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COMBINED EFFECT OF NOISE AND VIBRATION ON PASSENGER ACCEPTANCE

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INTRODUCTION

The NASA Langley Research Center has conducted an extensive research program to develop a comprehensive model for estimating passenger comfort response to combined interior noise and vibration environments typical of existing and future transportation vehicles. This model is intended for use in the design of future vehicles and for comparative assessment/diagnosis of ride quality within current vehicles. The model has the unique capability of transforming individual components of a vehicle noise and vibration environment into subjective units and then combining the subjective units to produce a single discomfort index and other useful indices typifying passenger acceptance of the environment. Results of individual studies in the NASA research program have been reported in references 1 through 11, and the resultant model is presented in reference 12.

This paper presents a brief overview of the development of the NASA ride comfort model including the methodology employed, major elements of the model, applications, and a description of an operational portable ride quality meter that is a direct hardware/software implementation of the NASA comfort model. For additional information on the model studies, definition of the various discomfort indices, and practical use of the model the reader is referred to references 1 through 12.

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ABSTRACT

An extensive research program conducted at NASA Langley Research Center to develop a comprehensive model of passenger comfort response to combined noise and vibration environments has been completed. This model was developed for use in the prediction and/or assessment of vehicle ride quality and as a ride quality design tool. The model has the unique capability to transform individual elements of vehicle interior noise and vibration into subjective units and combining the subjective units to produce a total subjective discomfort index as well as other useful subjective indices. This paper summarizes the basic approach used in the development of the NASA ride comfort model, presents some of the more fundamental results obtained, describes several applications of the model to operational vehicles, and discusses a portable, self-contained ride quality meter system that is a direct hardware/software implementation of the NASA comfort algorithm.

BACKGROUND

The NASA ride comfort research program was a direct offspring of NASA studies involving the application of active controls to the problem of achieving acceptable rides within aircraft and surface transportation systems. In particular, the concepts of active ride smoothing for aircraft and active suspensions for advanced surface vehicles such as high speed air cushion vehicles and magnetically levitated vehicles were under investigation. During the course of that research a number of questions arose for which adequate answers were unavailable. These included: (1) how to specify acceptable levels of comfort for single and multiaxis vibration environments both with and without interior noise; (2) the nature of the relationship between passenger comfort and the levels of noise and vibration acting singly and in combination; (3) the tradeoff available between passenger comfort and level of noise and/or vibration; and (4) the format for developing and applying useful combined noise and vibration criteria. Answers to these questions were required in order to develop a valid model for estimating noise and vibration effects on passenger comfort and for the ultimate development of ride comfort criteria. Once developed such a model could be applied (see figure 1) to assess the impact of various design concepts upon passenger comfort response in new designs or prototype vehicles as well as to identify and diagnose ride comfort problems within existing vehicles.

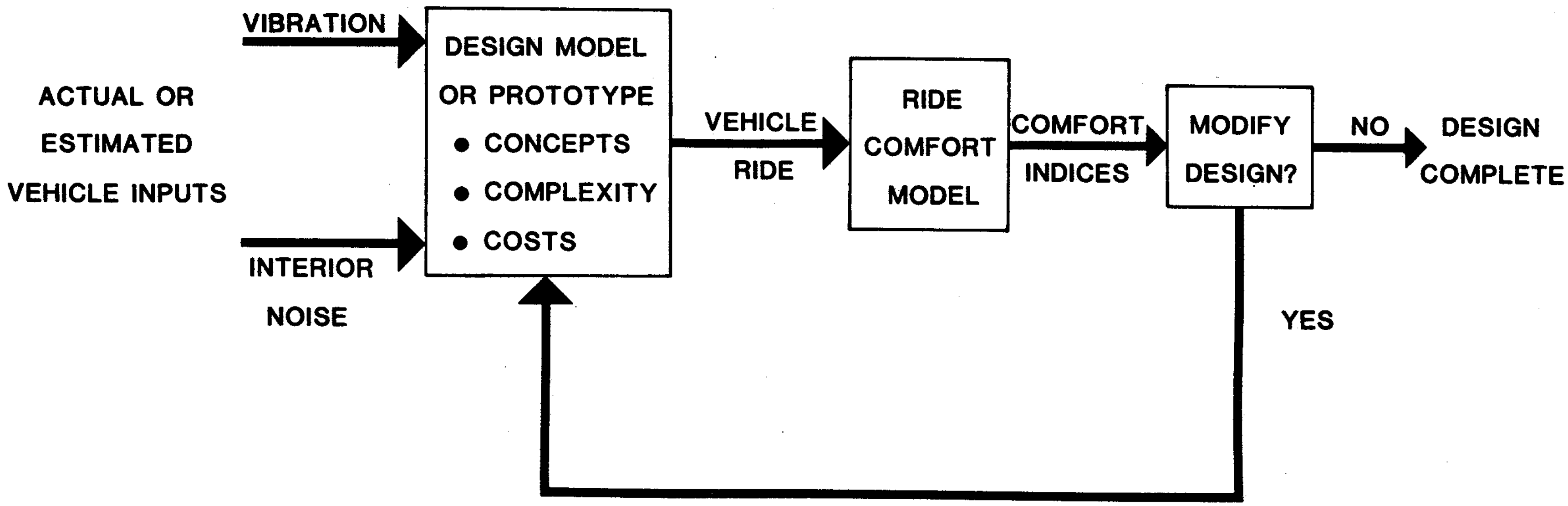


Figure 1.- Application of Ride Comfort Model.

BASIC NASA APPROACH

The approach used in developing the NASA ride comfort model involved determination of the fundamental psychophysical relationships governing human subjective comfort response to noise and vibration. Using the Langley Research Center's ride quality simulator (see next section) and experimental designs employing ratio scaling methods (magnitude estimation), human comfort responses to single and multiple axis vibration and combined noise and vibration were quantified. The key to the NASA approach involved transforming physical units of vehicle noise and vibration into subjective comfort units and then combining the subjective units according to empirically determined relationships. This process is illustrated in figure 2. It is this conversion of the individual elements of noise and vibration into subjective comfort units that permits the effects of vibration of different frequencies and in different axes to be directly summed with the effects of noise to produce various meaningful indices of passenger comfort.

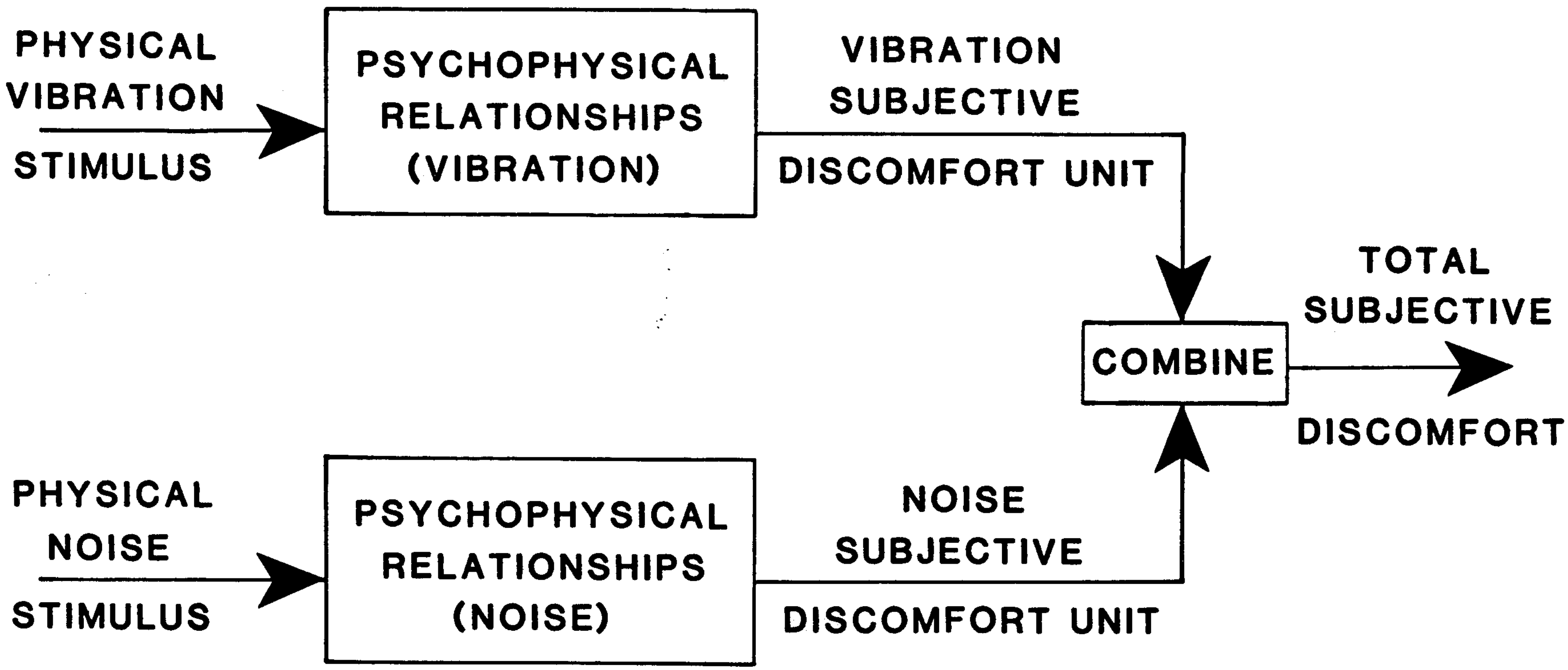


Figure 2.- NASA Ride Comfort Model Approach.

RIDE QUALITY SIMULATOR

The apparatus used in the NASA ride comfort research program was the Langley Research Center's Passenger Ride Quality Apparatus (PRQA). The PRQA is a three degree-of-freedom motion simulator capable of applying vibration (in three axes simultaneously) and noise to as many as six seated subjects. It is equipped to resemble the interior of a modern commercial jet transport aircraft. Several interior and exterior views of the PRQA are presented in figure 3. Exterior views are shown in figures 3(b) and 3(c) and interior views showing the cabin fitted with tourist class seats are shown in figures 3(f), 3(h), and 3(i). First class aircraft seats are shown in figure 3(g).

The PRQA is driven by electrohydraulic actuators located beneath the pictured floor. A view of a model of the PRQA showing simulated supports, actuators, and restraints of the three-axis drive system is given in figure 3(d). During the course of the NASA ride comfort research program on the PRQA more than 3000 test subjects were utilized. These subjects were obtained from a contractual subject pool.

Figure 3.- Passenger Ride Quality Apparatus.

METHODOLOGY CONSIDERATIONS

A number of methodology studies related to practical issues affecting the form and complexity of the ride comfort model were conducted. Several of the specific methodological issues addressed are listed in Table 1. Results of the methodology investigations indicated the following:

(1) Floor acceleration was as good an estimator of passenger comfort as seat acceleration for subjects seated in the tourist and first class aircraft seats. Thus, for purposes of comfort modelling, the more readily measured floor accelerations of a vehicle can be used as the independent variable in the predictor equations. Use of seats substantially different from those used in the NASA studies can be corrected for if required.

(2) Demographic variables such as age, sex, and weight did not have a significant practical influence upon subjective reactions. Hence, these variables were not included in the comfort model.

(3) Ratio scaling (magnitude estimation) was selected as the best approach for development of the comfort scale. The resultant scale provides absolute measures of comfort having pure ratio properties. Further, the scale is unbounded as compared to category scales and avoids problems due to "ceiling" effects, number of scale intervals, adjectives, etc. that may be encountered in category scaling.

(4) Location of seated subjects relative to the PRQA roll (or pitch) axis (which was located at or near floor level at the center of the cabin) did not significantly influence subjective comfort responses.

(5) A linear law was found most appropriate for describing the relationship between subjective comfort and vibration level whereas a power law was most appropriate for noise.

Table 1.- Methodological Issues

QUESTIONS	ANSWERS
● WHERE TO MEASURE	● MEASURE AT FLOOR
● DEMOGRAPHICS AGE, WEIGHT, SEX	● NOT IMPORTANT
● RATING SCALE	● PURE RATIO SCALE
● SEAT LOCATION (FOR ANGULAR MOTIONS)	● NOT IMPORTANT (FOR ROLL AXIS AT OR NEAR FLOOR LEVEL)
● FORM OF HUMAN RESPONSE FUNCTIONS	● LINEAR LAW—VIBRATION POWER LAW—NOISE

NOISE AND VIBRATION STIMULI

Vibration.- Comfort response to vibration was quantified for both sinusoidal and random vibrations in one or more of the five axes of interest (vertical, lateral, longitudinal, roll, and pitch). A summary of the frequency characteristics and ranges of root-mean-square acceleration levels for sinusoidal and random vibration are given in Tables 2(a) and 2(b) respectively. These ranges were selected to cover the values most likely to influence passenger comfort in surface and air transportation systems. Note that sinusoidal vibrations were applied only in the vertical, lateral, and roll axes whereas random vibrations were applied in all five axes.

Noise.- The ranges of frequency and noise levels used in the determination of subjective comfort responses to noise are given in Table 2(c). The noise stimuli consisted of individual octave bands of noise over a center frequency range of 63 to 2000 Hz and a level range of 65 to 100 dBA. Pure tone noise was not considered.

Table 2.- Summary of the Range of Noise and Vibration Stimuli used in the NASA Langley Research Center Ride Comfort Program.

(a) SINUSOIDAL VIBRATIONS

AXIS	FREQUENCY	RMS ACCELERATION LEVEL
VERT	1–30	0.04–0.34g
LAT	1–10	0.04–0.34g
ROLL	1–4	0.23–2.62 rad/s^2

(b) RANDOM VIBRATIONS

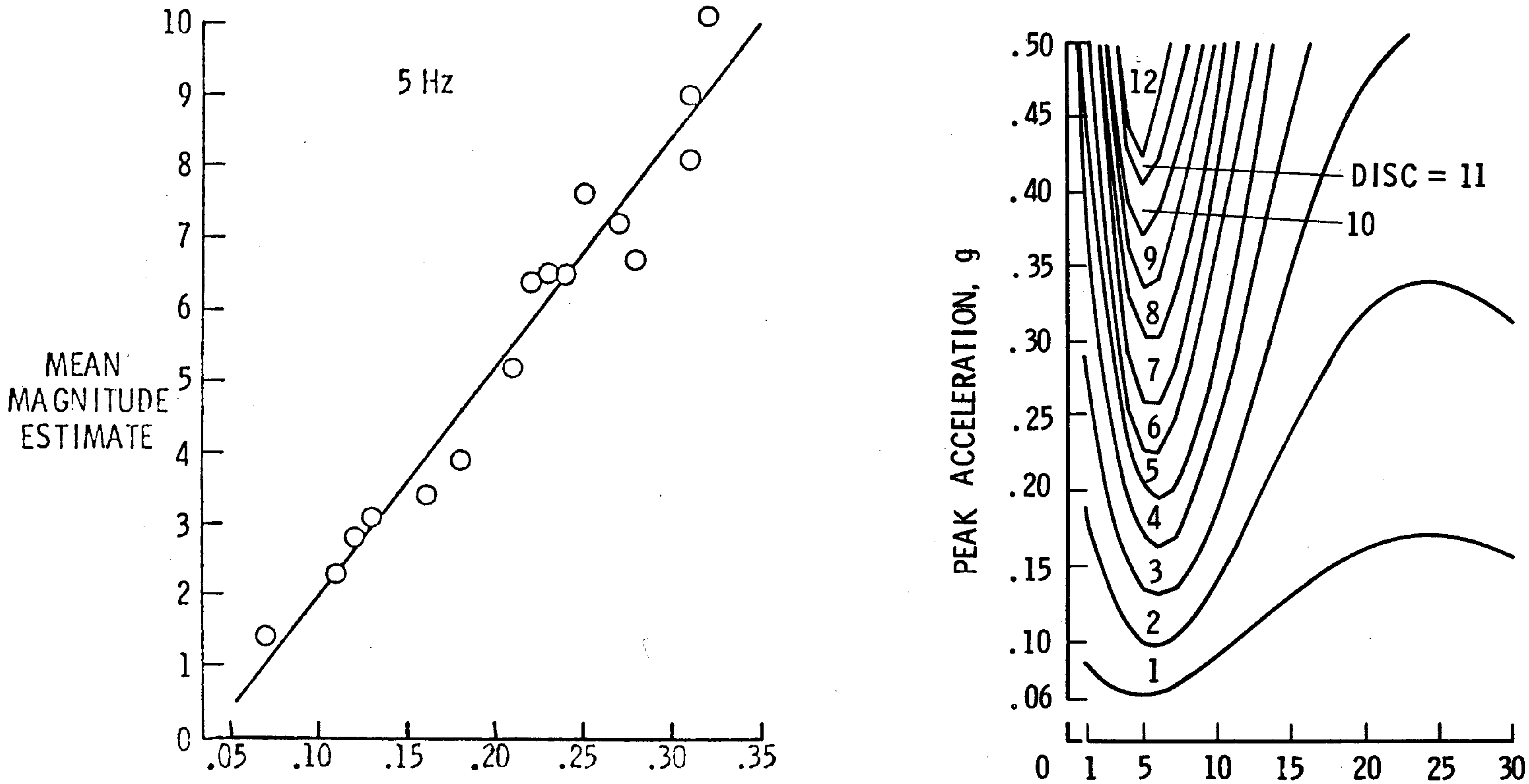
AXIS	CENTER FREQUENCY, Hz	BANDWIDTH, Hz	RMS ACCELERATION LEVEL
VERT	2-13	2-10	0.03-0.12g
LAT	2-9	2-10	0.03-0.129g
LONG	5-10	5-10	0.03-0.15g
ROLL	3	5	0.18-1.54 rad/s^2
PITCH	3	5	0.20-1.10 rad/s^2

(c) NOISE

OCTAVE FREQUENCY, Hz	A-WEIGHTED LEVEL
63	65-100dB
125	65-100dB
250	65-100dB
500	65-100dB
1000	65-100dB
2000	65-100dB

SINGLE AXIS VIBRATION RESULTS

Discomfort responses to both sinusoidal and random single axis vibrations were obtained for each of the conditions given in Tables 2(a) and 2(b). Results indicated that, for all axes and conditions, the relationship between discomfort and vibration level was linear. A typical example is presented in figure 4(a) which shows the obtained magnitude estimates of discomfort as a function of peak floor acceleration level for a sinusoidal vibration applied at a frequency of 5 Hz. Using the set of relations for all integer vertical axis frequencies from 1 to 30 Hz it was possible to develop the family of equal discomfort curves shown in figure 4(b). These curves represent acceleration/frequency contours along which subjective discomfort is constant. The numbers bear a direct ratio relationship to one another with the higher numbers representing increasing discomfort. The dip in the curves between 5 and 6 Hz reflects the influence of large body resonances. The rolloff of the curves at the higher frequencies resulted from the presence of cabin noise generated by the vibrations. (Effects of added noise is discussed in detail in a later section of this paper). Similar sets of equal discomfort curves were obtained for other axes of vibration and are presented in reference 9. Since the curves of figure 4(b) bear a direct ratio relationship to one another, the DISC = 2 curve can be interpreted as representing twice the discomfort associated with the DISC = 1 curve and one-half the discomfort of the DISC = 4 curve.



(a) Magnitude Estimates of Discomfort (Freq = 5 Hz)

(b) Vertical Equal Discomfort Curves

Figure 4.- Sample of Single Axis Vibration Results.

COMBINED FREQUENCY AND COMBINED AXIS VIBRATIONS

Most air and surface transportation vehicles produce vibrations in more than one axis and at more than one frequency within an axis. Thus, any method for estimating passenger comfort within such vehicles must account for multiple axis and multiple frequency situations. A number of different approaches to modelling these effects were considered and the following methods were recommended.

For the combined frequency situation the vibration within an axis is frequency-weighted by an experimentally derived human response weighting function applicable to that particular axis. These weighting functions represent human comfort sensitivity to vibration as a function of vibration frequency. The actual weighting functions are given in reference 12. The root-mean-square value of each weighted vibration is then determined and used to compute the discomfort due to the integrated effect of all frequencies contained within that particular vibration spectrum. The relationships used to compute discomfort due to the weighted vibration level of each axis are given in reference 12.

The approaches considered in modelling discomfort due to combined vibration in the vertical, lateral, and roll axes are listed in Table 3. The approach selected as the best is the mixed model given at the bottom of Table 3. Note that the model is written in terms of subjective discomfort units for each axis of vibration. Thus the effects of multiple frequencies within each axis are inherently accounted for prior to computation of combined axis discomfort.

Table 3.- Approaches to Combined Axis Modelling.

MODEL APPROACH	PREDICTION EQUATION
ARITHMETIC SUM	$D_{COMB} = D_{VERT} + D_{LAT} + D_{ROLL}$
MULTIPLE REGRESSION	$D_{COMB} = A_0 + A_1 D_{VERT} + A_2 D_{LAT} + A_3 D_{ROLL}$
VECTOR SUM	$D_{COMB} = \sqrt{D^2_{VERT} + D^2_{LAT} + D^2_{ROLL}}$
MIXED	$D_{COMB} = B_0 + B_1 D_C$ $D_C = \sqrt{D^2_{VERT} + D^2_{LAT} + D^2_{ROLL}}$

COMBINED NOISE AND VIBRATION

In addition to vibration many transportation vehicles contain significant levels of interior noise. Any attempt to quantify or predict passenger comfort within these vehicles must take into account the added effects of the noise. Results of the NASA ride comfort research (reference 10) indicate that subjective comfort response in a combined noise and vibration environment is due to a complex interaction between the two variables. This interaction is illustrated in figure 5 in which the additional discomfort (noise correction) due to added noise is shown as a function of the level of vibration discomfort present in the environment at several A-weighted noise levels. Defining the interaction effect in terms of subjective discomfort units for vibration and noise has the important advantage of inherently accounting for the effects of frequency as well as permitting the direct addition of the effects due to noise and vibration.

The interactive effect between noise and vibration is apparent from inspection of figure 5. For example, if vibration is present in an environment at a level sufficient to produce subjective discomfort equivalent to four subjective units, then the addition of noise having an A-weighted level of 94 dB produces approximately 1.3 additional units of subjective discomfort. However, if the vibration environment is reduced such that only one unit of vibration discomfort is produced then the same noise level (94 dBA) would introduce an additional 2.5 units of subjective discomfort. Thus the level of subjective discomfort attributable to the presence of a given noise is dependent upon the level of vibration also present in the environment. This means that knowledge of the noise and vibration levels alone is inadequate to accurately estimate passenger ride comfort. The interaction of the two variables must also be accounted for. This interaction has been incorporated in the NASA ride comfort modelling process.

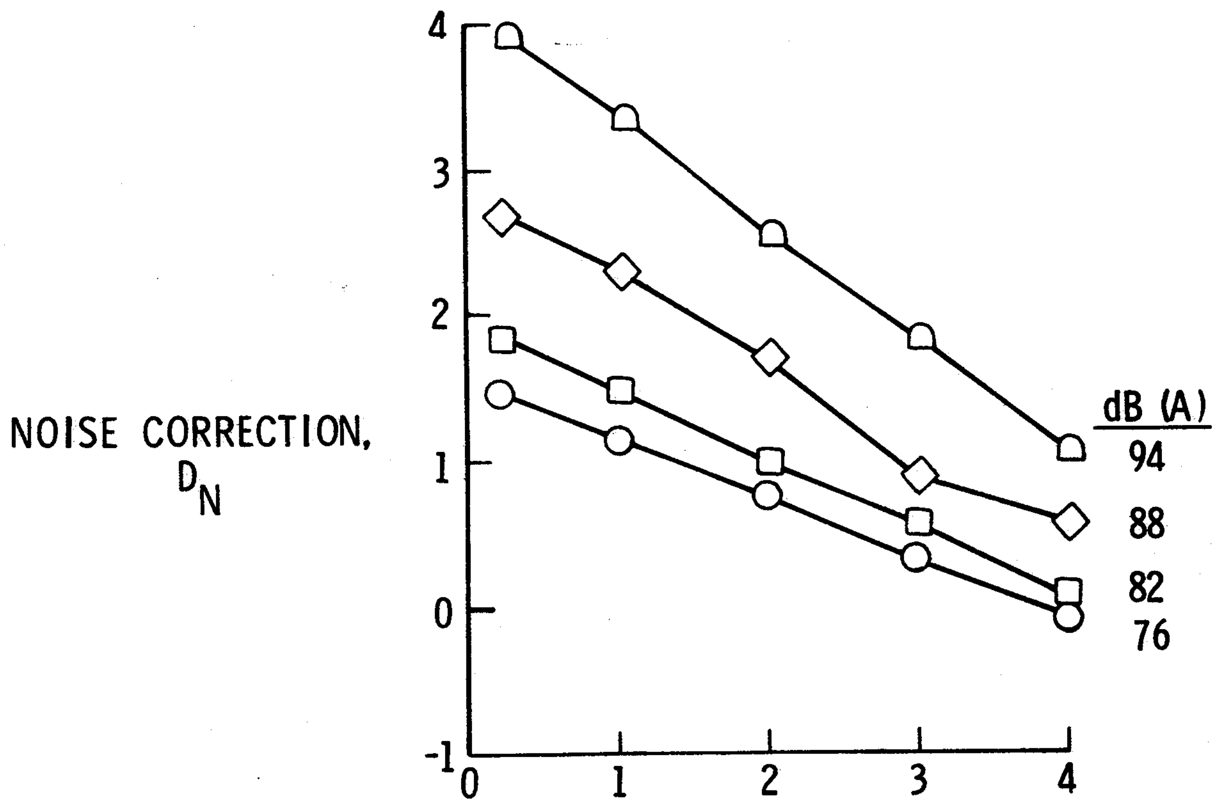


Figure 5.- Interactive Effects of Combined Noise and Vibration on Passenger Discomfort.

TOTAL RIDE COMFORT MODEL

The various results described earlier provided the basis for developing the ride comfort model shown schematically in figure 6. This model takes as input the vibration and noise characteristics of a vehicle, applies appropriate algorithms to convert the physical data into subjective discomfort units, and combines the subjective discomfort units into a single total subjective discomfort index. The total discomfort index represents a total assessment of passenger subjective comfort that reflects the combined effects of multiple frequency, multiple axis vibrations and vehicle interior noise.

A very important feature of the model is the availability of various intermediate discomfort indices for use in detailed assessments and/or diagnosis of ride comfort. For example, the total subjective discomfort index, DTOTAL, is the direct sum of the noise, DNOISE, and vibration, DVIB, discomfort components. These values represent the relative contributions of noise and vibration to total discomfort and thus identify whether the source of a ride comfort problem is vibration or noise (or both). The model further provides discomfort indices for each axis of vibration and for each of six octave bands of noise. Although not shown in figure 6, the model can also determine the discomfort contributions of individual frequencies (or frequency bands) within an axis of vibration. This model, therefore, represents a powerful new tool for the design, assessment, and diagnosis of vehicle ride comfort.

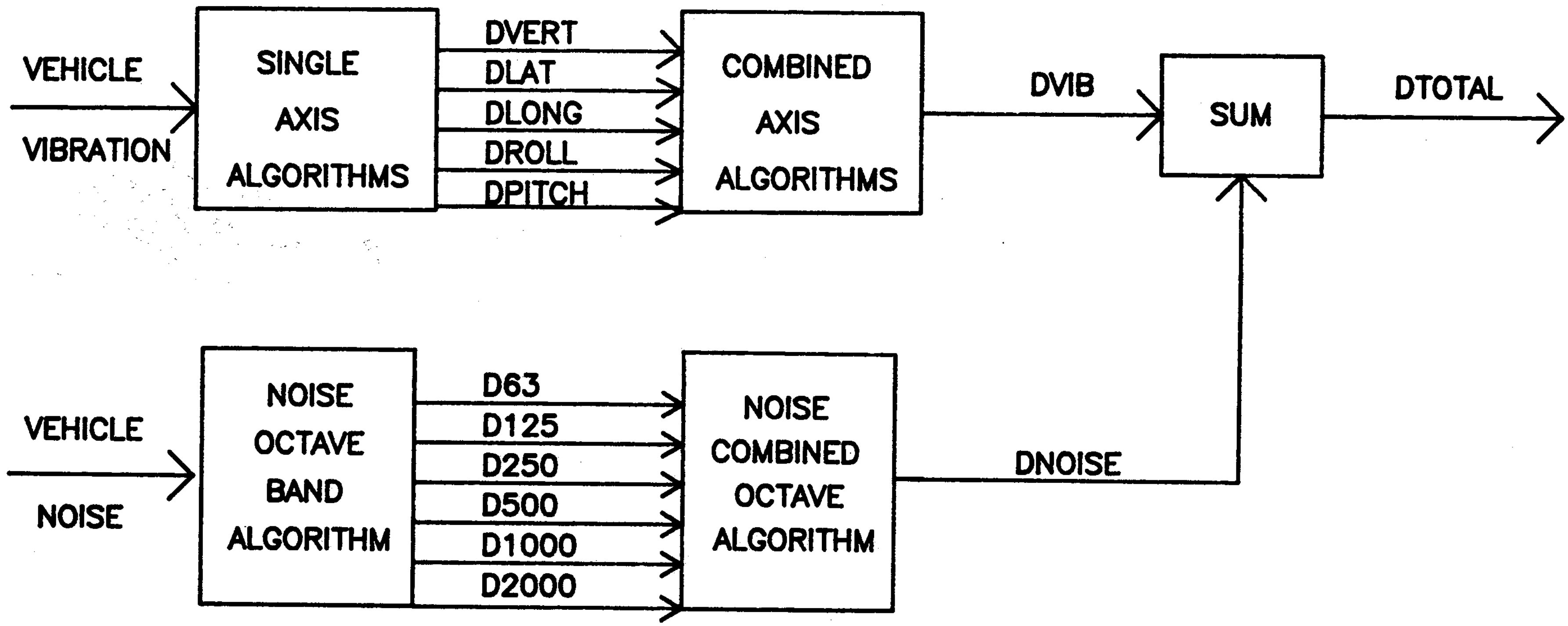


Figure 6.- Basic Elements of NASA Ride Comfort Model.

APPLICATION TO HELICOPTER ENVIRONMENTS

A study was conducted at NASA Langley Research Center (reference 13) to investigate the ability of the NASA ride comfort model to estimate comfort within helicopter environments. The study utilized a group of 35 military helicopter pilots who were exposed to simulated helicopter noise and vertical vibration on Langley Research Center's Passenger Ride Quality Apparatus. The simulated environments were obtained by playing measured helicopter environments into the PRQA. Each pilot made subjective comfort evaluations of the simulated ride environments corresponding to four military helicopters. Relative levels of interior noise and vertical vibration were systematically varied in order to provide a range of subjective responses for correlation studies.

An example of the results contained in reference 13 is presented in figure 7 which shows a comparison between obtained pilots ratings and NASA ride comfort model predictions as a function of interior A-weighted noise level and cabin vertical floor vibration level. These results indicate that the NASA total discomfort index performed well and predicted with good accuracy the discomfort due to various combinations of interior noise and vertical vibration. The reader should note that this example represents a condition in which noise is acting in combination with a single axis of vibration. The next section discusses an example of combined axis vibrations in the absence of noise.

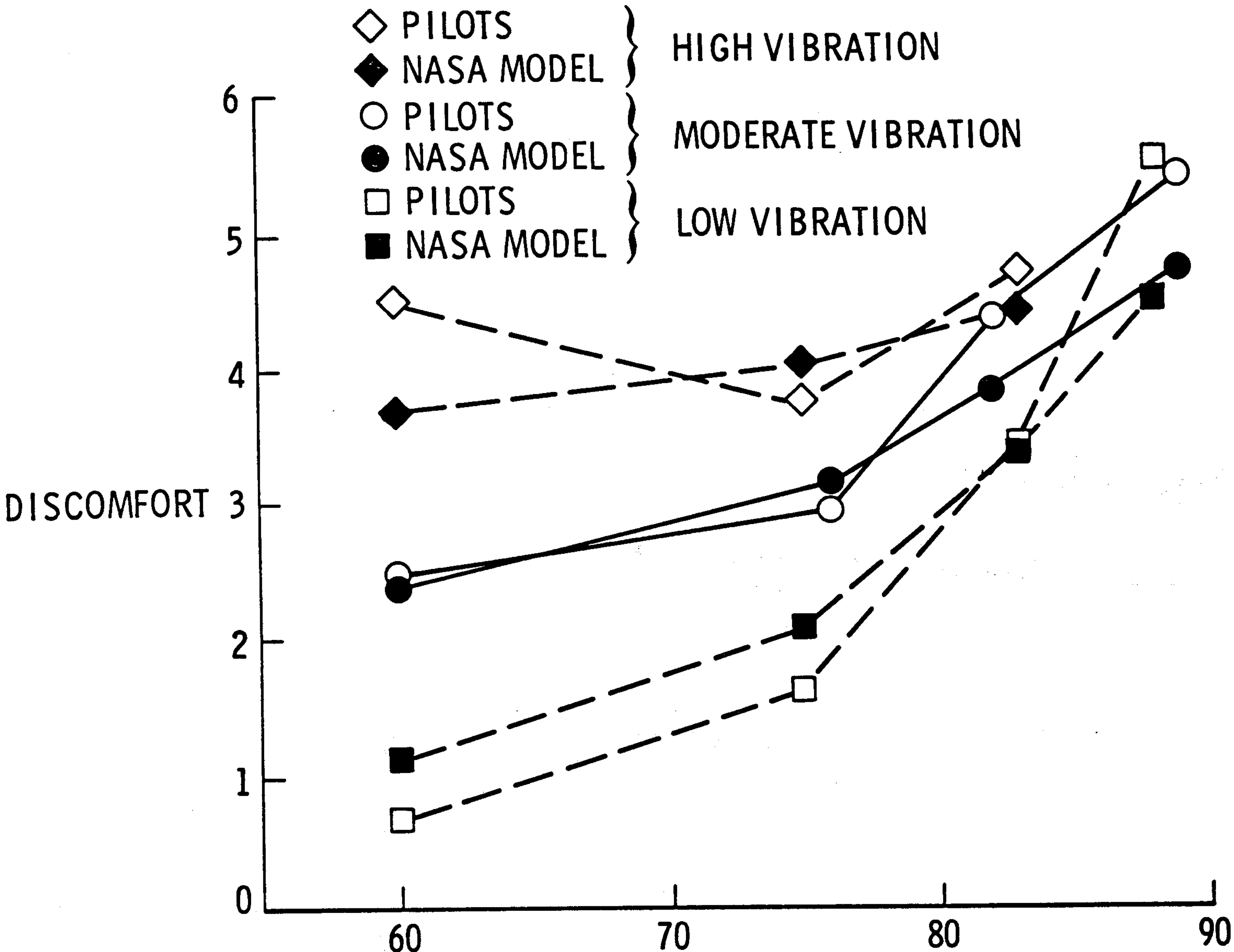


Figure 7.- Comparison of Obtained Ratings of Discomfort with NASA Ride Comfort Model Predictions for a Helicopter Environment.

APPLICATION TO AUTOMOBILE ENVIRONMENTS

An example of the applicability of the NASA ride comfort model to the prediction of passenger ride comfort within automobiles is presented in figure 8. These results were taken from a study conducted on the Passenger Ride Quality Apparatus in which subjective comfort ratings of various simulated automobile ride environments were obtained. The simulations were based upon actual vibration environments measured in several automobiles operating on a number of different road surfaces. They were directly applied as input to the simulator which reproduced each environment with very good fidelity.

A comparison of obtained ratings with NASA comfort model predictions is shown in figure 8 as a function of lateral rms acceleration (in g units). The ride environment also contained vertical and roll vibration at levels that varied from condition to condition, hence the lack of an increasing discomfort trend with increasing levels of lateral acceleration. The data shown in figure 8 correspond to simulated rides within a single automobile operating over three different road surfaces (S1, S2, S3). It is seen that the model also performed well for these combined-axis situations and generally predicted both the trends and relative levels of comfort reasonably accurately.

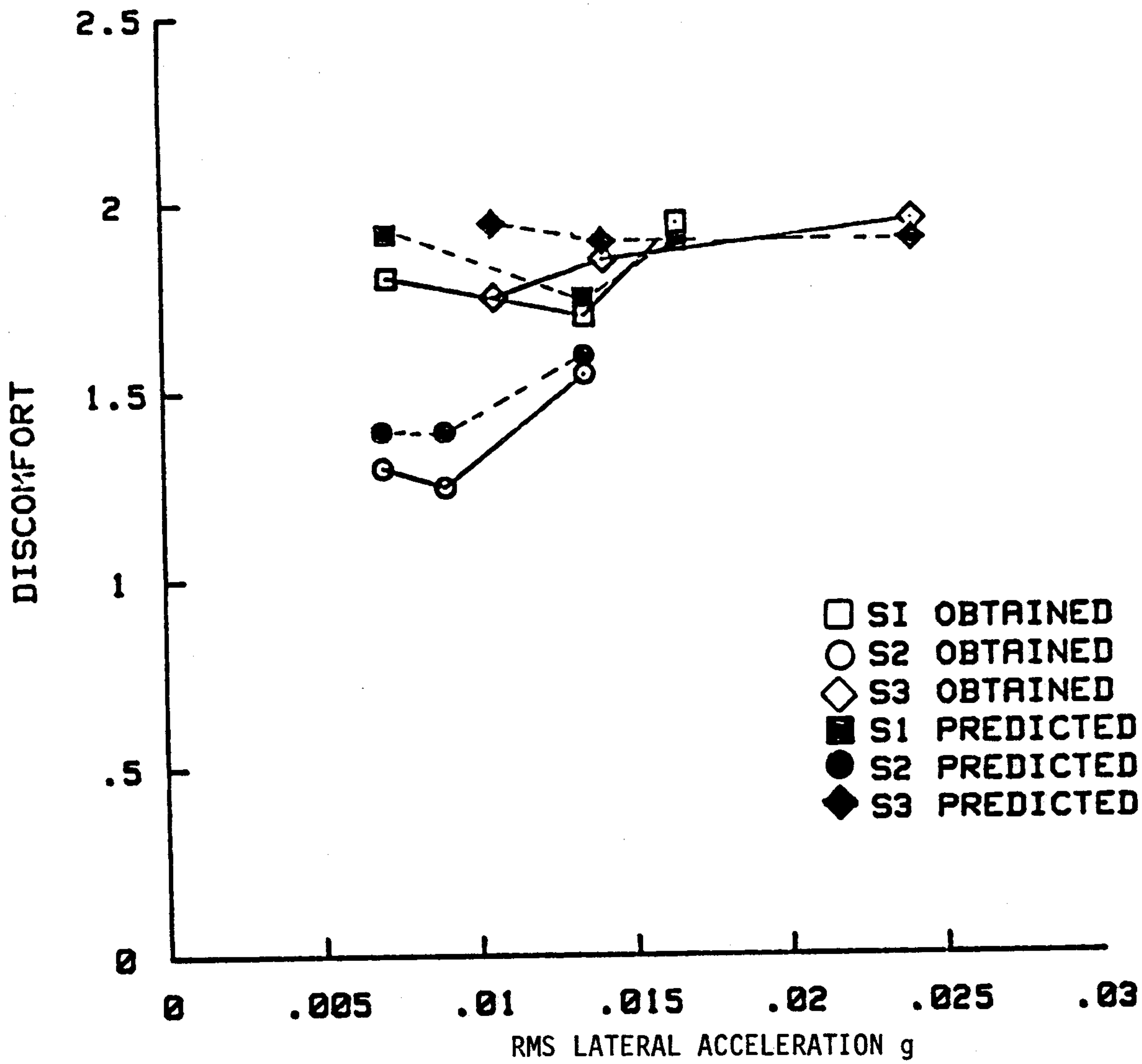


Figure 8.- Comparison of Obtained Ratings of Discomfort with NASA Ride Comfort Model Predictions for an Automobile Environment.

NOISE/VIBRATION CRITERIA

The data obtained from the helicopter ride quality study (reference 13) described earlier was used to derive approximate constant comfort criteria for the simulated helicopter environments. The data obtained were applied to a contour-generating computer program which, using best-fit least-square methods, determined values of A-weighted noise level and rms vertical floor acceleration that produce constant values of discomfort. The results are presented in figure 9, which gives the noise levels and rms floor acceleration levels that would produce constant values of percent uncomfortable. Percent uncomfortable is defined as the percent of pilots who would evaluate a given condition as uncomfortable. The data used as input to the contour-generating program were dichotomous evaluations (comfortable/uncomfortable) made by the pilots. The usefulness of these curves rests in the fact that they provide a possible format for future ride comfort criteria incorporating the effects of both noise and vibration. A set of such curves, combined with the analysis/assessment capabilities of the NASA ride comfort model would provide a powerful new approach to the evaluation and specification of vehicle ride quality.

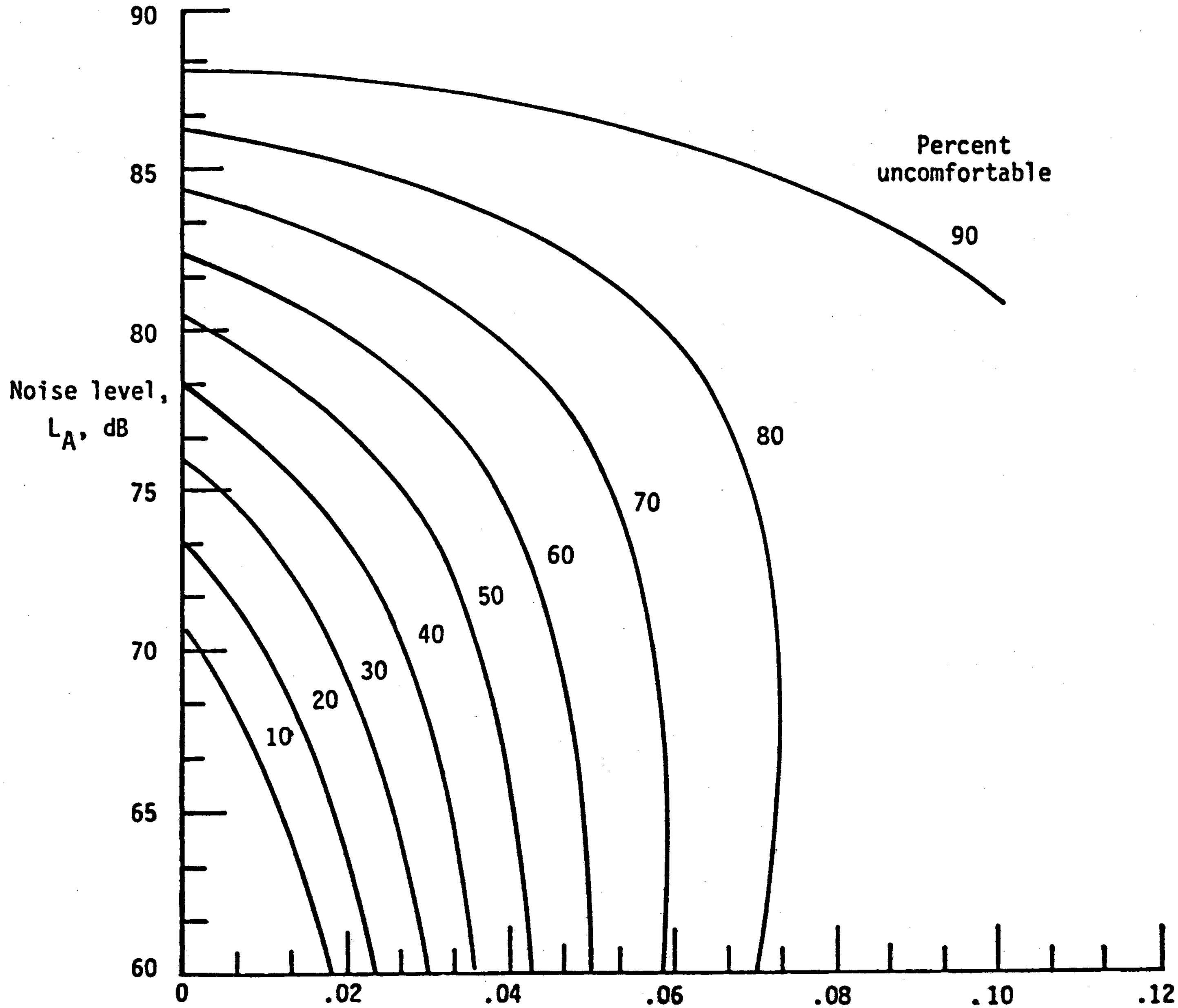


Figure 9.- Tentative Noise/Vibration Comfort Criteria for Helicopter Environments.

NASA RIDE QUALITY METER

The NASA ride comfort model was suitable for direct implementation as a portable meter system for onboard, real-time evaluation of vehicle ride comfort. Development of such a meter was undertaken by NASA Langley Research Center and produced the prototype ride quality meter system illustrated in figure 10. This figure shows the meter in a typical setup to obtain field measurements of vehicle ride quality. The meter consists of three basic components: acceleration sensor package, microphone, and central processing/display unit. As shown in figure 10 the accelerometer package is separate from the central processing unit and is placed or the floor of a vehicle to measure vibration in the vertical, lateral, longitudinal, roll, and pitch axes. The exact location at which the accelerometer package is placed is selected by the user. Similarly, the microphone can be placed at a user selected location considered as most appropriate for measuring vehicle interior noise. Signals from both the accelerometer package and microphone are fed via cables to the central processing unit which conditions and processes each one according to the NASA comfort algorithms. Meter output is provided via a printer located on the front panel of the central processing unit. Several output options are available for use in assessment of vehicle ride comfort and identification of contributing sources of passenger discomfort. These option include: total overall discomfort, vibration component of total discomfort, noise component of total discomfort, discomfort due to individual axes of vibration, discomfort due to individual octave bands of noise, and discomfort corrected for trip duration. The meter system can be operated on vehicle power (12 volt) when available or by use of rechargeable batteries.

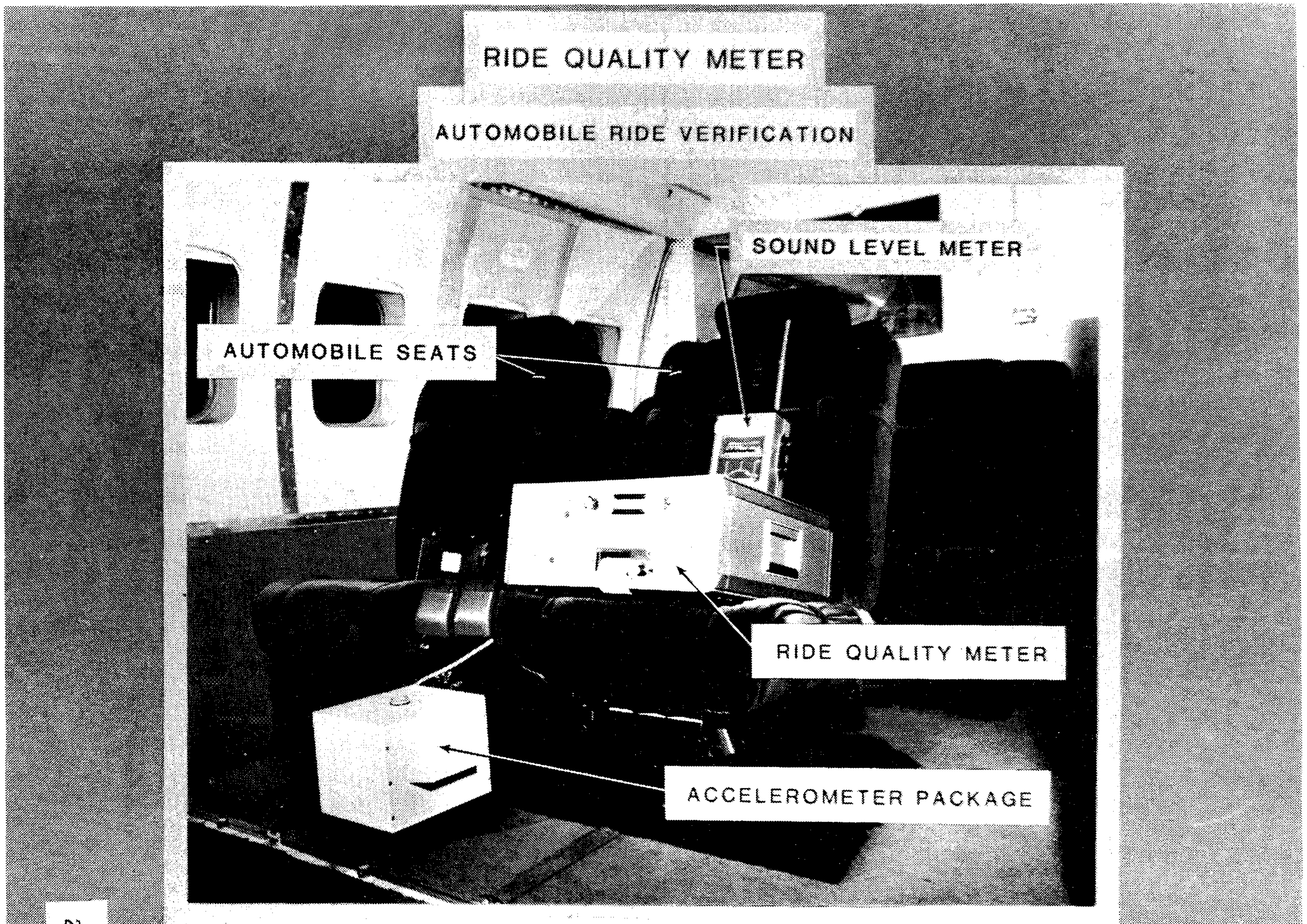


Figure 10.- NASA Ride Quality Meter shown in a Typical Field Setup.

METER APPLICATION TO HELICOPTERS

The ride comfort meter was used to obtain ride comfort measurements onboard an Emergency Medical Services (EMS) helicopter over a wide range of flight conditions. Results of these measurements in terms of measured total discomfort index, vibration discomfort index, and noise discomfort index for various flight conditions are presented in figure 11. The flight conditions are not specifically identified but ranged from ground runup and hover to cruise, descent, and landing. These results indicate that total discomfort varied between approximately 4 to 5.5 discomfort units over the range of flight conditions and represented a moderately unacceptable ride environment. The vibration and noise discomfort components that contribute to total discomfort are also shown. These indices took on values that varied above and below approximately 2.5 discomfort units. Either of these indices, taken alone, would represent comfort levels that would be marginally acceptable to a passenger. However, when acting in combination, the total environment would be rated much less acceptable. These data also show that neither noise or vibration (for this particular helicopter) was a dominant influence on total measured discomfort. Of particular importance is the capability of the meter to separate out the relative contributions of noise and vibration to the total discomfort within the environment.

EMS HELICOPTER RIDE COMFORT MEASUREMENTS

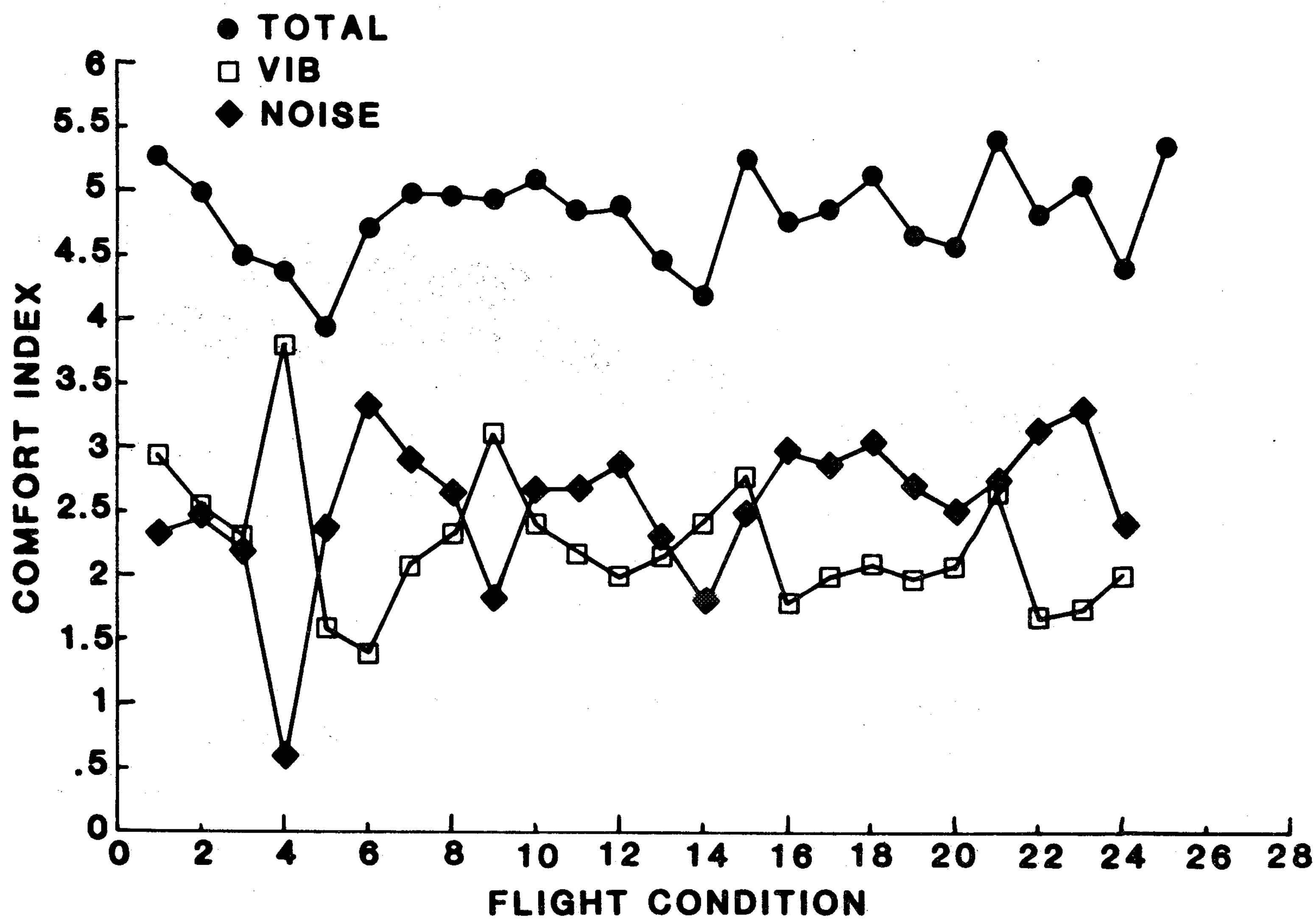


Figure 11.- Example of Ride Quality Meter Measurements of Ride Comfort within an Emergency Medical Services Helicopter.

SUMMARY

This paper has presented a brief description of the approach, methodology, results, accomplishments, and applications of the NASA ride comfort research program. This discussion indicated that passenger comfort response to noise and/or vibration has been quantified in detail and a universal comfort scale developed. Use of this scale permits direct summation of the individual effects of vibration and noise to produce a single number discomfort index characterizing passenger comfort within a ride environment. It was noted that results of the various studies were used to develop a generalized comfort model for use as a ride quality design/assessment tool. Implementation of this model as a portable, self-contained ride quality meter for operational use in the field was described. Both the model and the meter were applied to a variety of vehicles including helicopters, trains, automobiles, and trucks. In all cases the model/meter evaluations correlated highly with passenger ratings of the ride comfort.

Future research at NASA Langley Research Center will be directed towards the effects of interior noise upon passenger/crew annoyance, communications, performance, and sleep interference. This research will generally be applied to environments typical of space station, advanced turboprop aircraft, and emergency medical service helicopters.

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