acceleration, g's								
Longitudinal	0.00301	0.00792	0.00126	0.0572	0.0610	0.00213	0.00221	0.00476
Transverse	.00188	.0330	.00342	.0370	.02424	.0221	.00390	.0330
Vertical	.00835	.0190	.00337	.00663	.00420	.00508	.00712	.01630

TABLE III.- SUBJECTIVE RIDE QUALITY RESPONSE RATINGS IN

SIMULATOR TESTS - ALL SUBJECT RATINGS

Segment	Average rating	Standard deviation
1	1.875	0.781
2	3.583	0.759
3	1.667	0.624
4	3.500	0.763
5	3.250	0.777
6	2.542	0.706
7	1.917	0.702
8	3.583	0.954

TABLE IV.- SUBJECTIVE RIDE QUALITY RESPONSE RATINGS IN

SIMULATOR TESTS - COMPARISON OF EXPERIENCED AND INEXPERIENCED SUBJECT RATINGS

Segment	Experienced subjects		Inexperienced subjects	
	Avg. rating	Std. dev.	Avg. rating	Std. dev.
1	1.750	0.595	2.000	0.913
2	3.750	0.433	3.417	0.954
3	1.667	0.471	1.667	0.745
4	3.667	0.471	3.333	0.943
5	3.500	0.500	3.000	0.913
6	2.500	0.500	2.583	0.878
7	2.000	0.707	1.833	0.687
8	3.750	0.433	3.417	1.256

TABLE V.- EMPERICALLY ESTABLISHED STIMULUS THRESHOLDS AND POWER EXPONENTS - BASED ON ROOT MEAN SQUARE (RMS) VALUES OF THE STIMULI

Degree of freedom	S_{Ti} [a]	K_i [b]
Pitch	0.000244	0.990
Roll	0.000166	0.650
Yaw	0.000763	1.940
Longitudinal	0.000767	1.100
Transverse	0.00122	1.140
Vertical	0.00299	1.570

a Values are in radians per second for the angular motions and g's for linear motions.

b Values represent slopes in terms of subjective rating per log of stimulus.

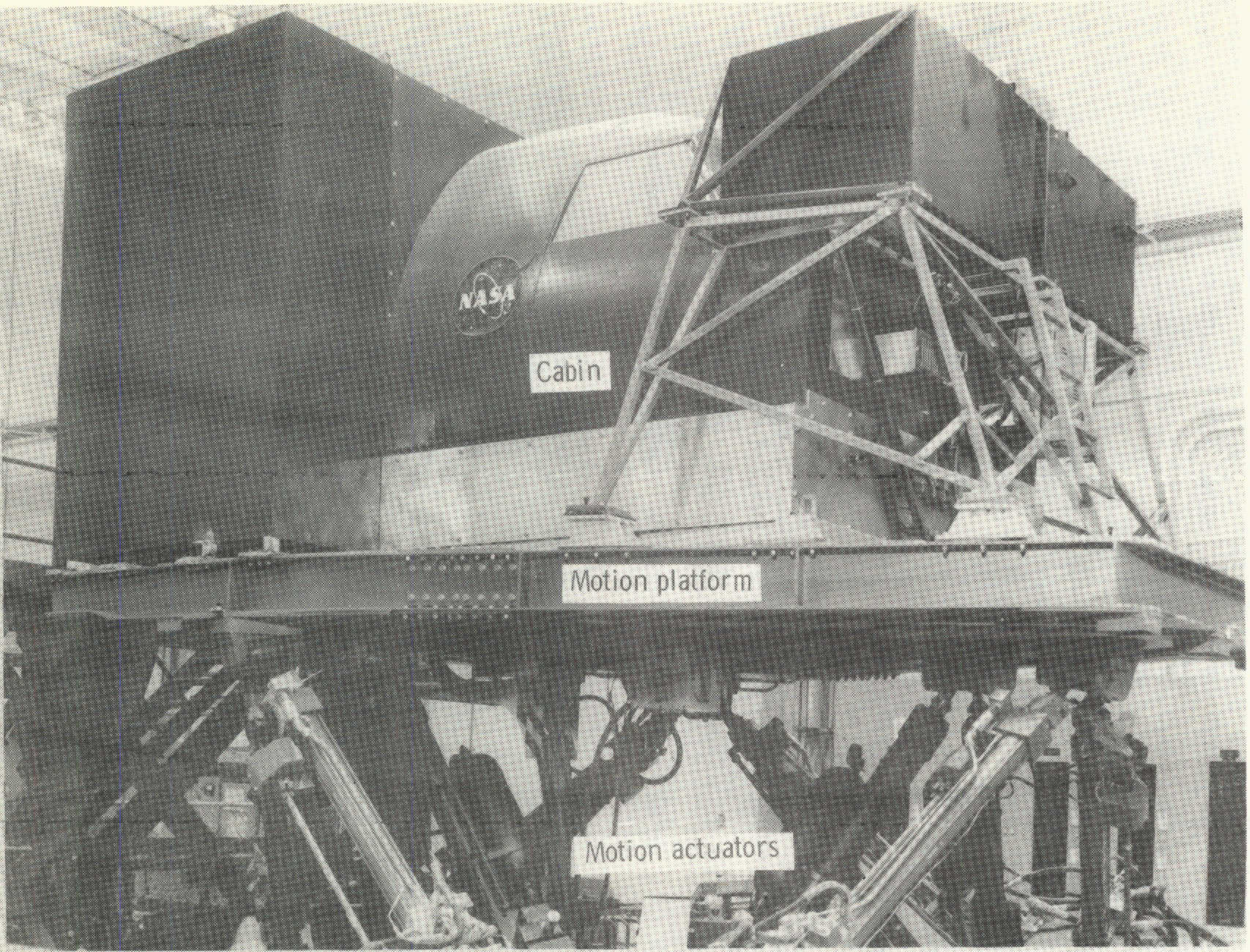


Figure 1.- Langley six-degree-of-freedom, vision motion simulator.

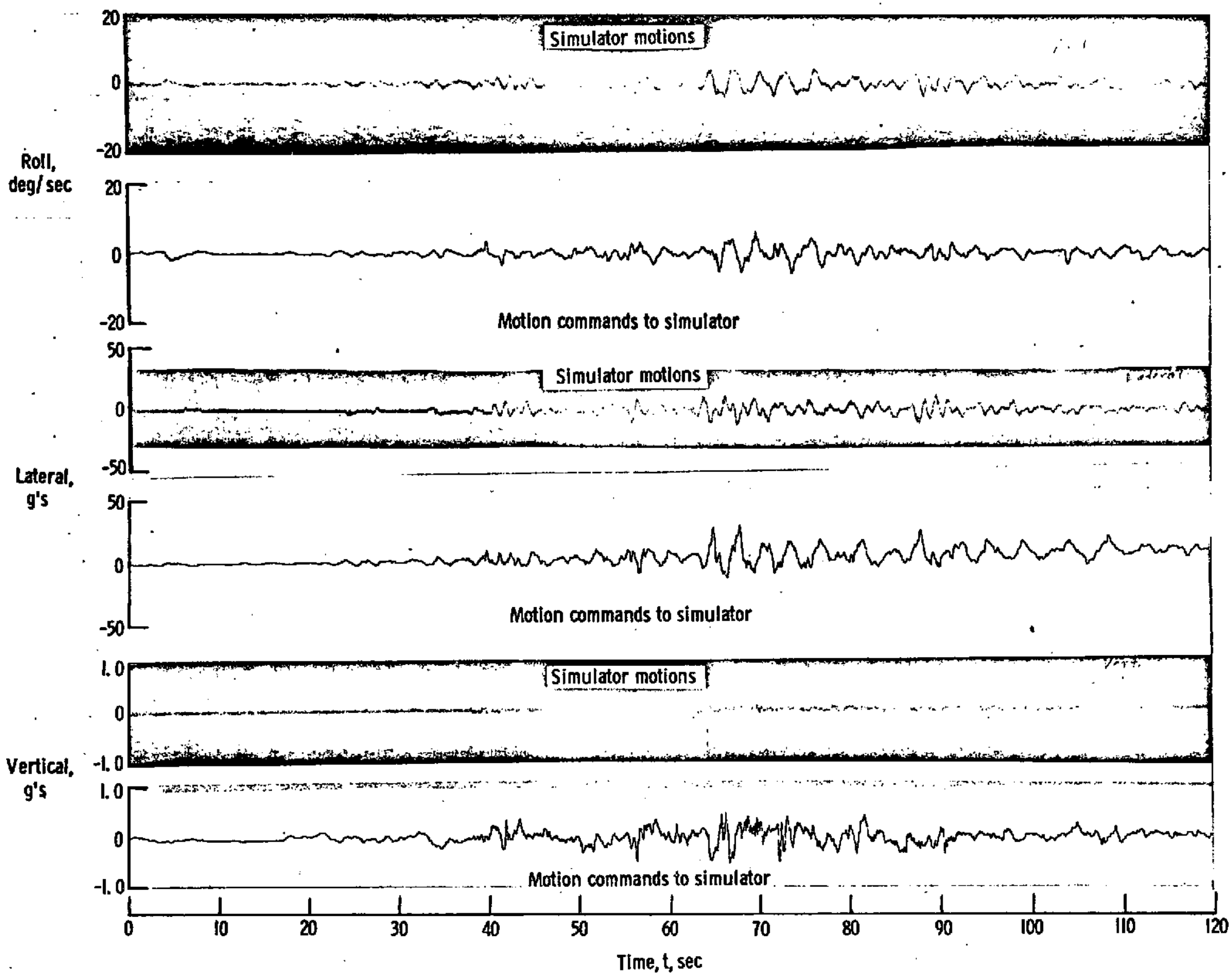
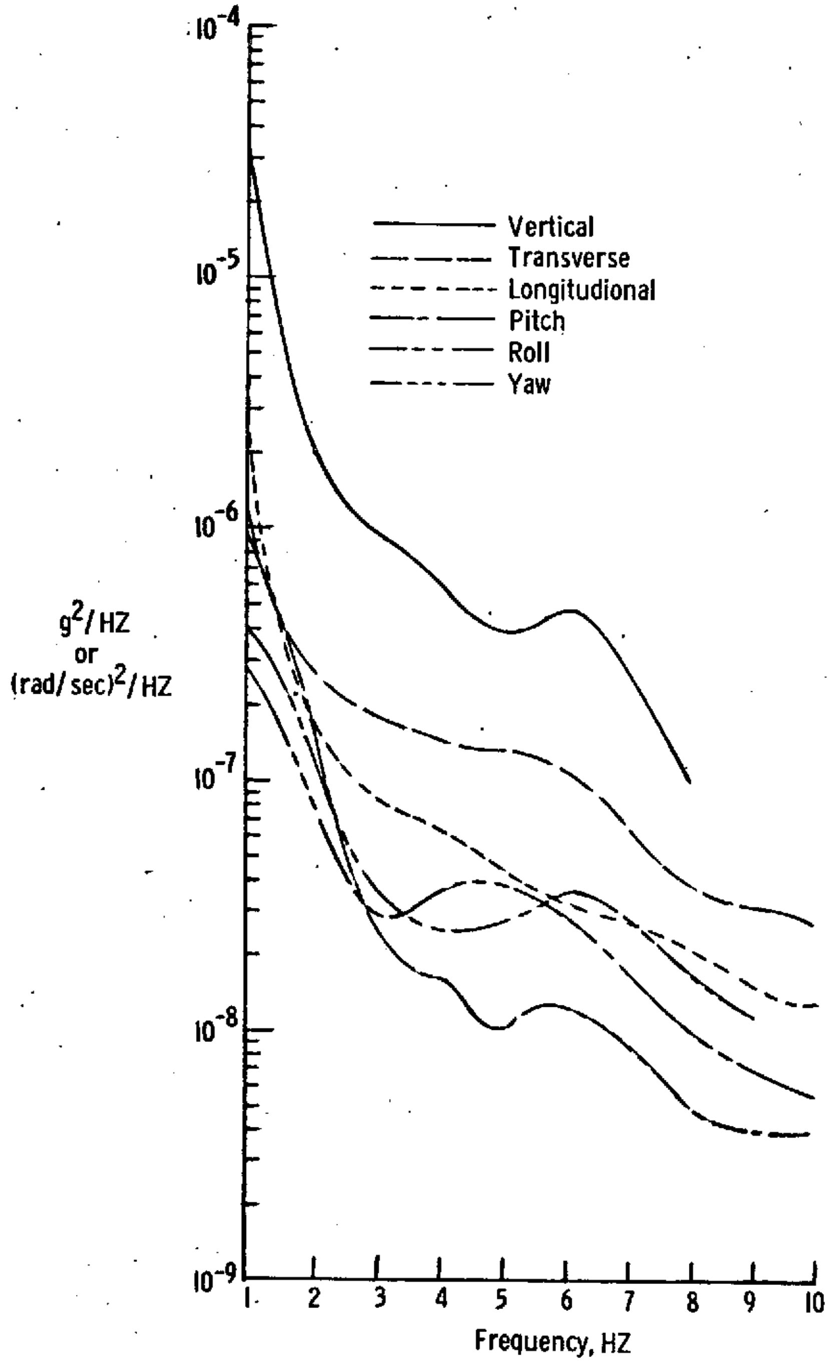
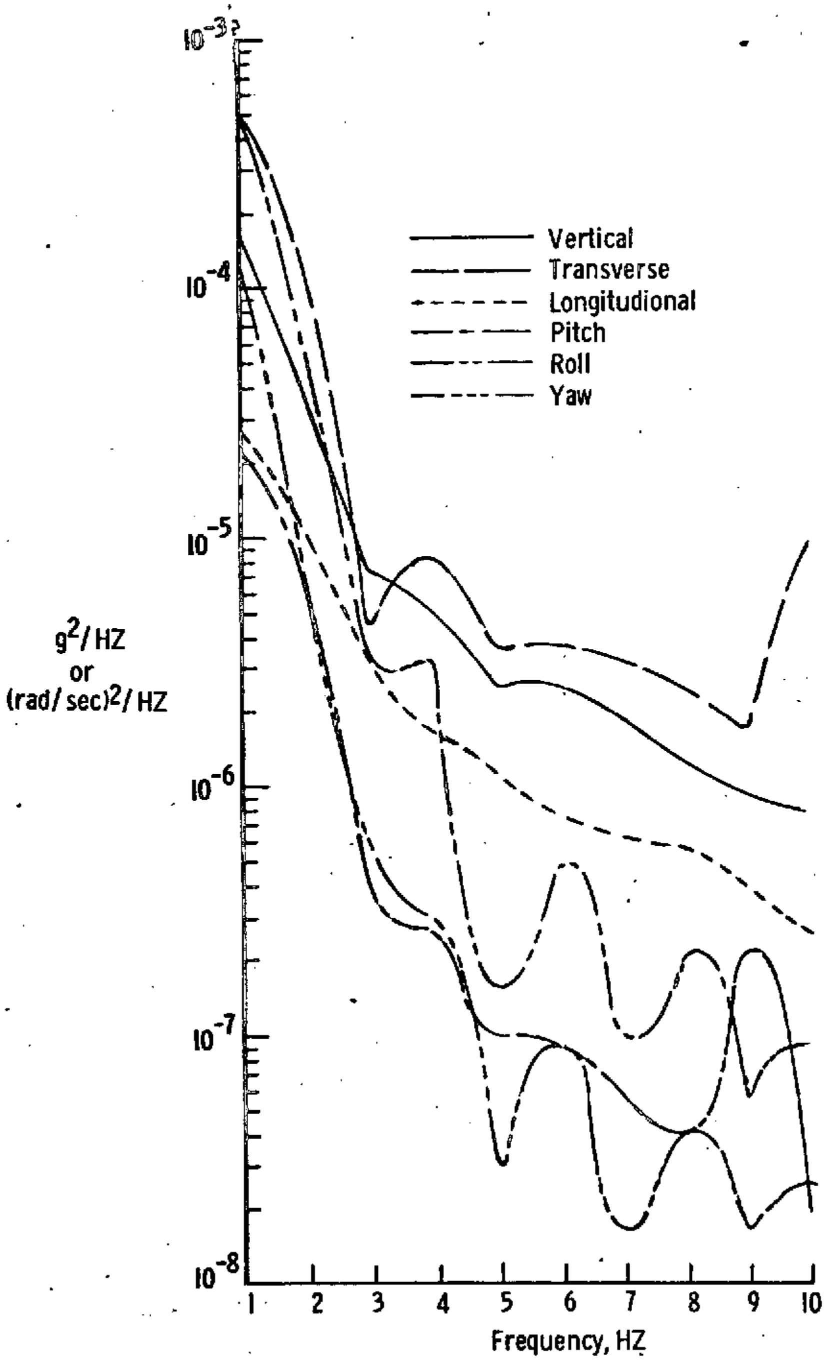


Figure 2.- A comparison of time histories of simulator motion components and motion commands to the simulator.



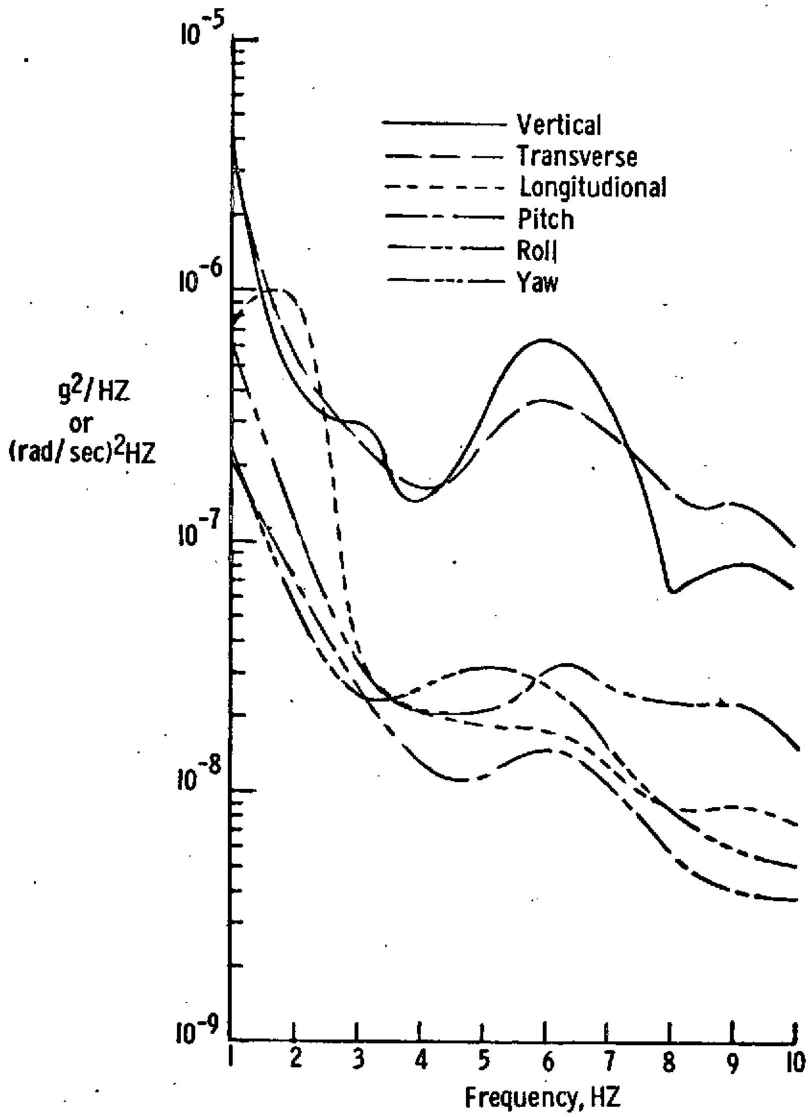
(a) Segment 1.

Figure 3.- Power spectrum of simulator motion components.



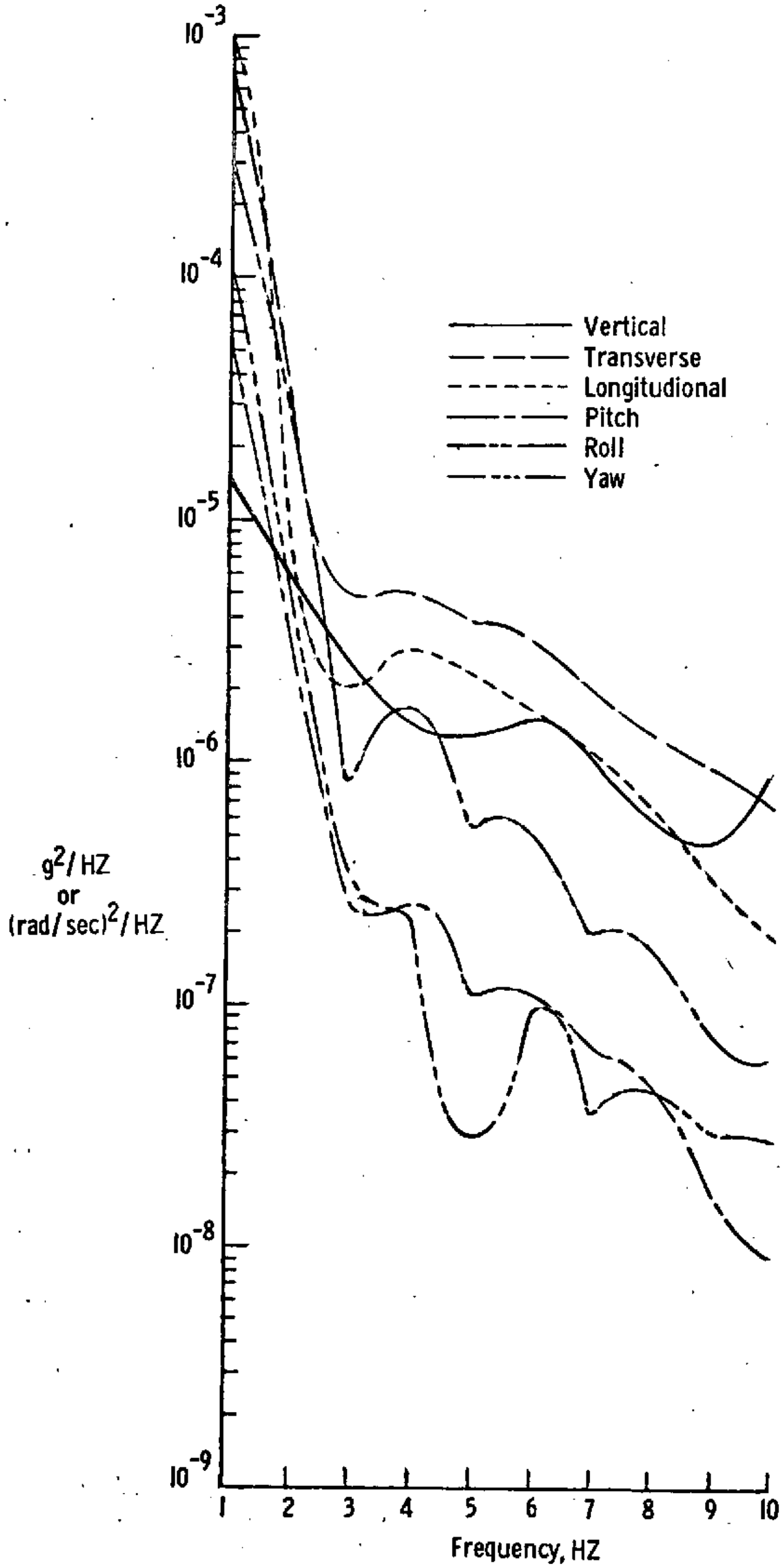
(b) Segment 2.

Figure 3.- Continued.



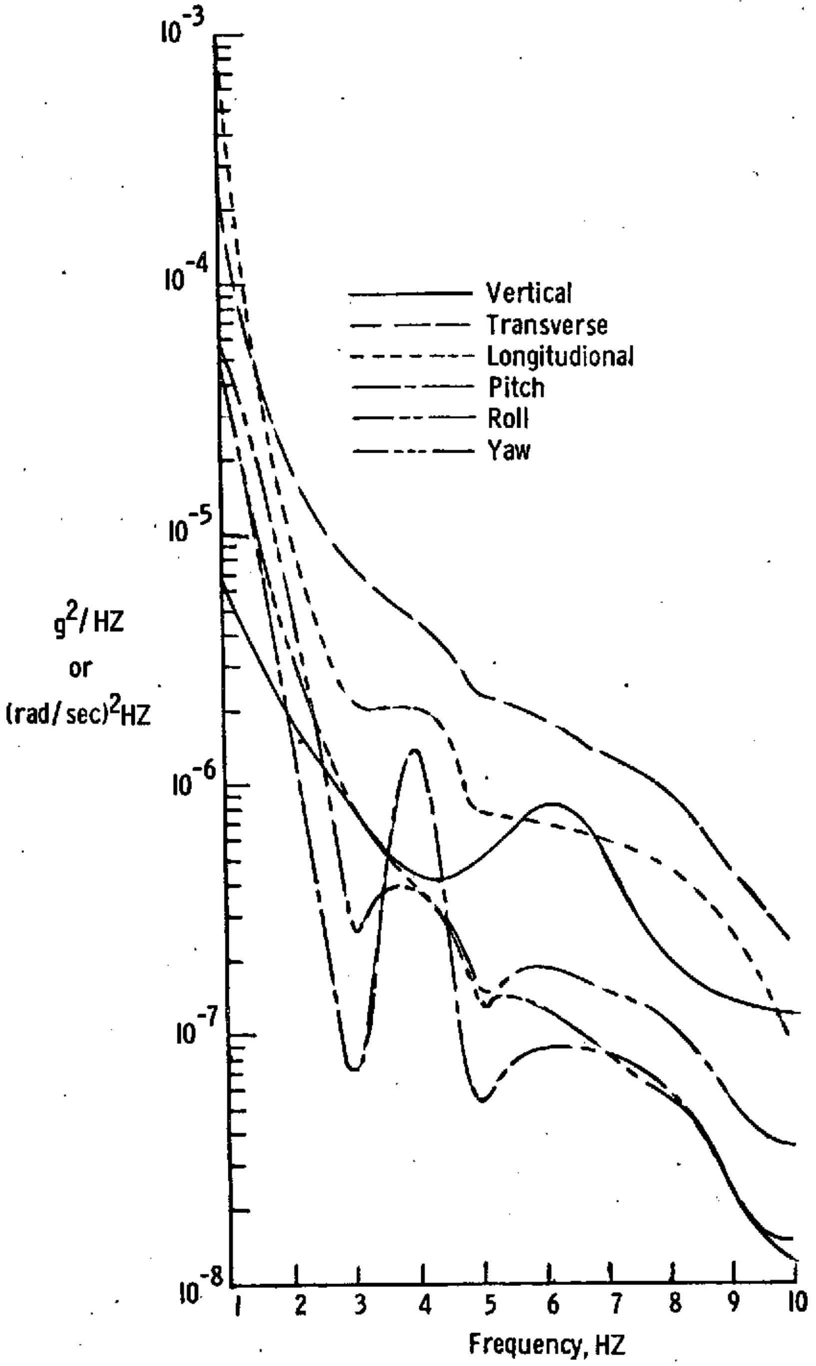
(c) Segment 3.

Figure 3.- Continued.



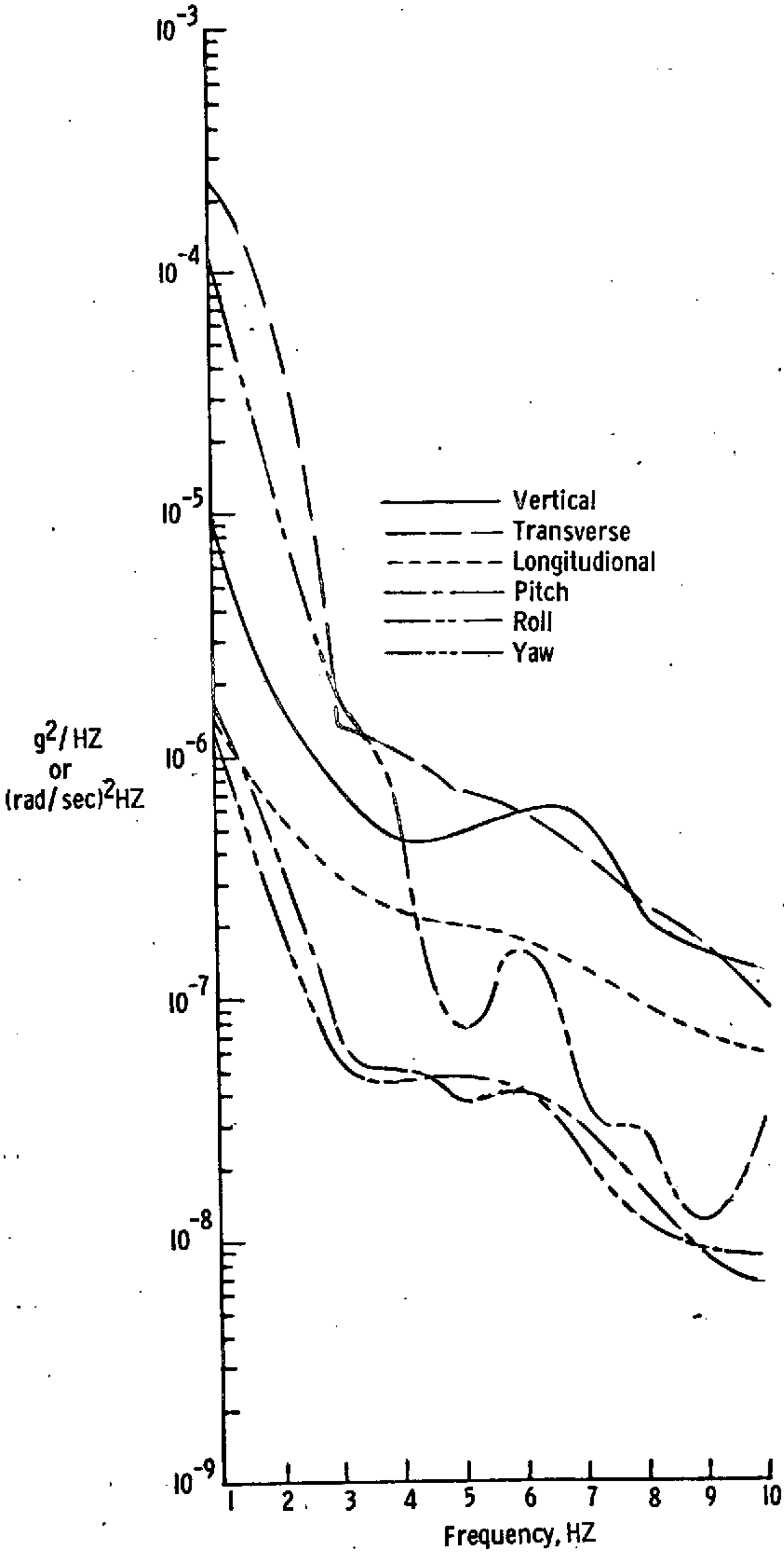
(d) Segment 4.

Figure 3.- Continued.



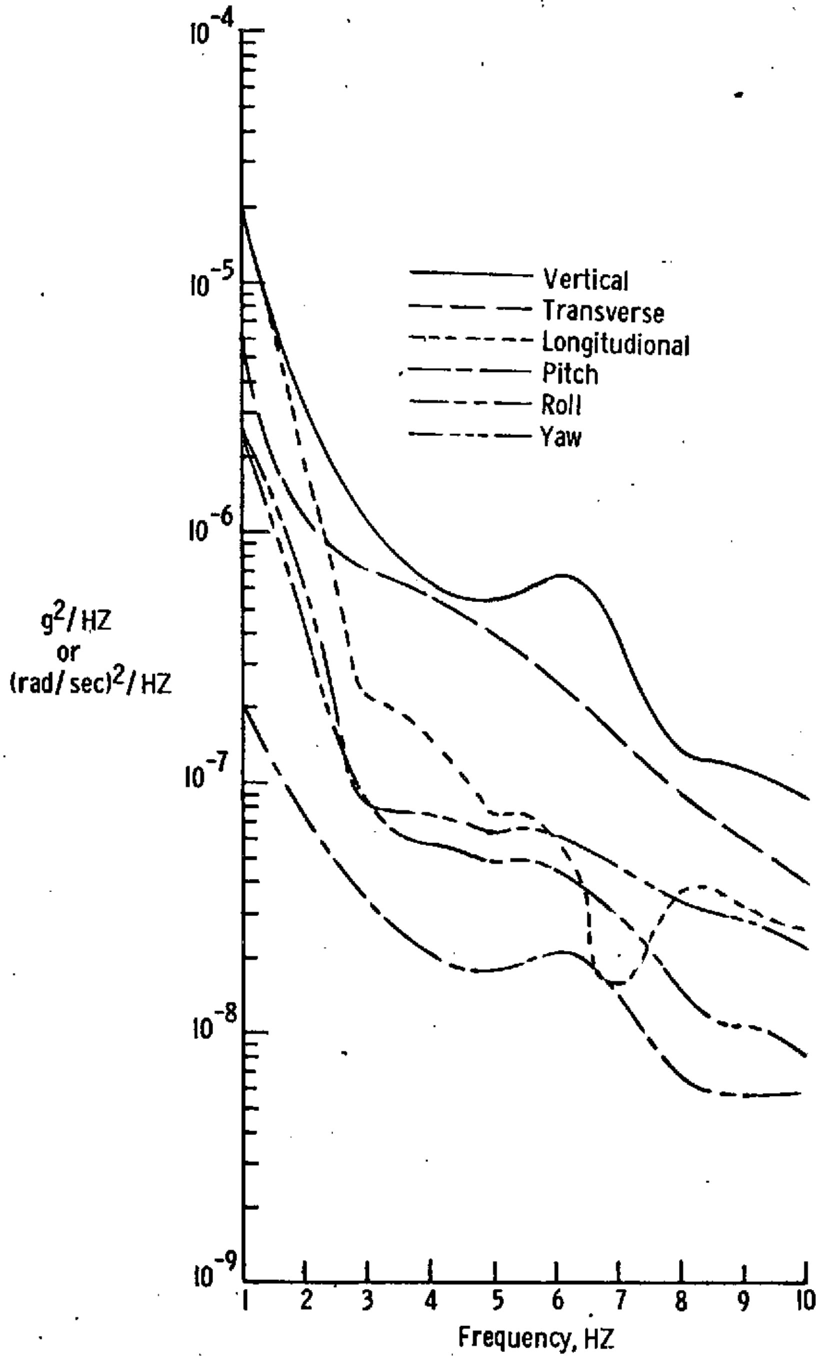
(e) Segment 5.

Figure 3.- Continued.



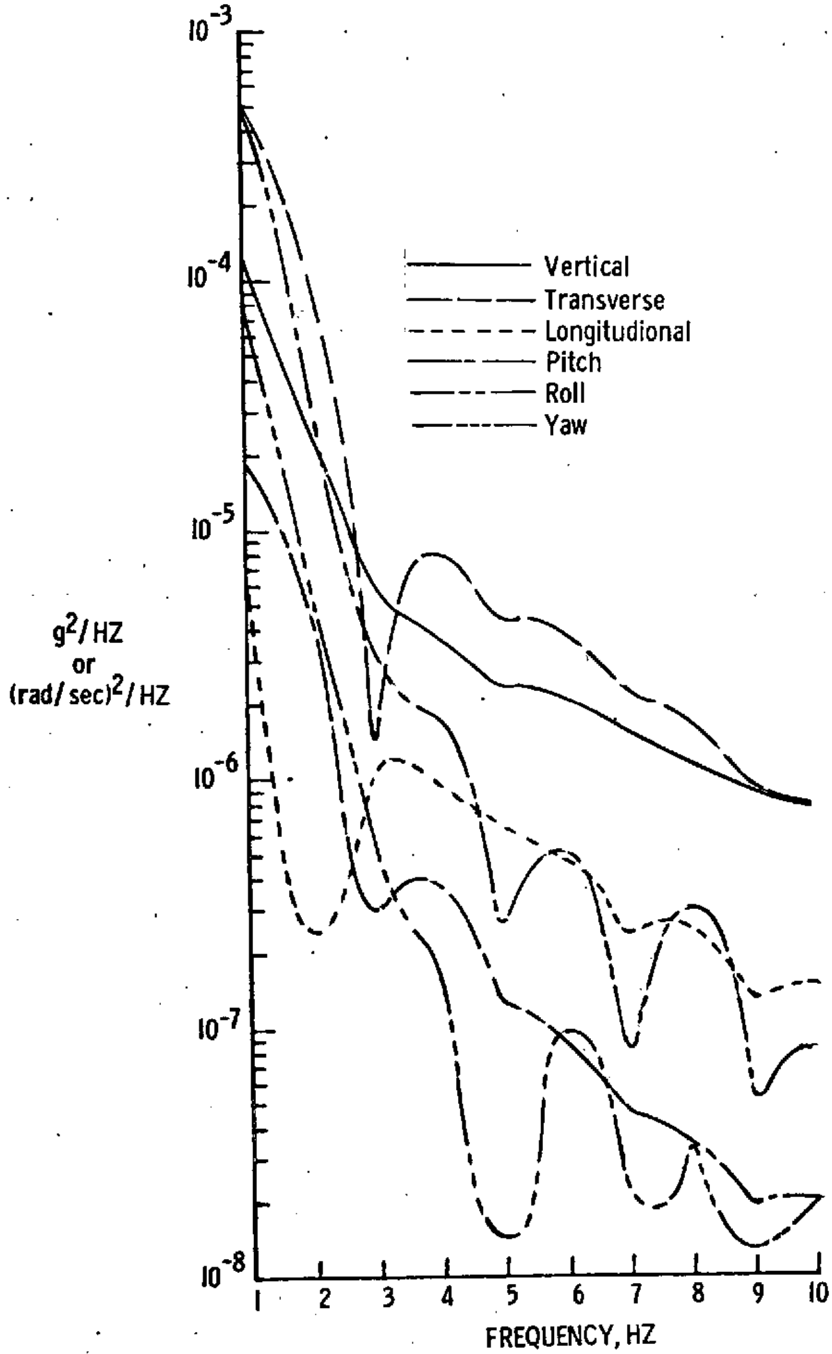
(f) Segment 6.

Figure 3.- Continued.



(g) Segment 7.

Figure 3.- Continued.



(h) Segment 8.

Figure 3.- Concluded.

Figure 4.- Interior of the Langley six-degree-of-freedom vision motion simulator.

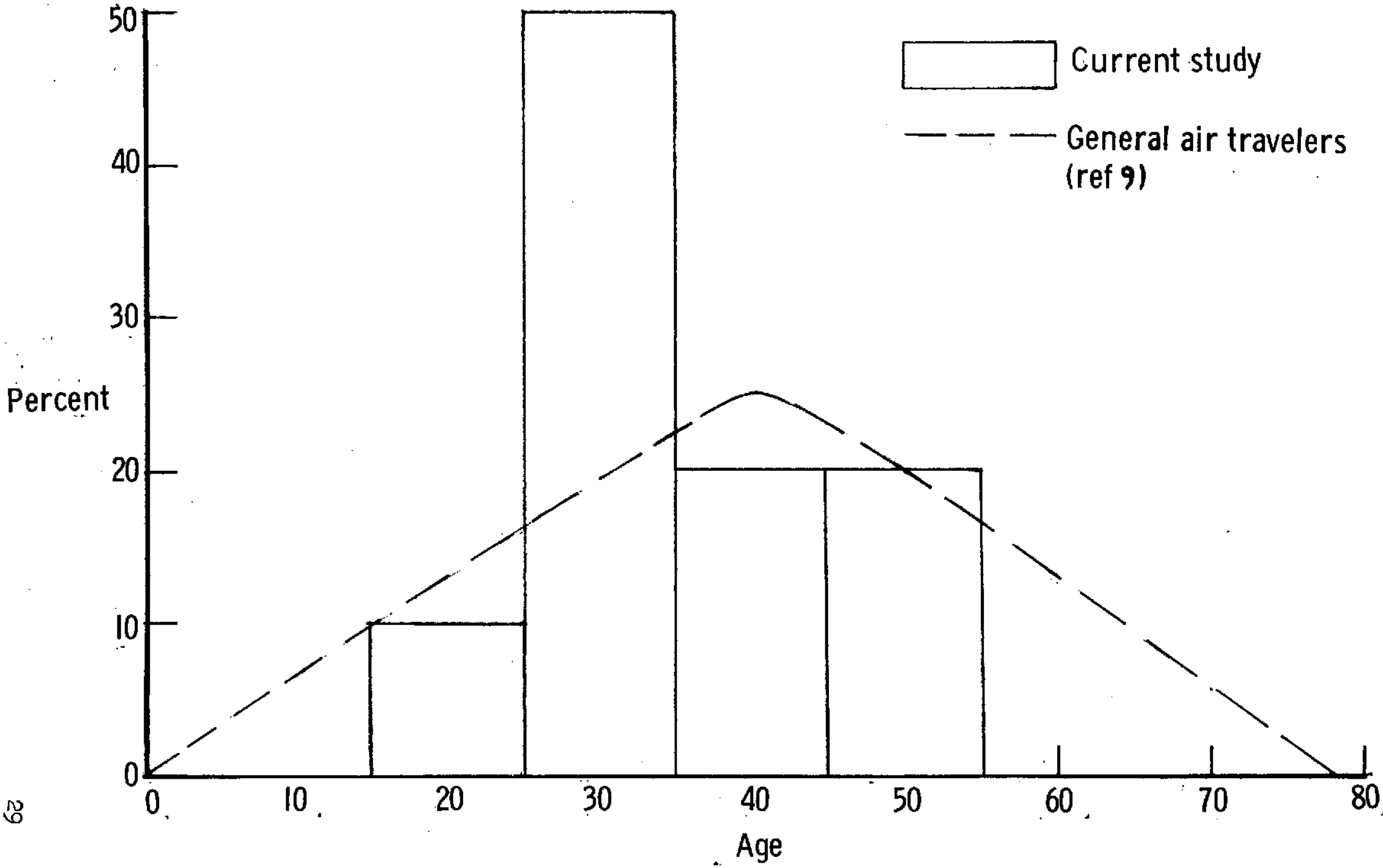


Figure 5.- Age distribution of simulator subjects.

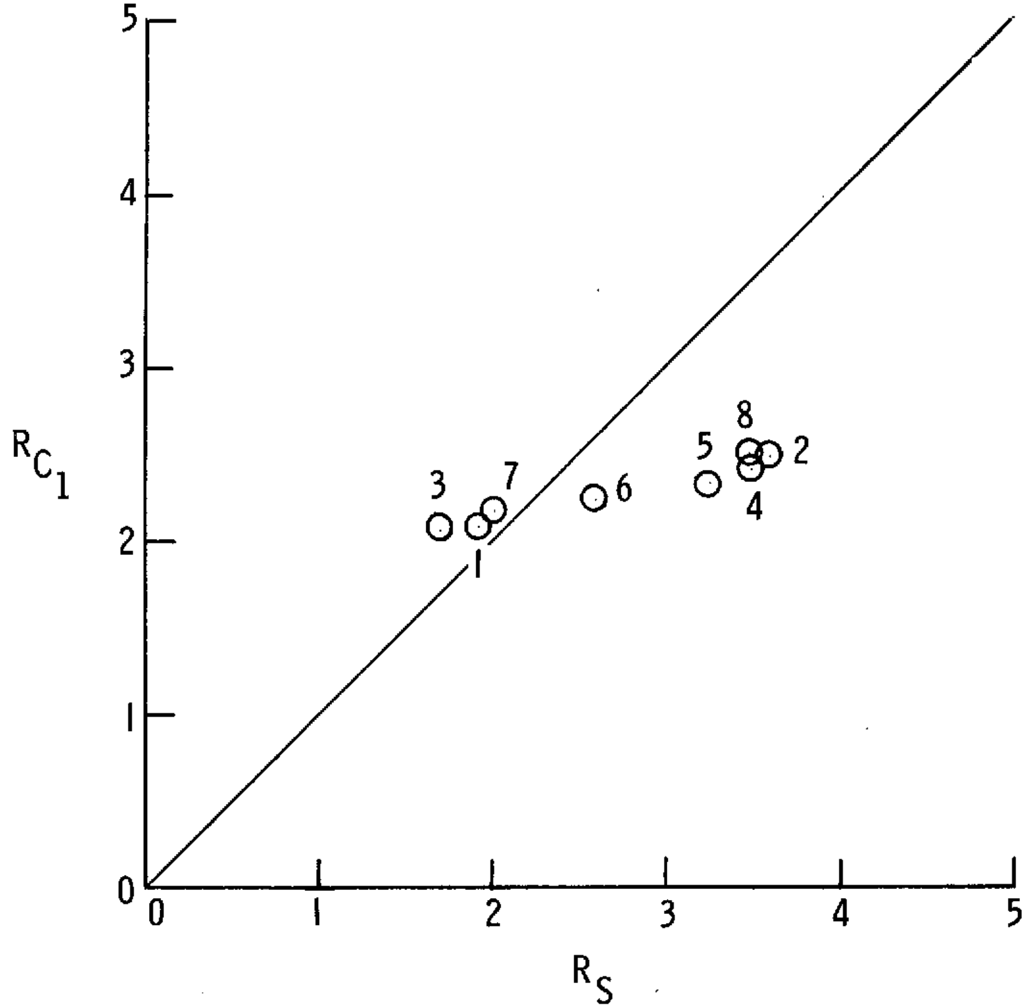


Figure 6.- A comparison of subjective ride quality response ratings and linear model calculated ride quality response ratings.

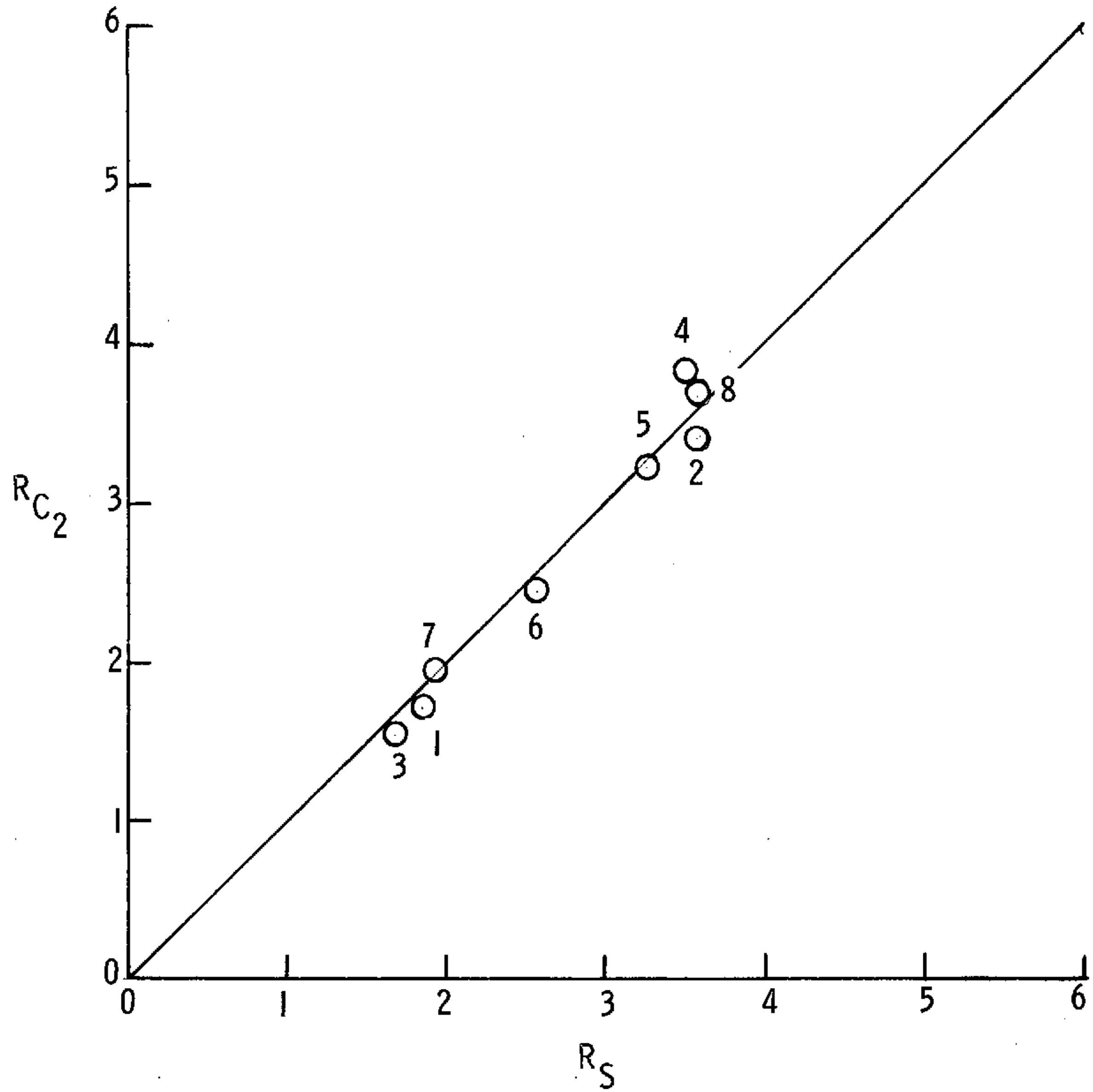


Figure 7.- A comparison of subjective ride quality response ratings and nonlinear model calculated ride quality response ratings.

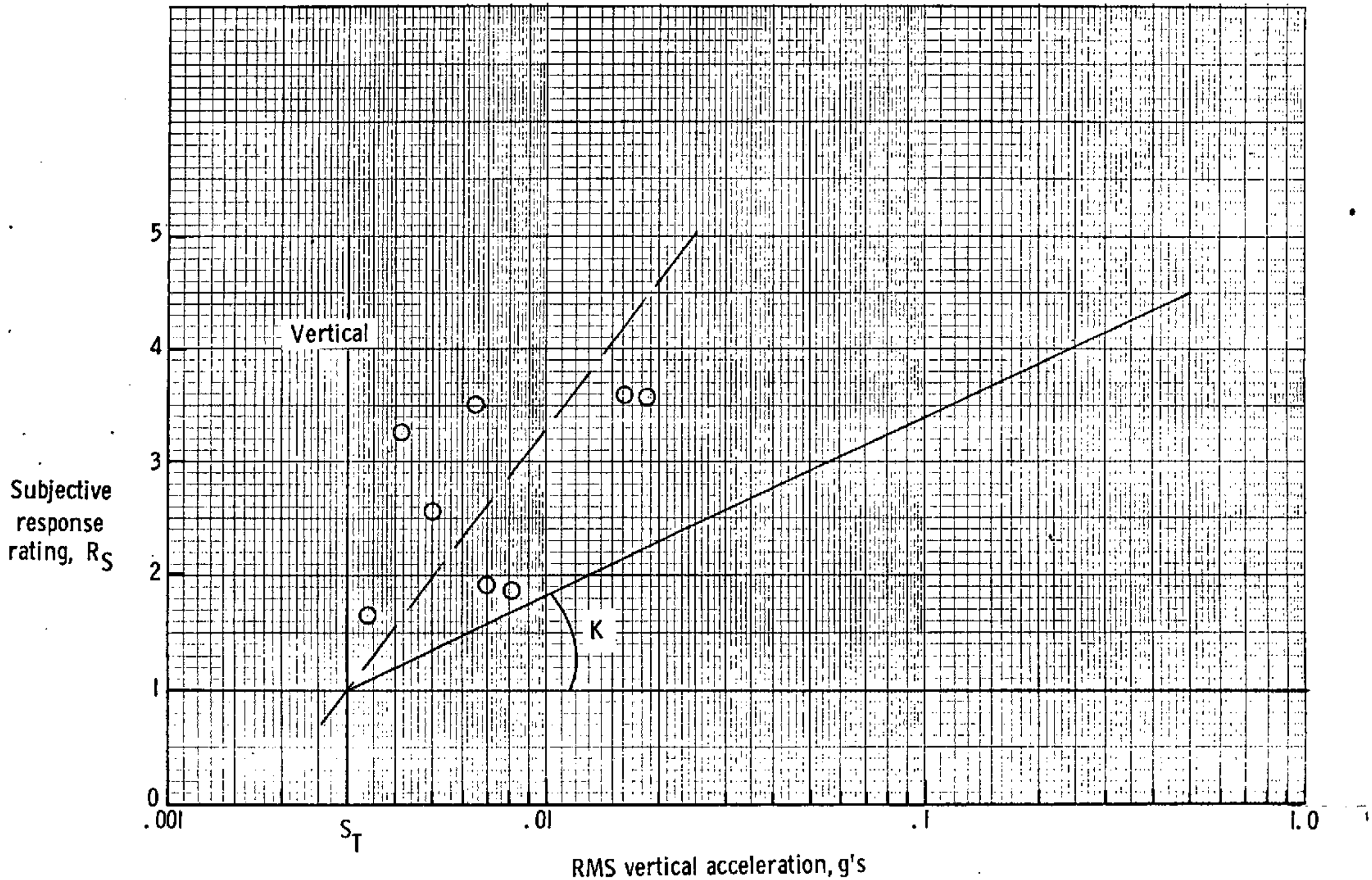


Figure 8.- The variation of subjective ride quality response ratings with the vertical acceleration stimuli of the simulator tests.