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THE DEVELOPMENT OF INTERIOR NOISE AND VIBRATION CRITERIA

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THE DEVELOPMENT OF INTERIOR NOISE AND VIBRATION CRITERIA

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Abstract

The NASA Langley Research Center has completed a comprehensive research program that resulted in the development of a generalized model for estimating passenger discomfort response to combined noise and vibration. This model accounts for broadband noise and vibration spectra and multiple axes of vibration as well as the interactive effects of combined noise and vibration. The model has the unique capability of transforming individual components of a noise/ vibration environment into subjective comfort units and then combining these comfort units to produce a total index of passenger discomfort and useful sub-indices that typify passenger comfort within the environment. This paper presents an overview of the model development including the methodology employed, major elements of the model, model applications, and a brief description of a commercially available portable ride comfort meter based directly upon the model algorithms. Also discussed are potential criteria formats that account for the interactive effects of noise and vibration on human discomfort response.

Introduction

Beginning in the early 1970's, the NASA Langley Research Center initiated an extensive and comprehensive research program to develop a generalized model for estimating passenger comfort response to combined noise and vibration environments typical of existing and future air and surface transportation vehicles. This effort was prompted by the need to: (1) specify acceptable levels of vibration for single and multi-axis environments both with and without interior noise; (2) understand the nature of the relationship between the levels of noise and/or vibration and passenger comfort; (3) determine the tradeoffs between comfort and level of noise and/or vibration; and (4) provide a format for developing and applying meaningful combined noise and vibration criteria. Once completed, the model could be used in the design of future vehicles, comparative assessment/diagnosis of passenger comfort within and between vehicle types, and specification of acceptable noise and/or vibration levels within a class of vehicles. It was recognized that, to be successful, such a model must accurately account for the effects of combined noise and vibration and for the effects of broadband noise and vibration spectra and multiple axes of vibration.

The development of the NASA ride comfort model was completed in 1980. It has the unique capability of transforming individual components of a noise/vibration environment into subjective comfort units and combining these comfort units to produce a single total index of passenger discomfort and other useful indices typifying passenger acceptance of the environment. The model and program have been reported in detail by Leatherwood et al., (1980) and Leatherwood et al., (1984a).

This paper presents an overview of the model development including the methodology employed, major elements of the model, applications, and a brief description of a commercially available portable ride comfort meter that is a direct hardware/software implementation of the comfort model. Also discussed are potential criteria formats that can account for combined noise and vibration and interaction effects between these two stimuli.

Methodological Considerations

The experimental apparatus (Figure 1) used to develop the NASA ride comfort model was a three degree-of-freedom motion simulator capable of applying vibration (in up to three axes simultaneously) and noise to as many as six seated subjects. It was configured to resemble the interior of a modern jet transport and contained six aircraft tourist class seats. The simulator was a substantial improvement over systems consisting of a single vibration shaker supporting a rigid platform upon which a single hard seat was attached. The simulator was large and had the interior appearance and comfort of a real transportation vehicle. It provided a relatively quiet ambient environment (approximately 60 dBA), with the subjects insulated from the system operating noise.

The use of actual seats required consideration of the fact that the acceleration levels at the subject/seat interface differed from those at the floor by virtue of the seat transfer functions. Of particular interest was the question of which location should be used in the model and in criteria specifications. Two studies (Dempsey et al., 1975a; Dempsey et al., 1975b) indicated that no particular advantage was gained by measuring seat acceleration. Thus floor acceleration was selected as the vibration parameter for use in the modeling process. This has the additional advantage of being easily and reliably measured.

Demographic variables such as age, sex, and weight were not found to have a significant practical influence (Dempsey et al., 1975b) on subjective comfort. Hence, these variables were not included in the ride comfort model.

Magnitude estimation was selected as the best approach for development of the model 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. encountered in category scaling. This method was particularly appropriate for use in the development of the NASA ride comfort model, since it was necessary to obtain measurements of subjective comfort to the combined dimensions of noise and vibration.

Using magnitude estimation, it was determined (Leatherwood et al., 1976) that a linear law was most appropriate for describing the relationship between subjective discomfort and vibration level and a power law was most appropriate for noise (Leatherwood, 1979). Further, the contributions of individual octave bands of noise to total noise discomfort were determined by Leatherwood (1979) to summate in a manner similar to the loudness summation procedure developed by S. S. Stevens (1956).

Range of Variables

Comfort response to vibration was quantified for both sinusoidal and random vibrations in one or more of five axes (vertical, lateral, longitudinal, roll, pitch). Summaries of the frequency characteristics and ranges of root-mean-square vibration levels for the sinusoidal and random vibrations used in the model development are given in Tables 1a and 1b, respectively. These ranges were selected to cover the values most likely to influence comfort within surface and air transportation vehicles. Note that sinusoidal vibrations were applied in only the vertical, lateral, and roll axes whereas random vibrations were applied in all five axes. The ranges of noise levels and frequencies used in the model development are given in Table 1c. The noises consisted of individual octave bands covering a center frequency range of 63 to 2000 Hz and a level range of 65 to 100 dBA. Pure tone noise was not considered.

Basic Model Approach

The NASA ride comfort model was developed in a research program that utilized approximately 3000 test subjects who experienced and evaluated controlled combinations of noise and vibration within a realistic ride quality simulator. The basic approach involved determination of the psychophysical relationships governing human subjective comfort response to noise and vibration. Using the Langley simulator and experimental designs employing ratio scaling methods (magnitude estimation), human comfort responses to single- and multi-axis vibration and combined noise and vibration were quantified. The key to the NASA approach involved transforming physical units of vibration and noise into subjective comfort units and then combining these according to empirically determined relationships. This method is illustrated in Figure 2. It was this conversion of individual noise and vibration elements into subjective units that permitted the effects of vibration at different frequencies and along different axes to be directly summed with the effects of noise to produce various meaningful indices of subjective discomfort.

Description of the Model

The NASA model takes as input a vehicle's vibration and noise characteristics, applies appropriate algorithms to convert the physical data into subjective comfort units, and combines the subjective comfort units into a single total discomfort index. This index represents a total assessment of passenger subjective discomfort which reflects the combined effects of broadband vibration spectra, multiple-axis vibration, and vehicle interior noise. This process is shown in Figure 3.

An important feature of the model is the availability of various intermediate discomfort indices. For example, the total subjective discomfort index is the direct sum of the noise and vibration indices which represent the relative contributions of noise and vibration to total discomfort. Thus, these can be used to identify whether the source of a ride comfort problem is noise, vibration, or both. The model further provides discomfort indices for each vibration axis and for each of six octave bands of noise. Of particular importance is the fact that the values of noise discomfort depend upon the level of vibration discomfort present within an environment (and vice-versa). This complex interaction is accounted for within the model.

Single Axis Vibration

Discomfort responses to both sinusoidal and random single axis vibrations were obtained for each of the conditions given in Tables 1a and 1b. A typical example is presented in Figure 4 which shows the magnitude estimates of discomfort obtained as a function of peak floor acceleration level for a sinusoidal vibration applied at a frequency of 5 Hz (see Dempsey et al., 1979a). Using similar data for all integer vertical axis frequencies from 1 to 30 Hz, the family of equal discomfort curves shown in Figure 5 was developed. 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 rolloff of the curves at the higher frequencies resulted from the presence of cabin interior noise generated by the vibrations and provided an early indication of the effect of noise within the test environment. Similar sets of equal discomfort curves were obtained (Dempsey et al., 1979) for other axes of vibration.

Combined Frequency and Combined Axis Vibrations

Since most vehicles produce vibrations in more than one axis and at more than one frequency, it was necessary to account for multiple axis and multiple frequency situations. A number of different modelling approaches were considered and the methods described below were identified as best for estimating these effects.

For the multiple frequency situation, the vibration within a given axis was frequency-weighted by an experimentally derived human response weighting function applicable to that particular axis. The frequency weighting function for each axis reflected human comfort sensitivity to vibration frequency for that axis and are described by Leatherwood et al., (1984a). The root-mean-square value of each weighted vibration was then determined and used as input to the set of single axis comfort algorithms indicated in Figure 3. These algorithms are also described by Leatherwood et al., (1984a).

Subjective discomfort due to combined axis vibration was found to be best predicted by a modified vector summation of the subjective comfort units calculated for each participating axis (see Leatherwood, 1984c). Output of the combined axis algorithm is an estimate of the total subjective discomfort due to vibration within the prescribed environment. Note that use of subjective comfort units to characterize the single axis vibrations inherently accounts for the effects of vibration frequency prior to calculation of combined axis comfort. The procedures described above are illustrated schematically in the top half of Figure 3.

Combined Noise and Vibration

Results of the NASA ride comfort research (Dempsey et al., 1979b; Leatherwood, 1979) indicated that subjective comfort response in a combined noise and vibration environment was due to a complex interaction between the two variables. This interaction is illustrated in Figure 6 which shows the noise correction (in comfort units) as a function of the level of vibration discomfort (also in comfort units) for several A-weighted noise levels. Defining the interaction in terms of subjective comfort units has the important advantage of inherently accounting for multiple-frequency and multiple-axis vibration effects as well as permitting direct addition of the effects due to noise and vibration.

To assist in interpreting the interaction shown in Figure 6, it should be noted that increasing values of the subjective discomfort indices represent increasing levels of subjective discomfort. Thus the curves of Figure 6 show that the additional discomfort produced by a given, constant noise level decreases with increasing level of vibration discomfort. For example, if the vibration component of a ride environment is small, then the presence of interior noise at a level of 94 dBA would produce an increase in subjective discomfort equivalent to about 4 comfort units, and the noise would be the dominant factor in the environment. However, if the vibration component is substantial, say 4 comfort units, then the presence of the same 94 dBA noise level would add only about 1.3 comfort units and vibration would be the dominant factor. For these two cases, the total subjective discomfort would be equivalent to about 4.0 and 5.3 comfort units, respectively. This example illustrates the very important point that knowledge of both variables and their interaction effect is necessary in order to properly assess their impact on vehicle occupants.

Model Applications

One of the first applications of the NASA comfort model was the assessment of passenger/crew comfort within helicopters (Leatherwood et al., 1984b). Thirty-five military pilots experienced and rated selected combinations of helicopter interior noise and vertical vibration representative of that measured during routine flights. Their ratings were compared with comfort model estimates to determine how well the model would predict actual crew member comfort within a "real world" combined noise and vibration environment. Typical results are presented in Figure 7 which shows a comparison between pilots ratings and NASA ride comfort predictions as a function of interior A-weighted noise level and cabin vertical floor vibration level. These data indicate that the NASA total discomfort index performs well and predicts with good accuracy the discomfort due to various combinations of interior noise and vertical vibration. Note especially the interaction effect which is in complete agreement with that discussed earlier in Figure 6. 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 vibration in the absence of noise.

A second application of the model was the prediction of passenger comfort within automobiles. These results were taken from a study (unpublished) in which subjective comfort ratings of various simulated automobile ride environments were obtained. The simulations were based upon actual measurements of several automobiles operating on a number of different road surfaces. A comparison of subjective ratings with comfort model predictions is presented in Figure 8 for a single automobile operating over three different road surfaces. Discomfort in the figure is plotted against rms lateral acceleration. It is important to note, however, that both vertical and roll vibrations were present and their relative levels varied from test condition to test condition. It is seen that the model performs well for these combined-axis situations and generally predicts both the trends and relative levels of comfort reasonably well.

A third application (Stewart, 1989) of the ride comfort model was the assessment of the ride comfort of a light twin-engine airplane intended for use as a testbed for an experimental gust alleviation system. Measurements were made for all phases of flight, from takeoff to landing and in smooth to moderate turbulence. A typical example illustrating the assessment/diagnostic capability of the model in a multi-axis vibration and noise environment is presented in Figure 9 for different phases of flight in smooth air. Shown are the measured total discomfort values and the relative contributions to these values of vibration (shaded portion) and noise (unshaded portion) for several flight conditions. The three horizontal lines represent the discomfort values that were rated as uncomfortable by 50, 75, and 90 percent of helicopter pilots in the first study mentioned above. These are included as a reference to assist in interpreting the discomfort scale. The model analysis indicated that during ground operations vehicle vibration was the major source of discomfort with noise becoming a significant factor only during engine run-up. During the flight phases, however, noise was the dominant factor influencing comfort, particularly for the smooth air conditions. Both of these results are consistent with actual experiences with this aircraft.

Combined Noise and Vibration Criteria Considerations

Because of the strong interaction effects, it is difficult to develop criteria in terms of simple "limit" curves except for special cases. For example, the data in the helicopter ride comfort study (Leatherwood, 1984b) described earlier was used to derive approximate constant comfort criteria for the simulated helicopter interior environment. Recall that those ride environments consisted of noise and vertical vibration. The subjective responses of the military pilot group 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 produced constant values of discomfort. The results are presented in Figure 10 which gives the noise levels and rms floor acceleration levels that produced constant values of percent uncomfortable. Percent uncomfortable was 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 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 possible new approach to the evaluation and specification of ride comfort. The criteria approach described above could be generalized by developing the constant comfort curves in terms of vibration and noise discomfort units instead of physical units. This would be required for complex environments containing noise and multi-axis vibrations. However, actual definition of constant comfort boundaries in terms of a discomfort unit reference frame may depend somewhat upon the class of vehicle (e.g. aircraft, trains, trucks, etc.) under consideration. This would result from factors unrelated to the actual noise and vibrations such as passenger expectations, fear/anxiety, physical environment, and other variables (such as temperature and humidity). Thus it may be necessary, for a given class of vehicles, to "calibrate" the set of constant comfort curves using subjective judgements (uncomfortable/ comfortable) obtained from a small representative sample of vehicle passengers and/or operators. These judgements could then be used to assign a critiera measure, such as "Percent Uncomfortable" to the subjective discomfort units to develop a criteria format such as the constant comfort lines illustrated in Figure 11. Since the data in hand at present is inadequate for such development, this refinement must remain a topic for future research. In this case, the physical noise and vibration components of an environment would be processed through the ride comfort model to transform the physical units into noise and vibration subjective discomfort units. These subjective unit pairs could then be located relative to the constant comfort contours of Figure 11 to determine if they fall within specified constant comfort boundaries. In the event a criteria specification is exceeded, the intermediate discomfort indices developed within the ride comfort model could be used to determine the particular components (for example, noise octave band, vibration axis, frequency) that are the source of the problem.

Ride Comfort Meter

The NASA ride comfort model has been implemented in the form of a commercially available ride quality meter. The meter is shown in Figure 12 and described in detail by Wood et al., 1985. It is a portable unit which provides real time estimates of passenger comfort during actual vehicle operations, based on measurement of the interior noise and vibration environment. Vibration is measured in five axes (vertical, lateral, longitudinal, pitch, and roll) using a small external accelerometer package. The accelerometer package is intended for mounting on a vehicle floor, usually under a seat. Acoustic data are obtained using a commercial sound level meter or external microphone located at head level. Comfort data in terms of the total discomfort index and various intermediate indices are displayed continuously via an internal printer or stored on magnetic media for future analysis. In addition, the overall and octave-band A-weighted noise levels and frequency-weighted vibration levels within each axis of vibration are also output. This meter was used to obtain the comfort data during the NASA light aircraft ride quality study described earlier and has been used to measure ride comfort on helicopters and in surface effect ships. Also a number of meters are currently being used by members of the truck, tire, and automotive industries.

Concluding Remarks

An extensive research program at NASA Langley Research Center resulted in development of a comprehensive model for estimating passenger discomfort due to combined noise and vibration environments typical of surface and air transportation systems. Discomfort estimates (model outputs) are in the form of discomfort indices measured along a ratio scale anchored at discomfort threshold. Thus the discomfort indices are measured in terms of subjective comfort units.

The model has several important features that distinguish it from other models. First, the modeling is based upon empirically derived psychophysical functions relating human comfort response to the levels of the physical stimuli that produce the response. Thus, discomfort is modeled as a continuous function of the stimulus parameters. Secondly, the model is sensitive to changes in individual stimulus parameters such as vibration frequency, vibration acceleration level, noise octave band frequency, and noise level. Hence it is very useful for making ride comfort design tradeoffs and as a tool for comparative assessment of ride comfort. In addition, the model applies to multiple frequency and multiple axis vibrations and to either single or contiguous octave band noise spectra.

The model has been applied to a variety of vehicles (helicopters, automobiles, trucks, surface effect ships, aircraft) and has been validated within these environments. It may be particularly applicable to the development of combined noise and vibration comfort criteria since it accounts for, and is based upon, the interaction effects between noise and vibration. Specification of criteria in terms of noise and vibration discomfort units will permit development of a generalized criteria applicable to arbitrary ride environments containing physical noise and vibration components within the range of the NASA comfort model.

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Table 1. Range of noise and vibration stimuli used in development of NASA ride comfort model.

(a) Sinusoidal vibrations

Axis	Frequency, Hz	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

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Fig. 1. NASA passenger ride quality simulator

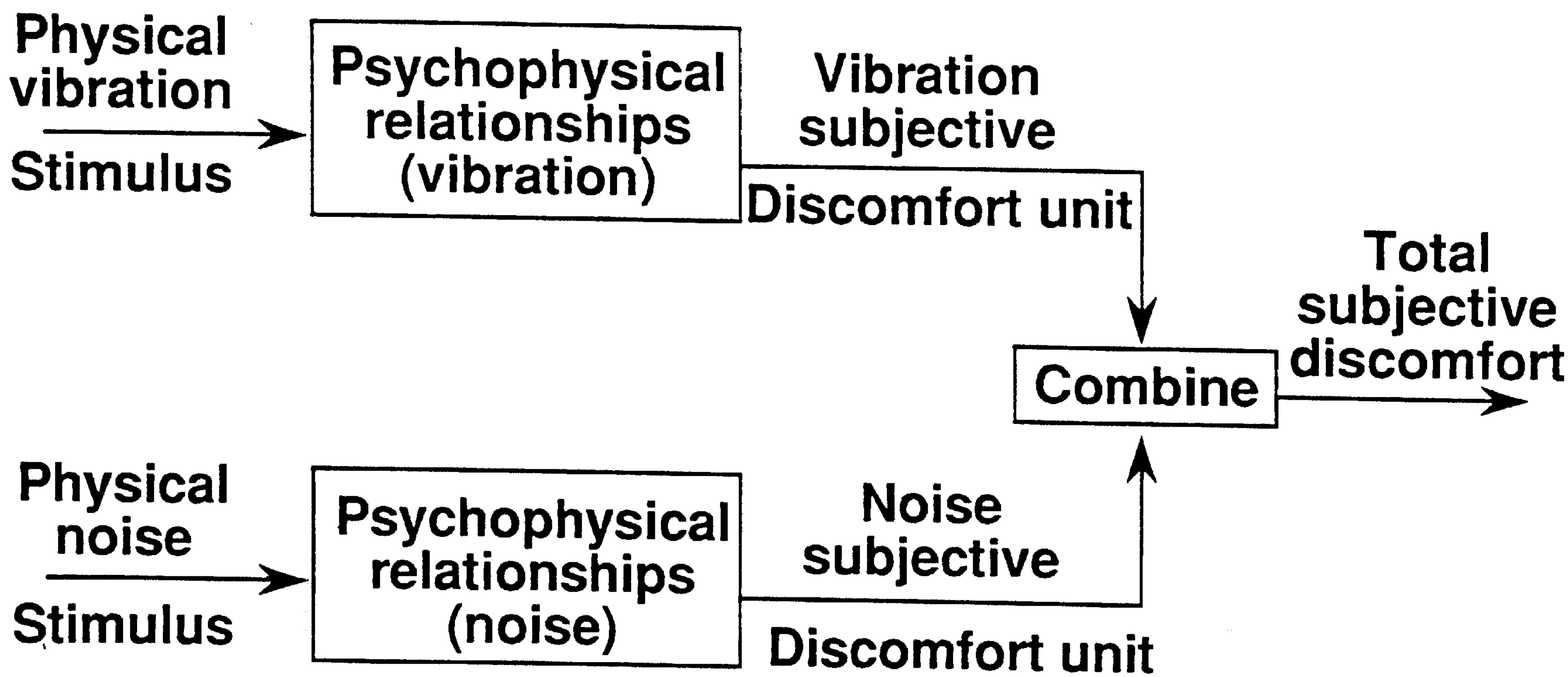

Fig. 2. NASA ride comfort model

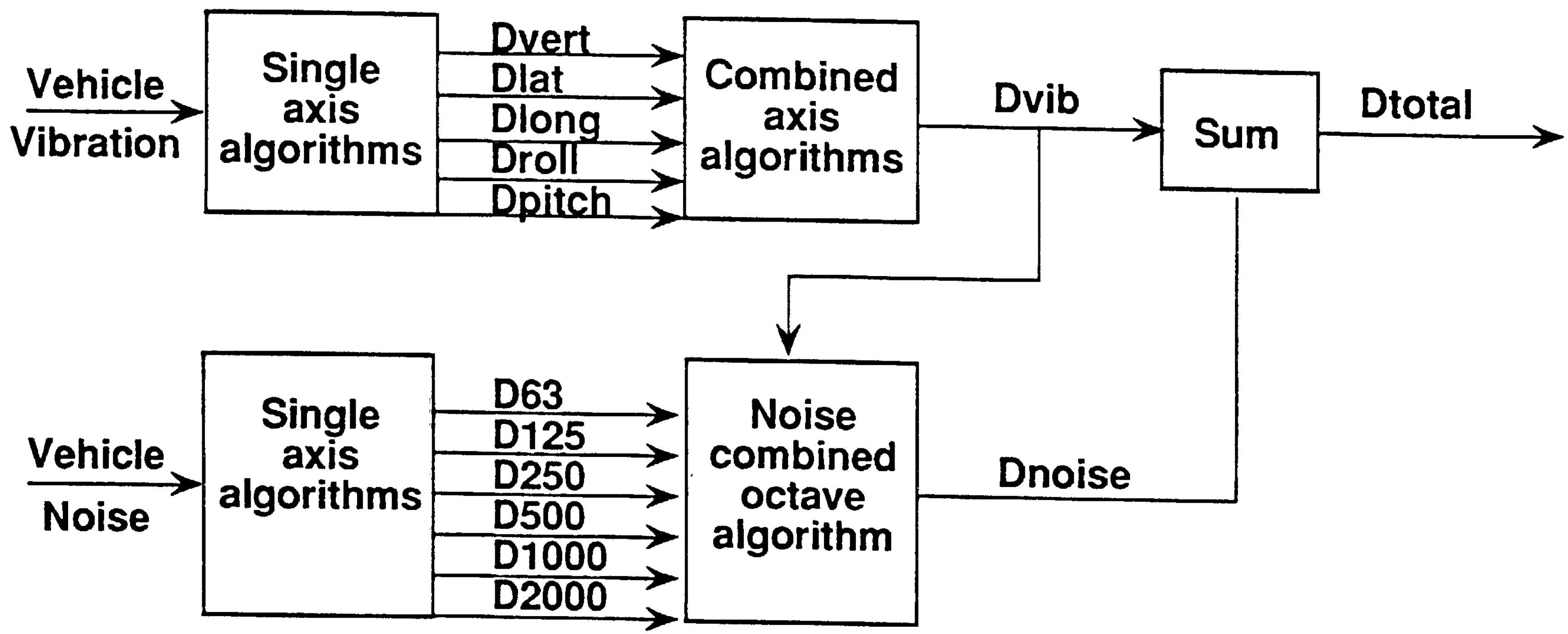

Fig. 3. Basic elements of the NASA ride comfort model

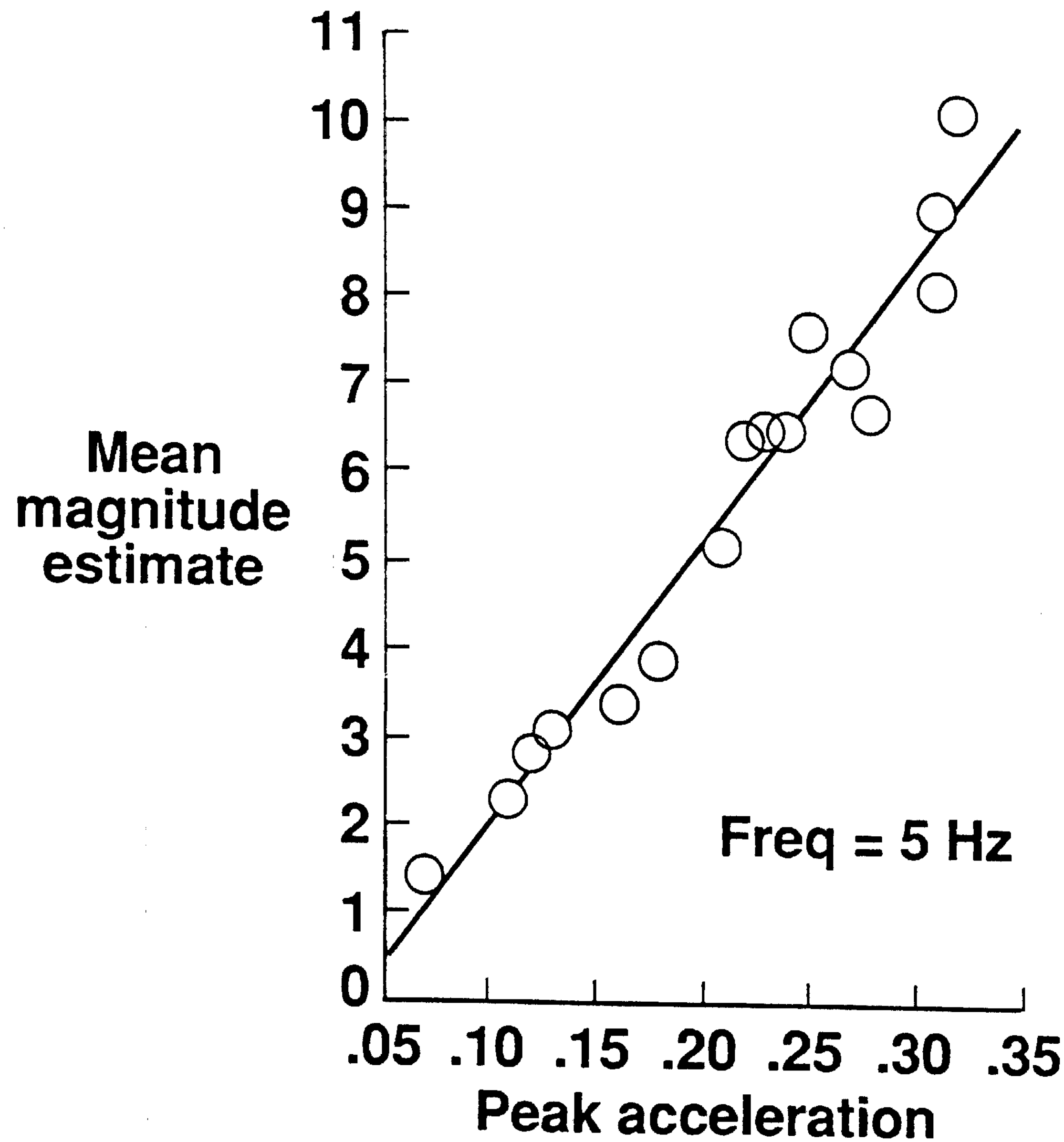

Fig. 4. Magnitude estimates of discomfort (Freq = 5 Hz)

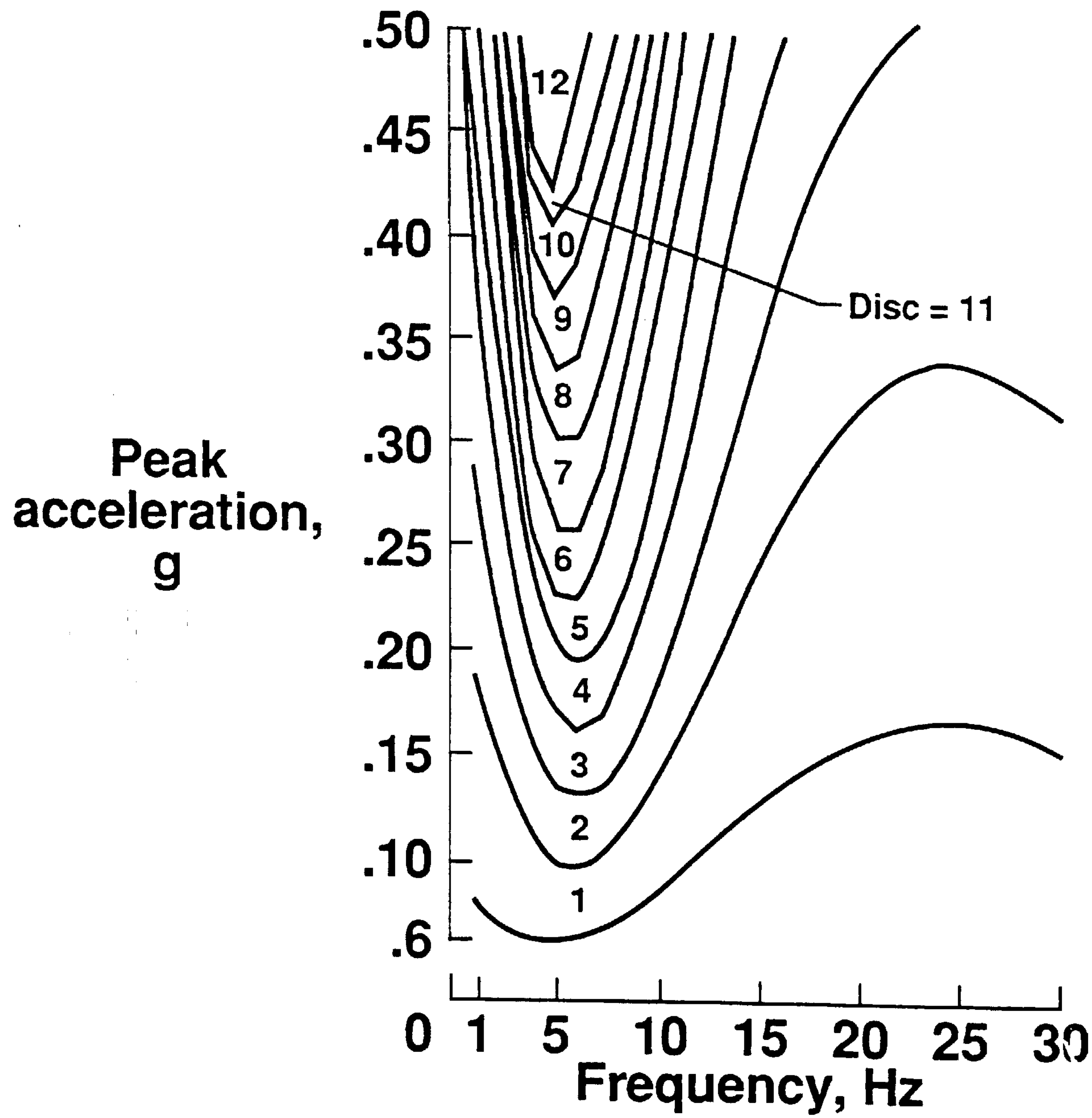

Fig. 5. Vertical equal discomfort curves (vertical sinusoidal vibration)

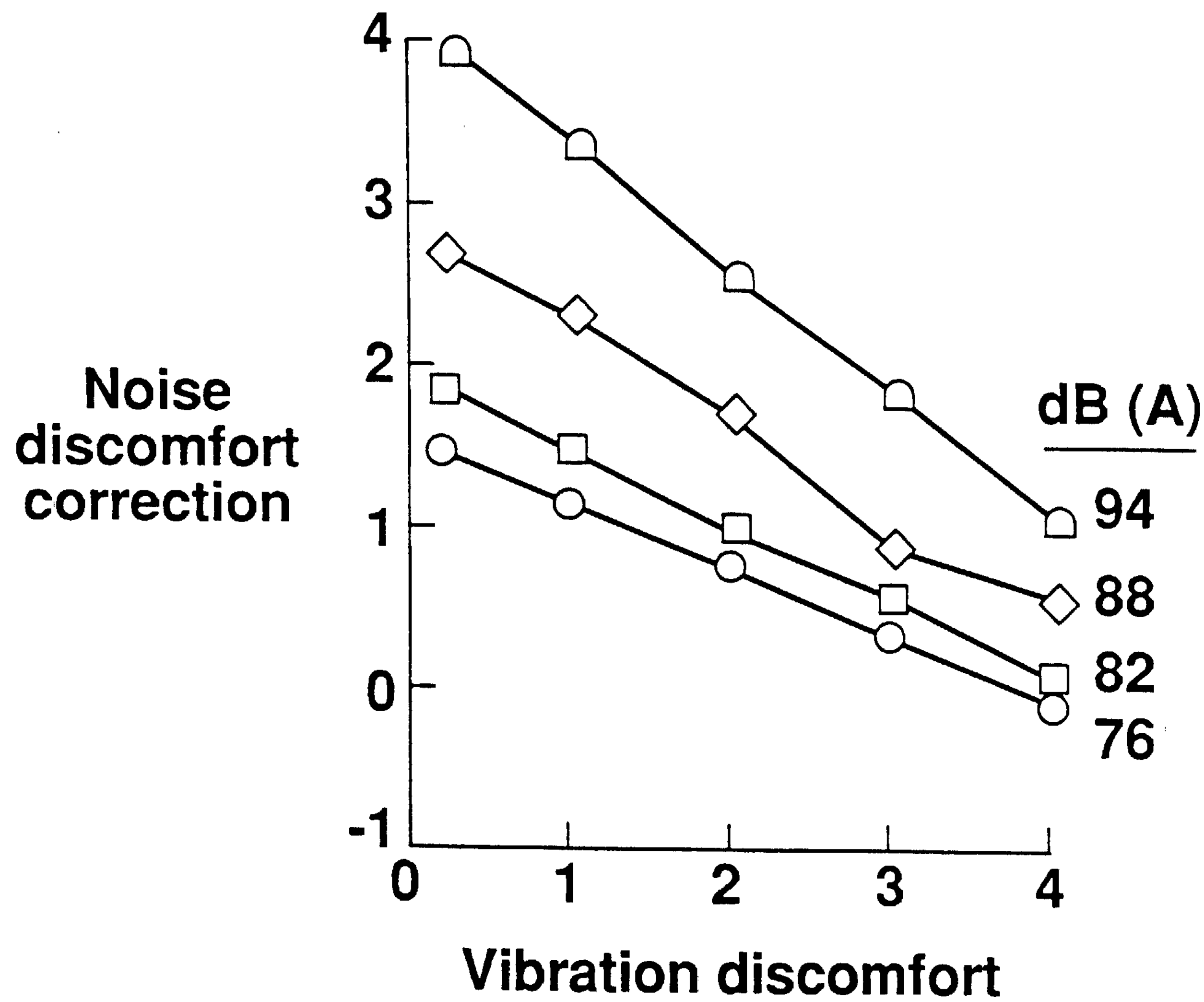

Fig. 6. Noise and vibration discomfort interaction

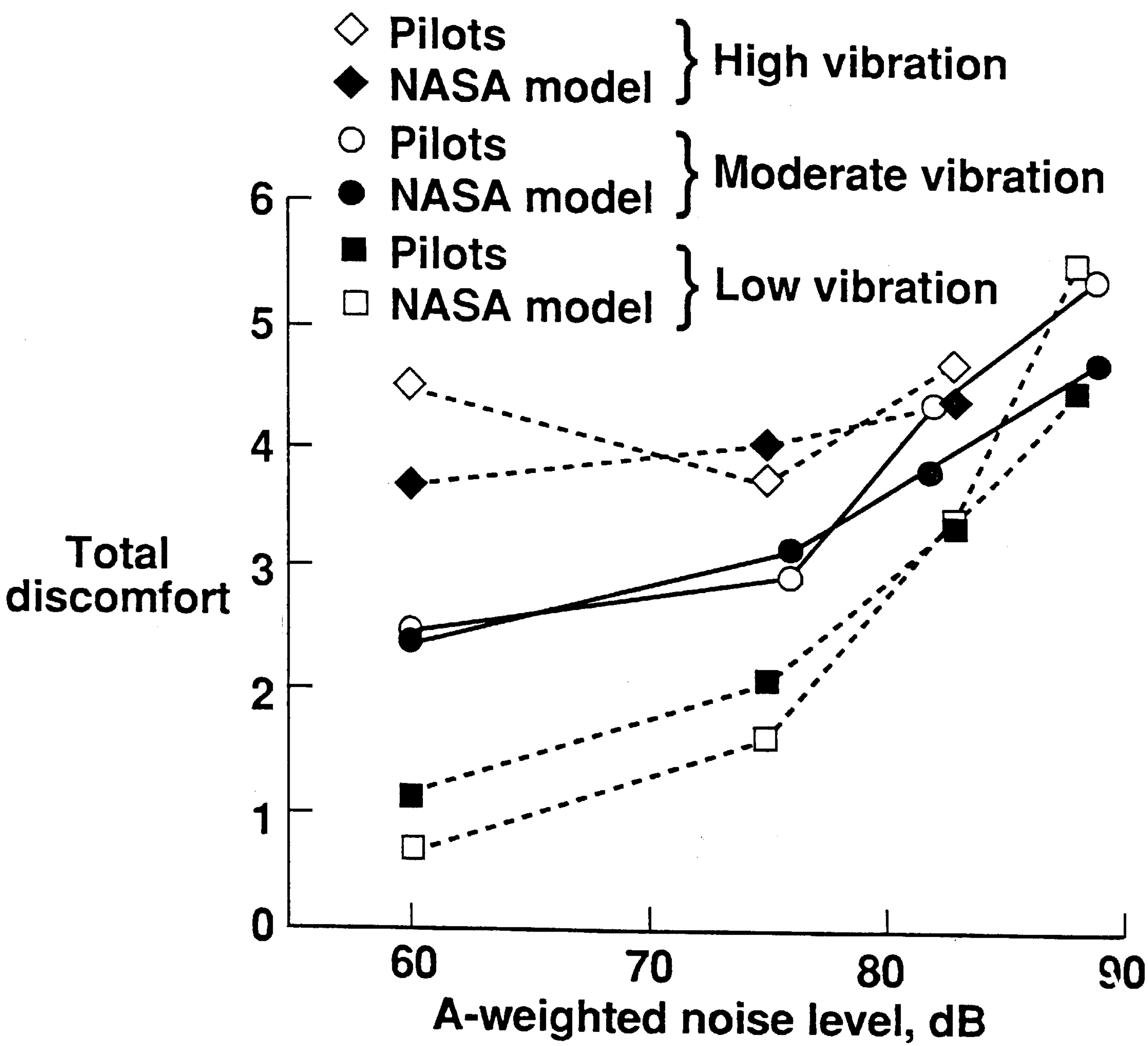

Fig. 7. Comparison of helicopter pilots' ratings with NASA ride comfort estimates

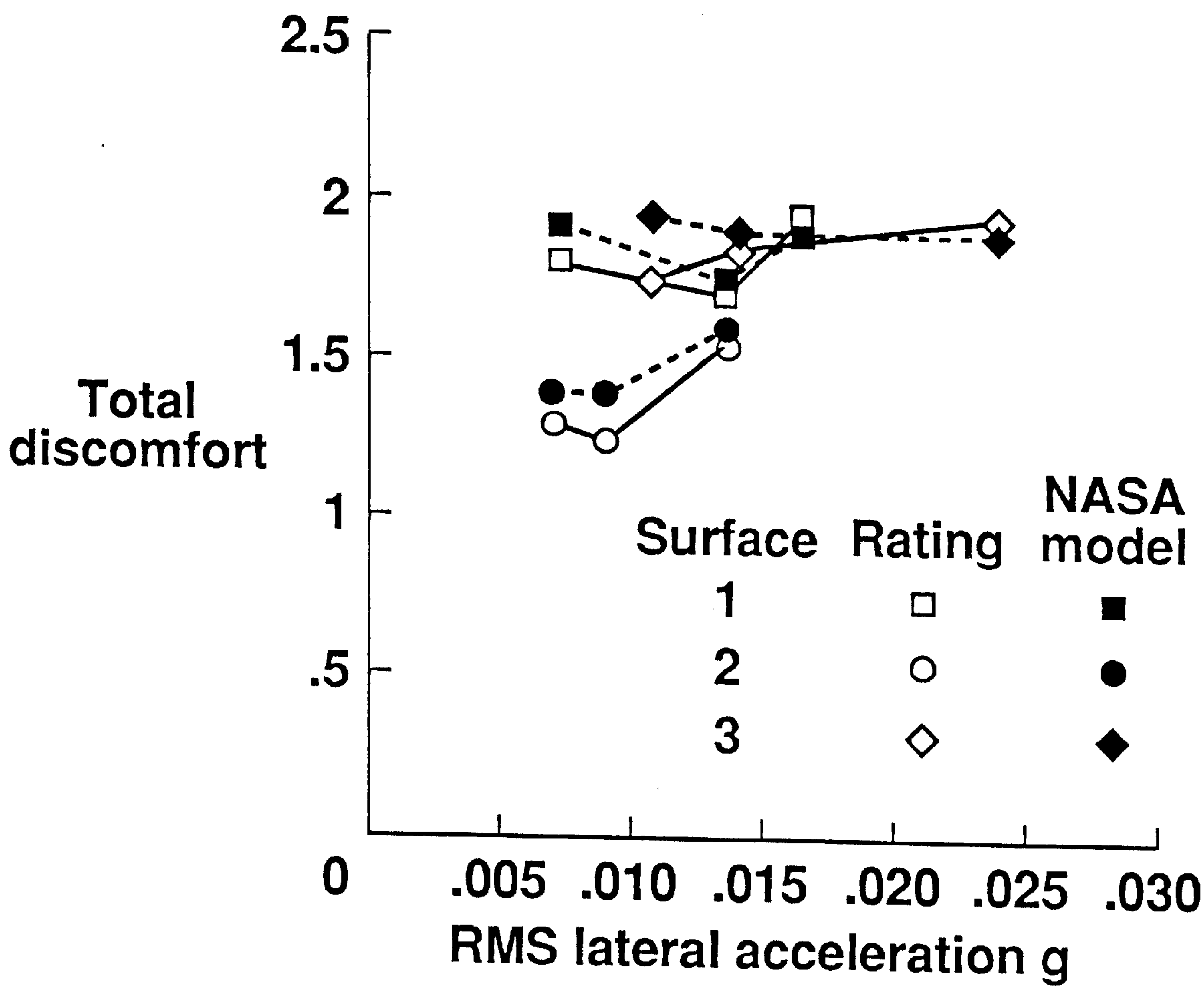

Fig. 8. Comparison of automobile passenger ratings with NASA ride comfort estimates

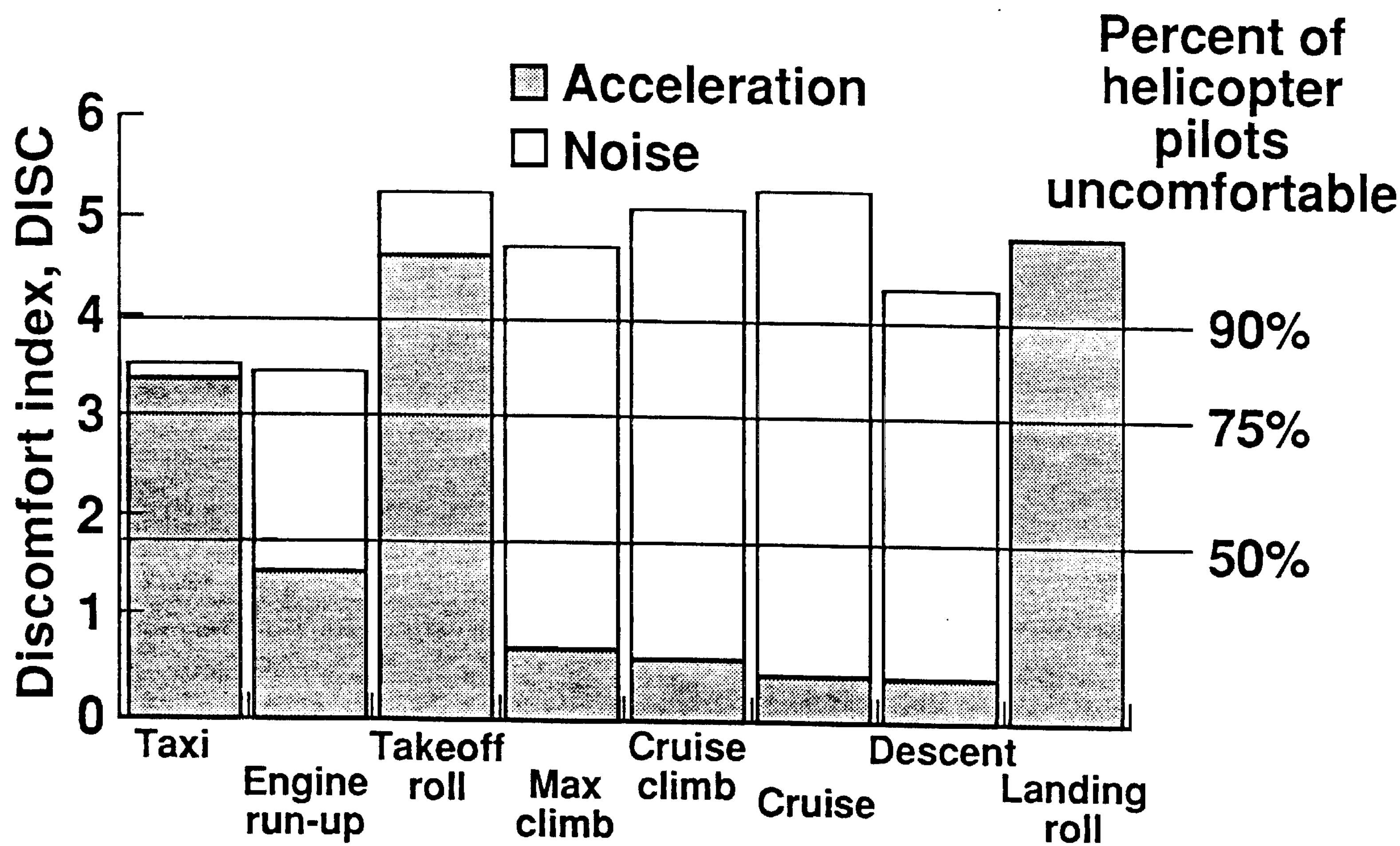

Fig. 9. NASA ride comfort model application to a light aircraft

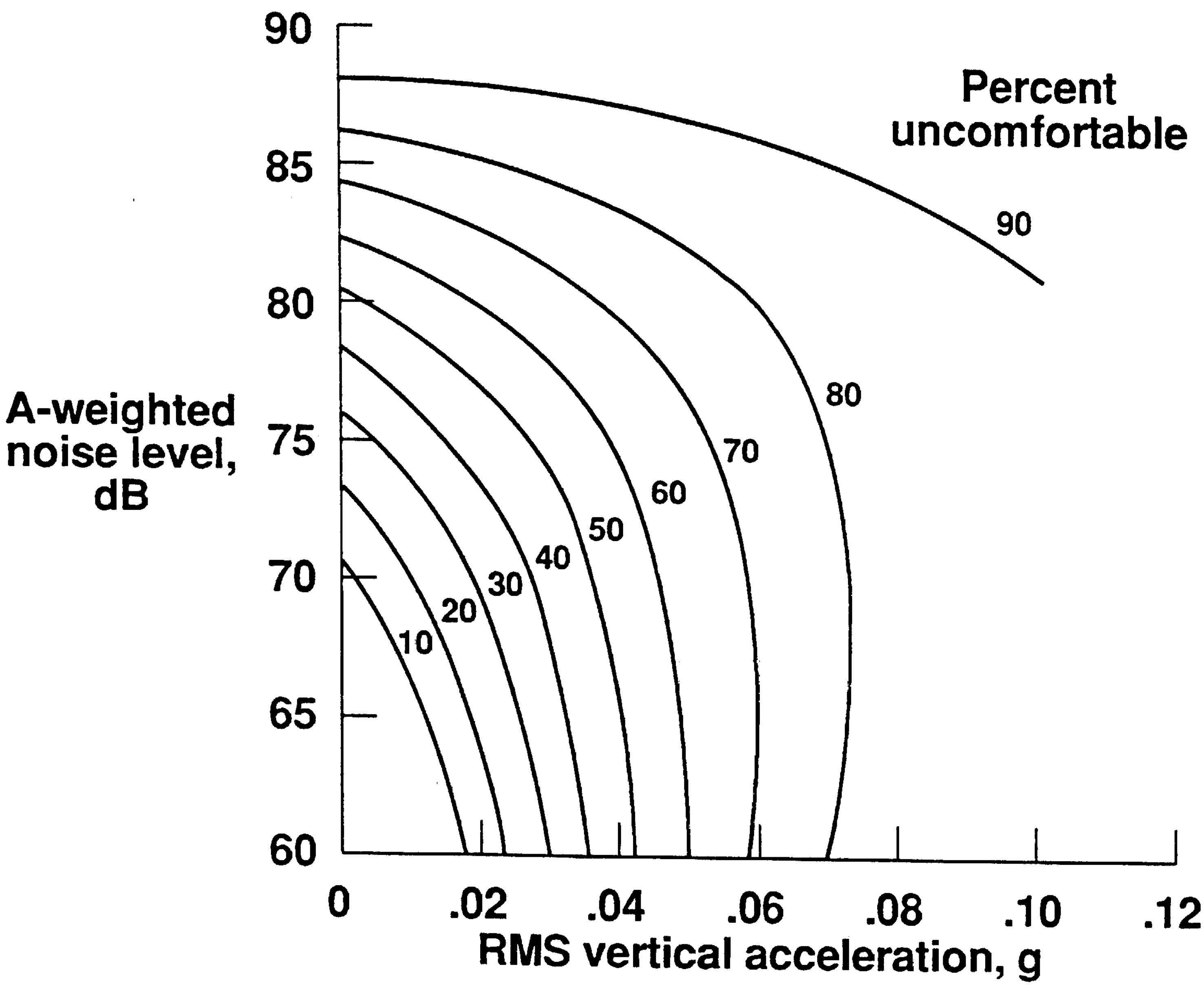

Fig. 10. Noise/vibration equal comfort contours for helicopter environments

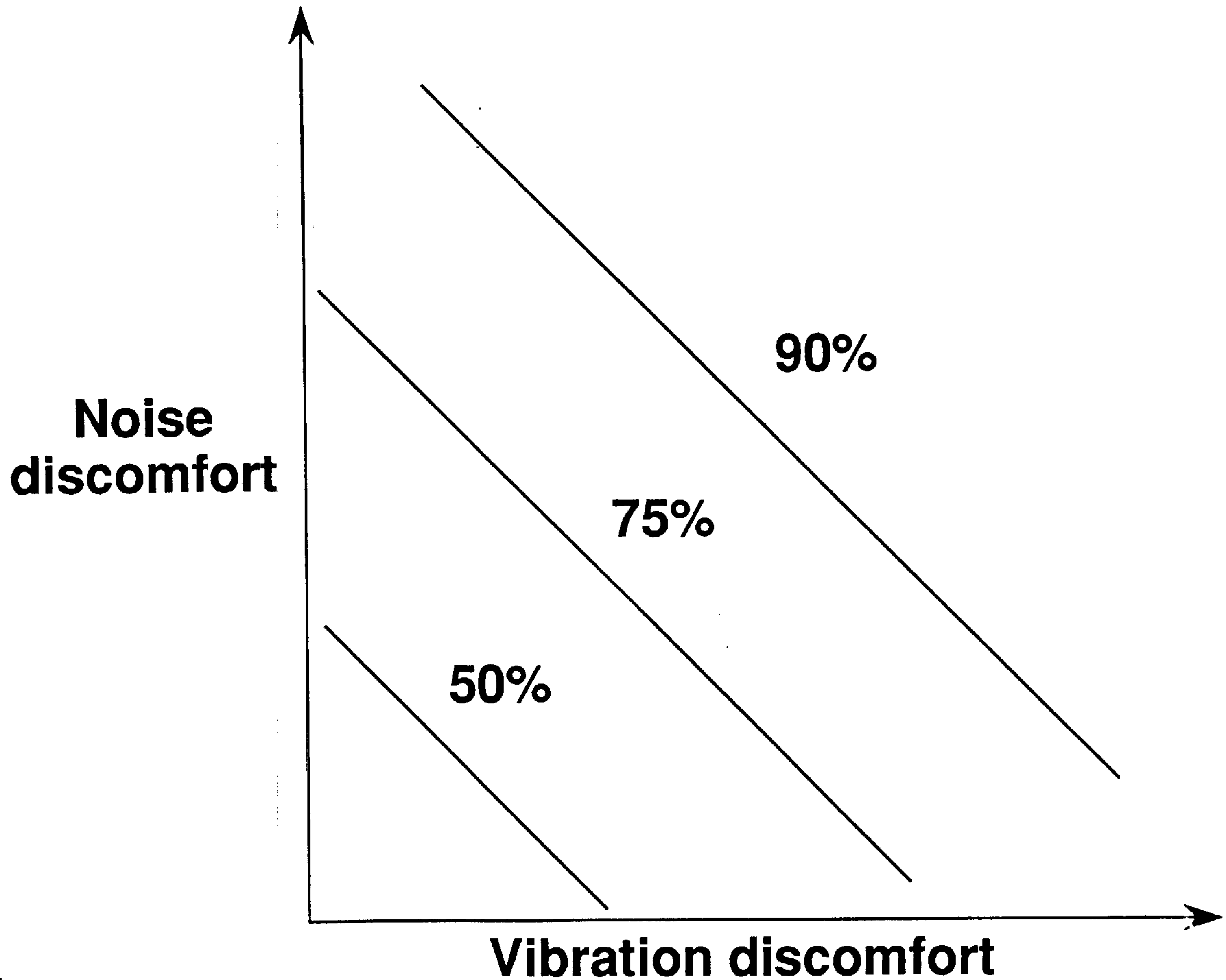

Fig. 11. Generalized noise/vibration equal comfort lines

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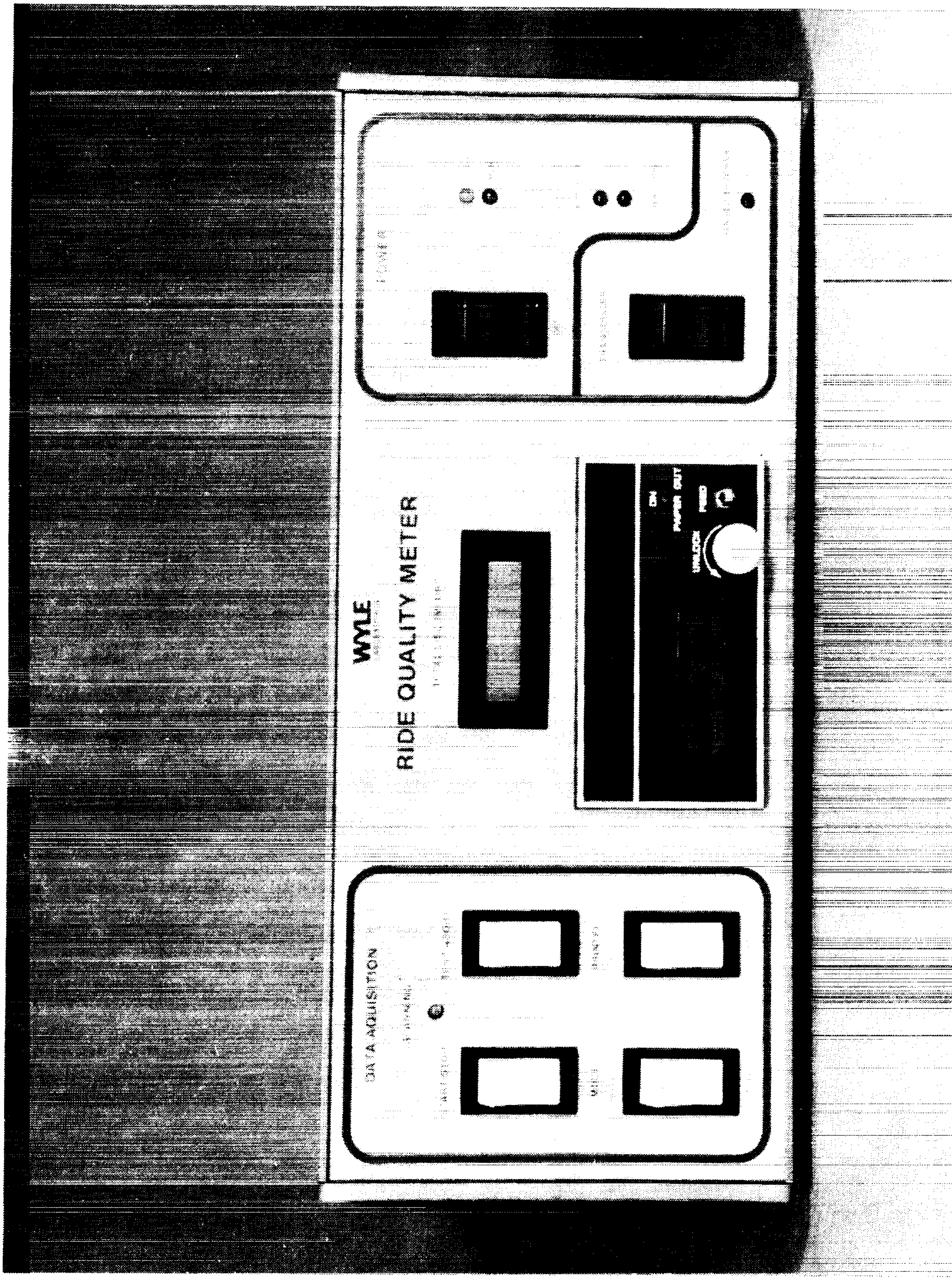

Fig. 12. NASA ride quality meter

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16. Abstract

The NASA Langley Research Center has completed a comprehensive research program that resulted in the development of a generalized model for estimating passenger discomfort response to combined noise and vibration. This model accounts for multiple frequency and multiple axes of vibration as well as the interactive effects of combined noise and vibration. The model has the unique capability of transforming individual components of a noise/vibration environment into subjective comfort units and then combining these comfort units to produce a total index of passenger discomfort and useful sub-indices that typify passenger comfort within the environment. This paper presents an overview of the model development including the methodology employed, major elements of the model, model applications, and a brief description of a commercially available portable ride comfort meter based directly upon the model algorithms. Also discussed are potential criteria formats that account for the interactive effects of noise and vibration on human discomfort response.

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