NASA Technical Paper 1422

Discomfort Criteria for Single-Axis Vibrations

Thomas K. Dempsey, Jack D. Leatherwood,
and Sherman A. Clevenson

MAY 1979

NASA Technical Paper 1422

Discomfort Criteria for Single-Axis Vibrations

Thomas K. Dempsey, Jack D. Leatherwood,
and Sherman A. Clevenson
Langley Research Center
Hampton, Virginia

National Aeronautics
and Space Administration

**Scientific and Technical
Information Office**

1979

SUMMARY

A series of studies was conducted to develop criteria for prediction of passenger discomfort due to vibration in each of five axes of motion. The axes were the vertical, lateral, longitudinal, roll, and pitch axes. The studies involved applying sinusoidal and random vibrations in these axes to a total of 852 passenger-subjects. The discomfort evaluations provided by the subjects formed the basis for development of the discomfort criteria.

A single scale of passenger discomfort common to all axes of vibration was developed. The scale provided a simple and concise technique for expressing the individual criterion of an axis as well as a method of comparing criteria of various axes. Discomfort criteria for sinusoidal vibration were developed for vertical, lateral, and roll axes, whereas random-vibration discomfort criteria were derived for all five axes of motion. On the basis of these criteria, empirical equations were derived for use in the prediction of passenger discomfort associated with each axis and type of vibration. The discomfort criteria of these studies did not agree with recommendations of the International Standards Organization with regard to acceptable levels of vibration acceleration or with regard to the equivalence of the type of vibration, that is, random or sinusoidal. The test results for angular vibration provide data for extension of current information to establish a universal set of discomfort criteria.

INTRODUCTION

Passenger comfort in various transportation vehicles is influenced by several factors, such as vibration, noise, temperature, and seating space. (See refs. 1 and 2.) Thus prediction of, and subsequently the optimization of, passenger comfort is dependent upon the appropriate integration of these factors in a model for vehicle ride quality. Such a model that would account for the relative importance of both the vibratory and nonvibratory aspects of these vehicle environments upon human discomfort responses is under development at the Langley Research Center (refs. 3 to 5). However, the development of a model with wide applicability to various vehicles requires a comprehensive understanding of the fundamental effects of vibration on passenger comfort. Such an understanding has heretofore not been available. This paper presents the results from an extensive number of NASA studies that have led to a more detailed understanding of passenger discomfort response to vibration and the development of general discomfort criteria for each axis of vibration.

A recent review and summary of the vibration-criteria literature (ref. 6) points out that most ride quality studies have concentrated on only the vertical axis and, to a lesser extent, the lateral axis of vibration. Thus, a need to develop criteria for the other axes of vibration is apparent. Reference 6 further indicates that many differences and contradictions exist in the various reported investigations. For example, it is not unusual for the vibration levels associated with the proposed criteria for an axis to differ from one another by as much as an order of magnitude. The reasons offered to explain this diversity of results included factors such as poor experimental design, unrealistic laboratory environments, use of inadequate rating scales, small subject samples, and lack of information regarding fundamental psychophysical relationships between human discomfort response and the characteristics of the vibration stimuli (ref. 3). Several investigations did apply improved methodologies to the problem of determining the psychophysics of human subjective response to whole-body vibrations (refs. 7 to 9). However, a recent investigation (ref. 10) demonstrated that subjective evaluations of the intensity of vibration differed from subjective evaluations of the discomfort of vibration. Consequently, caution must be used in applying experimental results (criteria) from studies of intensity to problems related to human discomfort. Therefore an important consideration in the development of criteria is that the criteria apply to passenger discomfort.

Another important consideration for criteria development is the need for a practical subjective scale of discomfort. Such a scale should be common to all axes of vibration and should be anchored to a defined threshold of passenger discomfort. A scale of this type would allow meaningful and accurate comparison between, and summation of, the passenger discomfort to the various axes of vibration.

The major objective of this paper is to present the results from an extensive series of studies that were conducted to develop criteria for passenger discomfort for each of the major axes of vibration found in transportation vehicles. These axes include the vertical, lateral, longitudinal, roll, and pitch axes. Included within and integral to this general objective was the development of a single scale of passenger discomfort common to each axis of vibration, as well as a comparison of criteria derived in these studies with the recommendations of the International Standard Organization (ISO) (ref. 11).

METHOD

A series of interconnected studies were conducted in the passenger ride quality apparatus (PRQA) at the Langley Research Center. The following sections provide a brief description of the apparatus, subjects, experimental design, vibration stimuli, and test procedure of these studies.

Apparatus

Figure 1 shows the passenger ride quality apparatus (PRQA - front panel removed) which was used to expose passengers to vibrations. The apparatus is described in detail in references 12 and 13, and the reader is referred to those references for detailed information related to the simulator's operation, capabilities, and design. For the present tests, the interior of the simulator was fitted with tourist-class aircraft seats (three abreast) which permitted testing of six subjects at a time.

Subjects

A total of 852 subjects participated in the series of experiments in the present report. These subjects were paid volunteers obtained from Old Dominion University and from a contractual subject pool. Although previous research (refs. 14 and 15) indicated that the demographic factors of age, weight, and sex were not important predictors of passenger ride quality, this information is provided in table I for descriptive purposes. Previous research (refs. 14 and 15) also indicated that discomfort responses were not dependent upon the amount of experience a subject had had with vibration. Thus, the subjects described in table I were not trained.

Experimental Design

An overview of the experimental designs of the various studies is displayed in table II. This table indicates the general vibration test areas, specific tests completed in each area, and the axes of vibration to which subjects were exposed for each of the various tests. The entries in the table indicate the type of evaluation procedure used by the subjects for each specific test. The following subsections - scale anchoring, criteria development, and scale transformation - provide a review of the specific tests completed in each test area.

Scale anchoring.- This test area involved a single test to determine the threshold of passenger discomfort for use as the origin for the scale of discomfort. For this test the subjects' task was simply to indicate whether successively applied ride segments, consisting of 10- to 15-second vibrations, were comfortable or uncomfortable (dichotomous comfort responses). The instructions for this task are reproduced in appendix A, along with instructions for other subject evaluation tasks.

Criteria development.- This test area involved an extensive series of tests to derive sinusoidal- and/or random-discomfort criteria for the various axes of vibration. Generation of the sinusoidal-discomfort criteria (for vertical, lateral, and roll vibrations) involved two specific tests, frequency equating and sinusoidal dose response. Frequency equating refers to the test procedure used to obtain the acceleration levels of different frequencies, within an axis, that produce identical discomfort responses. For this test the subjects used the task of constant stimuli. This task required subjects to indicate whether one ride segment (termed a comparison) provided greater or less discomfort than a second type of ride segment (termed a standard).

The sinusoidal dose response tests, on the other hand, were used to determine the empirical relationship between discomfort responses and acceleration level for each separate frequency within an axis of vibration. For this test the subjects were assigned the evaluation task of magnitude estimation.

A third type of specific test, random dose response testing, was also used for criteria development. The purpose of this test was to derive discomfort criteria for random vibration for each of the five axes of vibration. This testing involved the use of the magnitude estimation procedure to derive the discomfort of various random vibrations within an axis as compared with the discomfort of specific sinusoidal vibrations of that axis. (Exceptions to this were completed for pitch and longitudinal vibrations, as noted below.) In order to compare the discomfort produced by vibrations within each of the different axes on a common scale of discomfort, it was necessary to conduct a fourth type of test for criteria development, referred to in table II as axis equating tests. In these tests the discomfort produced by lateral-axis (5-Hz) and roll-axis (3-Hz) vibrations was subjectively equated to the known discomfort produced by vertical vibration (9 Hz) through the evaluation task of constant stimuli.

Axis equating was not conducted for pitch and longitudinal vibrations. Since vibrations of these axes rarely occur with any magnitude in most public transportation vehicles, there was no need to complete extensive testing of these axes for ride quality research. The common subjective scale of discomfort DISC was maintained in these axes, however. This was accomplished by requiring subjects to evaluate the random vibrations of these axes (in the third test) in relation to the known discomfort of a vertical vibration, rather than to a vibration in either the pitch or longitudinal axis.

Scale transformation.- This area involved a single specific test of scale equating in which subjects evaluated selected vibrations with a category scale. The purpose of the test was to derive a transformation between the discomfort scale developed in this report and category-scale discomfort responses. The transformation, once specified, is of particular importance because it provides a mechanism for relating laboratory-developed discomfort criteria to field-test results which use category scales, and vice versa.

Vibration Stimuli

Previous research (refs. 14 and 15) indicated that the floor location, as opposed to seat location, can be used for measurement of vibration as well as for specification of criteria. Consequently, all the vibrations investigated in the current studies were based on floor measurements. The transfer function for the seats used in these studies is given in a previous report (ref. 16). If the seat characteristics of a particular vehicle differ considerably from those used herein then it would be necessary to adjust the discomfort criteria according to the specific differences in seat response characteristics. This is readily accomplished once the seat response characteristics of the alternative seat are determined.

The vibration characteristics of ride segments for the scale anchoring and scale transformation tests are displayed in table III. Since the tests for scale anchoring required subjects to evaluate the absolute comfort of a vibration (i.e., comfortable versus uncomfortable) rather than a relative comparison of the discomfort of ride segments, there were no standard ride segments for this test.

Table IV shows the vibration characteristics of the standard and comparison ride segments that were used for specific criteria-development tests within each axis of vibration. As indicated in table IV the frequency and acceleration values of the standard ride segments were variable for the tests involving discomfort response to sinusoidal vibration. For these tests the frequency of the standard ride segments was always the same as the frequency of the comparison ride segments. The range of acceleration corresponding to each vibration frequency was varied because of the strong effect of vibration frequency on human discomfort (refs. 15 and 17). For example, the same acceleration level applied at different frequencies will result in different amounts of discomfort. The random vibration spectra used in these studies were produced by using selected bandpass filters having roll-off characteristics of 24 dB/octave. At the cutoff frequencies (upper and lower band limits) the spectra were generally down by 3 dB. For this special condition, where a nominal 10-Hz bandwidth of vibration centered at 5 Hz was desired, the low-frequency roll-off was governed by the frequency response characteristics of the simulator - which was limited to frequencies above 1 Hz. Thus, for this special condition, the effective bandwidth was approximately 9 Hz.

A point of interest with regard to the discomfort criteria for the rotational axes is the fact that, for the simulator used in these studies, the distance between a seated subject and the axis of rotation was not a factor of concern. This was demonstrated in an earlier study (ref. 18) which indicated that discomfort responses did not vary significantly with the distance of a seated subject from the axis of rotation.

Test Procedure

A typical day's testing consisted of instructing a group of six subjects in one of the four tasks they would need for evaluation of vibrations and then exposing them to about a $2\frac{1}{2}$-hour test period. The general test procedure consisted of exposing subjects to a sequence containing between 12 and 15 ride segments, divided into standard and comparison ride segments where appropriate. Each such sequence defined a short period of testing, termed a session, and a total test period consisted of 8 to 16 sessions. The number of ride segments per session as well as the total number of sessions was a function of the type of vibration investigated. After each session the subjects were given a 1-minute rest interval, except for the middle session (halfway through testing), after which the subjects were given a 15-minute rest interval. Information as to presentation order for vibration stimuli and the basis for expansion of vibration testing to address a methodological problem related to using the magnitude-estimation procedure are provided in appendix B.

RESULTS

This section presents the results obtained from the series of interconnected studies described in the preceding sections. Successive subsections address scale anchoring, sinusoidal-vibration criteria, random-vibration criteria, and scale transformation. A final subsection provides a comparison of these results with the recommendations of ISO, the International Standards Organization (ref. 11).

Scale Anchoring

The subjective-discomfort scale (DISC scale) developed for use in these studies is a ratio scale of passenger discomfort obtained by a magnitude-estimation procedure. In order for this scale to be useful for the purposes of evaluating ride comfort on an absolute basis, the scale was anchored to the threshold of discomfort. The results of the initial tests conducted to determine the threshold of discomfort, and hence derive the anchor point for the scale, are presented in figure 2. This figure shows the standard normal score z, a transformation of the percentage of 9-Hz vertical-vibration ride segments evaluated as being uncomfortable as a function of peak vertical floor acceleration level. The 9-Hz vibration frequency was selected as the anchor for the scale because (1) it is near the frequency range (i.e., 4 to 8 Hz) that produces maximum discomfort (refs. 17 and 19), (2) previous research indicated that it provided the least variability in discomfort responses as compared with other sinusoidal-vibration frequencies (refs. 14 and 15), and (3) the seat-floor transmissibility function is approximately unity at 9 Hz (ref. 16).

In figure 2, a z-score value of zero (used to define discomfort threshold) corresponds to the condition in which 50 percent of the subjective evaluations of 9-Hz vibrations were rated uncomfortable. For the data in figure 2 the discomfort threshold ($z = 0$) corresponds to a floor acceleration level of 0.086g. This value of floor acceleration was then used to develop the scale of discomfort DISC shown in figure 3. The data in figure 3 were generated by having subjects make magnitude estimates of the discomfort of various acceleration levels of a 9-Hz vertical vibration. The mean magnitude estimates at each acceleration level of discomfort are indicated by the ordinate at the right of the figure. The procedure for converting magnitude estimates to units of discomfort DISC was accomplished by referencing the mean magnitude estimates to a value of unity (i.e., DISC = 1) at a peak floor acceleration level of 0.086g. Thus, the resultant discomfort DISC scale is indicated along the left ordinate of figure 3. To provide a practical interpretation of the meaning of a unit change along the DISC scale, the data of figures 2 and 3 were combined to generate figure 4. This figure shows the relationship between the DISC scale and the corresponding percentage of passengers that would find that DISC value uncomfortable. For example, a ride segment having a discomfort level of DISC = 3 would be evaluated as uncomfortable by approximately 100 percent of the passengers experiencing it.

Sinusoidal-Vibration Criteria

Vertical axis.- The sinusoidal vertical-vibration criteria developed in the present series of tests are shown in figure 5. This figure displays the values of peak vertical floor acceleration level at each frequency which are required to produce successive equal-discomfort curves. Figure 5 was obtained by combining the results of two separate criteria-development tests. The first set of tests (frequency equating) determined the acceleration level at different frequencies that produced the same discomfort as a 9-Hz vibration having a specified discomfort level. (Appendix C contains figs. C1 to C5. These figures show some of the typical test results for this study. See fig. C1 for typical frequency equating results.) The second set of tests used the magnitude-estimation procedure to determine the relationship between peak floor acceleration and subjective discomfort response for each frequency of sinusoidal vertical vibration (from 1 to 30 Hz). An example of the dose response relationship thus obtained is illustrated in figure C2 for a vertical sinusoidal frequency of 5 Hz. It is important to note that the results of the frequency equating tests were used to anchor the discomfort-magnitude estimates to units of discomfort DISC for each frequency investigated. The data for each frequency were then fit by a least-squares line and the resulting least-squares coefficients are presented in table V. These coefficients define the linear relationship between subjective discomfort and peak vertical floor acceleration at each frequency. The coefficients of table V were then used to derive the curves of figure 5.

The equal-discomfort curves of figure 5 range from DISC = 1, which is the discomfort threshold, to values as high as DISC = 12, which corresponds to an extremely high level of discomfort. The successive curves can be interpreted in a ratio fashion because of the procedures used for their derivation. For example, ride segments with DISC = 4 represent twice the discomfort of ride segments with DISC = 2. The curves of figure 5 further indicate that maximum passenger discomfort occurs in the frequency range of 4 to 8 Hz and that vibration frequencies above 10 Hz are of relatively minor importance.

For these tests it was found that neither the acceleration level assigned to the standard ride segment nor the range of acceleration levels associated with comparison ride segments (see appendix B) had a significant effect upon discomfort responses. (See fig. C2 for typical data.) Consequently, the discomfort responses obtained with the different procedures were averaged for the prediction coefficients provided in table V.

Lateral axis.- Sinusoidal lateral-vibration criteria are displayed in figure 6. This figure shows the peak lateral floor acceleration levels required to produce successive equal-discomfort curves as a function of lateral frequency. These criteria were developed in a fashion similar to those for vertical vibration (fig. 5), except that an additional test was required. This additional test involved equating discomfort across axes, that is, lateral to vertical. Specifically, the acceleration level of a 5-Hz lateral vibration was equated in discomfort to a 9-Hz vertical vibration with a peak acceleration level of 0.136g. (See fig. C3.) This procedure allowed the magnitude estimates of discomfort due to lateral vibrations also to be anchored in relation to discomfort threshold. The resultant coefficients for least-squares fits to the adjusted magnitude estimates are summarized in table VI. These coefficients for each lateral frequency relate discomfort DISC to the peak lateral floor acceleration level. The coefficients in table VI were then used to generate the equal-discomfort curves in figure 6.

The interpretation of the equal-discomfort curves in figure 6 is similar to that of figure 5. However, note that for this axis of vibration the frequency range for maximum discomfort (2 to 3 Hz) is lower than that for vertical-axis vibrations.

Roll axis.- The final set of sinusoidal-vibration criteria generated from these investigations was for the roll axis of vibration. Figure 7 displays these results in terms of the roll floor acceleration level, in radians per second squared, at each roll frequency that was required to produce various equal-discomfort curves. The method used to generate the sinusoidal roll criteria was similar to that used to develop the sinusoidal lateral criteria. Table VII presents the coefficients for linear least-squares fits relating discomfort to roll acceleration level for each of the four roll frequencies.

The interpretation of the discomfort values shown in figure 7 is identical with that for figures 5 and 6. Note that the maximum discomfort occurs for a roll vibration frequency of 2 Hz, which is similar to the frequency for maximum discomfort for sinusoidal lateral vibration (fig. 6). However, only a restricted range of roll frequencies was investigated, since roll frequencies greater than 4 to 5 Hz have minimal influence upon subjective discomfort. Consequently, it is difficult to make trend comparisons of the lateral and roll axes. However, since discomfort within each axis is measured on the same scale, the acceleration levels in each axis required to provide constant amounts of discomfort are directly comparable.

Random-Vibration Criteria

Random-vibration criteria were developed separately for vertical, lateral, roll, pitch, and longitudinal axes of vibration. Subsequent subsections give discussions of each of these criteria, which were based on results of tests in which subjective response to random vibrations was determined for each axis individually.

Vertical axis.- The random vertical-vibration criteria are shown in figure 8. This figure displays the root-mean-square (rms) random acceleration level required to produce successive equal-discomfort curves as a function of the center frequency of random vibration. Cubic-polynomial curve fitting and multiple regression analyses were used to develop a single equation to predict the discomfort due to any combination of rms acceleration level and center frequency of figure 8. This predictive equation is:

$$\mathrm{DISC}_{vert} = -1.75 + 33.4a_{vert} + 0.857f_c - 0.102f_c^2 + 0.00346f_c^3 \qquad (1)$$

where

DISC_{vert} discomfort due to random vertical vibration, DISC

a_{vert} rms random vertical floor acceleration level, g units

f_c center frequency of a band of random vibration, Hz

The discomfort responses for the vertical random dose tests, a summary of which is shown in figure 8, varied with center frequency and acceleration level, but not (no statistical differences) as a function of the bandwidth of vibration. (See fig. C4 for representative data.) Consequently, the response data for different bandwidths were combined. A least-squares line was then fit to the data for each center frequency of vertical vibration. The resultant coefficients relating discomfort to rms vertical floor acceleration for each center frequency are given in table VIII. These coefficients were then used to compute the acceleration level at successive center frequencies that provided constant discomfort.

Inspection of figure 8 reveals several important pieces of information. First, the rms vertical floor acceleration level required to achieve threshold of discomfort (DISC = 1) varies with the center frequency of the vibration. Thus, the random vertical criteria display a frequency dependence analogous to sinusoidal vertical criteria (fig. 5). However, the frequency range for maximum discomfort for the random criteria occurs between 6 and 8 Hz, whereas that for sinusoidal criteria occurs between 4 and 8 Hz. More important, however, is the fact that discomfort response to identical rms acceleration levels differs depending upon whether the vibration is sinusoidal or random. This is illustrated by the data of figure C4 which show that discomfort produced by sinusoidal vibration is much less than the discomfort due to random vibrations having an equivalent rms acceleration level. This has important implications with respect to the ISO assumption of equivalence between sinusoidal and random criteria boundaries. Contrary to the ISO recommendations, the results of this study imply that it is necessary to model the discomfort due to each type of vibration separately.

Lateral axis.- The random lateral-vibration criteria (equal-discomfort curves) derived from these tests are displayed in figure 9 for both 2-Hz and 5-Hz bandwidths of vibration. The data of figure 9 were input to a multiple linear regression program which produced the following single equation for predicting discomfort due to random lateral vibrations:

$$\mathrm{DISC}_{\mathrm{lat}} = 0.894 + 29.2a_{\mathrm{lat}} - 0.157f_c + 0.016(\mathrm{BW}) \tag{2}$$

where

$\mathrm{DISC}_{\mathrm{lat}}$	discomfort due to random lateral vibration, DISC
a_{lat}	rms random lateral floor acceleration level, g units
BW	bandwidth of vibration, Hz
f_c	center frequency of vibration, Hz

The basic data from which figure 9 was developed are shown in figure C5. It is obvious in this case that discomfort response was dependent on vibration bandwidth as well as center frequency and rms acceleration level. A summary of the linear least-squares regression coefficients for estimating discomfort associated with each center frequency and bandwidth of lateral vibration is given in table IX. The curves of figure 9 were generated by use of these coefficients and a procedure analagous to that used for random vertical vibrations.

Examination of figure 9 indicates that these criteria are also strongly frequency dependent. In addition, increasing the bandwidth of the vibration (i.e., from 2 to 5 Hz) generally results in an increase in discomfort for a constant random lateral floor acceleration level.

Roll axis.- The criteria developed in the present studies for random roll vibration are displayed in figure 10. This figure shows the discomfort DISC that occurred as a function of rms random roll floor acceleration level for a band of vibration centered at 3 Hz and having a bandwidth of 5 Hz. Linear least-squares regression analyses were used to develop two separate functions for the prediction of discomfort due to random roll vibration:

$$\mathrm{DISC}_{\mathrm{roll}} = 0.342 + 4.68\ddot{\phi} \qquad (\ddot{\phi} \geqq 0.141 \text{ rad/sec}^2) \tag{3}$$

$$\mathrm{DISC}_{\mathrm{roll}} = 7.04\ddot{\phi} \qquad (\ddot{\phi} < 0.141 \text{ rad/sec}^2) \tag{4}$$

where

$\mathrm{DISC}_{\mathrm{roll}}$ discomfort due to random roll vibration, DISC

$\ddot{\phi}$ rms random roll floor acceleration level, rad/sec^2

The derivation of equation (3) was based on the data in figure 10. However, since no data exist in figure 10 below DISC = 1.5, equation (4) represents a logical extrapolation to zero.

A strong linear relationship between discomfort and rms roll acceleration level is shown in figure 10. This relationship is consistent with that found for the vertical and lateral axes (for both sinusoidal and random vibrations) and indicates that the fundamental nature of the psychophysical relationship between discomfort and acceleration level remains linear for both translational and rotational vibrations.

Pitch axis.- The random pitch-vibration criteria are shown in figure 11 in terms of discomfort as a function of rms random pitch floor acceleration level for random vibration centered at 3 Hz and having a bandwidth of 5 Hz. The prediction equations for pitch vibrations are

$$\mathrm{DISC}_{\mathrm{pitch}} = 0.414 + 5.07\ddot{\theta} \qquad (\ddot{\theta} \geqq 0.116 \text{ rad/sec}^2) \tag{5}$$

$$\mathrm{DISC}_{\mathrm{pitch}} = 8.62\ddot{\theta} \qquad (\ddot{\theta} < 0.116 \text{ rad/sec}^2) \tag{6}$$

where

$\mathrm{DISC}_{\mathrm{pitch}}$ discomfort due to random pitch vibration, DISC

$\ddot{\theta}$ rms random pitch floor acceleration level, rad/sec^2

The procedures and rationale used for derivation of pitch criteria (fig. 11 and eqs. (5) and (6)) were similar to those for development of roll criteria (fig. 10 and eqs. (3) and (4)).

Inspection of figure 11 indicates that the criteria for random pitch vibration were similar to those for random roll vibration. To examine this similarity in more detail, the two criteria curves are presented in figure 12. The two solid lines in the figure represent the separate discomfort functions for roll and pitch accelerations and the dashed line corresponds to an average discomfort function. There is not a significant difference between the slope functions for roll and pitch criteria; therefore, the average discomfort function (dashed line of fig. 12) can be used to specify a general angular criterion. The respective functions are

$$\mathrm{DISC}_{\mathrm{angular}} = 0.378 + 4.88\ddot{\alpha} \qquad (\ddot{\alpha} \geqq 0.129 \text{ rad/sec}^2) \tag{7}$$

$$\mathrm{DISC}_{\mathrm{angular}} = 7.04\ddot{\alpha} \qquad (\ddot{\alpha} < 0.129 \text{ rad/sec}^2) \tag{8}$$

where

$\mathrm{DISC}_{\mathrm{angular}}$ discomfort of random angular vibration, DISC

$\ddot{\alpha}$ rms random angular floor acceleration level, rad/sec^2

Longitudinal axis.- The random longitudinal-vibration criteria are shown in figure 13 in terms of discomfort DISC as a function of rms random longitudinal floor acceleration level for two bandwidths (5 and 10 Hz) of random vibration centered at 5 Hz. Through t-tests it was determined that no statistical differences exist between discomfort responses for the two bandwidths. Hence, a least-squares line was fit to the total data of figure 13. The resulting equation is given by

$$\mathrm{DISC}_{\mathrm{long}} = -0.021 + 42.2a_{\mathrm{long}} \tag{9}$$

where

$\mathrm{DISC}_{\mathrm{long}}$ discomfort of random longitudinal vibration, DISC

a_{long} rms random longitudinal floor acceleration level, g units

Since the longitudinal axis involves vibrations within the same geometric plane as the lateral-axis vibrations, an important consideration is whether or not these two axes of vibration produce similar effects on passenger discomfort. Figures 14(a) and (b) show a comparison of the discomfort associated with each of these axes for both a 5-Hz and a 10-Hz bandwidth.

Application of statistical tests to the data in figures 14(a) and (b) (e.g., t-tests of slope and intercept differences) indicated that statistical differences exist between the discomfort responses for these two axes. This implies that vibration about the two axes produces differential effects on passenger discomfort. Therefore, the criteria for each axis cannot be interchanged. This is contrary to the ISO recommendations.

Scale Transformation

The objective of the last test of this report was to derive a transformation between subjective data collected with a nine-point category scale and the universal discomfort scale developed in this report. Previous research (ref. 20) provided the necessary mathematical equations to transform the subjective scores collected with a variety of category scales to the discomfort scores of a unipolar, nine-point, continuous-type category scale. The results of this test, displayed in figure 15, show the relationship between discomfort DISC (adjusted magnitude estimates) and category evaluations of discomfort for identical vibration stimuli. The shaded area of the figure includes the plus and minus standard error of estimate associated with the linear least-squares curve. The equation for the line of figure 15 is

$$DISC_T = -0.022 + 0.951x \qquad (10)$$

where

$DISC_T$ total discomfort of any vibration, DISC

x discomfort-evaluation score measured along the category scale

The correlation coefficient computed for the 336 data pairs of figure 15 was 0.86, indicating that a high degree of accuracy is associated with the transformation. However, this transformation should be used with caution. For example, if the data collected with the category scale involved the use of an anchor vibration for a specific level of discomfort (e.g., ref. 15), then the discomfort evaluations of the category scale could be shifted up or down (depending on vibration anchor) and display a ceiling effect. The ceiling effect refers to clustering of discomfort evaluations at the upper end of the category scale. Consequently, the curve of figure 15 is not appropriate for transformation of subjective data that involve this type of anchoring procedure.

ISO Comparisons

It is of special interest to compare the recommendations of the International Standards Organization (ISO, ref. 11) with the discomfort criteria of this paper. The resulting comparisons are displayed in figures 16 to 19 for sinusoidal vertical (fig. 5), random vertical (fig. 8), sinusoidal lateral (fig. 6), and random lateral (fig. 9) discomfort criteria, respectively. The appropriate 1-minute reduced-comfort boundary of ISO is included in each of figures 16 to 19. There are two important implications that can be derived from the comparisons shown in each figure. First, the ISO reduced-comfort boundaries show a frequency trend directly analogous to that of the criteria developed in the present series of studies. Second, the absolute levels of the ISO reduced-comfort boundaries are higher than the corresponding criteria developed in the present studies. For example, the ISO reduced-comfort boundaries generally fall between the DISC = 3 and 4 curves of figures 16 to 19. These acceleration levels of the ISO curves correspond to conditions which approximately 100 percent (see fig. 4) of the passengers would consider uncomfortable.

There are two additional important implications that can be derived from comparisons between results of the current studies and the ISO recommendations. First, it was demonstrated in figure 14 that identical lateral- and longitudinal-axis vibrations do not produce equal levels of subjective discomfort. Therefore, contrary to the ISO recommendation, the discomfort criteria for these axes are not interchangeable. Second, the data of figure 12 indicate that the same discomfort evaluation results from exposure of passengers to identical pitch- or roll-axis vibrations. These results imply that the discomfort criteria for these axes are interchangeable. This implication represents an extension of current information for establishment of a universal set of discomfort criteria.

CONCLUDING REMARKS

A series of studies was conducted to develop criteria that allow prediction of passenger discomfort that is produced by short-duration vibrations within each axis of motion. Important results and conclusions that were derived from these studies include

(1) A scale of passenger discomfort (DISC scale), which is common to different axes of vibration, was developed. A transformation was also presented which related the discomfort scale to the percent of passengers that would find a particular DISC value uncomfortable.

(2) Discomfort criteria for sinusoidal vibration with associated predictive equations were developed for vertical, lateral, and roll axes of motion.

(3) Discomfort criteria for random vibration with associated predictive equations were developed for vertical, lateral, roll, pitch, and longitudinal axes of motion.

(4) Random-vibration criteria for pitch and roll axes are interchangeable.

(5) Random-vibration criteria for lateral and longitudinal axes are not interchangeable.

(6) The criteria results of the present report agree with ISO recommendations with respect to frequency trend but not with respect to absolute acceleration level. Results indicated that the acceleration levels specified by ISO for a reduced-comfort boundary correspond to approximately 100 percent of passengers being uncomfortable.

Langley Research Center
National Aeronautics and Space Administration
Hampton, VA 23665
March 28, 1979

APPENDIX A

INSTRUCTIONS TO SUBJECTS

The instructions given to subjects for four different tasks are outlined in successive sections. Preliminary instructions of an introductory and safety nature, as well as instructions to subjects upon entering the simulator were common to each task and are provided prior to specific task instructions. For the test involving noise as well as vibration, the word "noise" was inserted in these instructions subsequent to the word "vibration."

Preliminary Instructions

You have volunteered to participate in a research program to investigate the quality of rides. Specifically, we wish to identify the types of vibration in transportation vehicles which most influence a person's sense of well-being. To assess the influence of these vibrations, we have built a simulator which can expose passengers to realistic ride motions. The simulator essentially provides no risk to passengers since it has been designed to meet stringent safety requirements such that it cannot expose subjects to motions which are known to cause injury. It contains many built-in safety features which automatically shut the system down if it does not perform properly.

The vibrations that you will receive today are representative of vibrations you may experience in an airplane. You will enter the simulator, take a seat, fasten the seatbelt, and assume a comfortable position with both feet on the floor. Selected vibrations will then be applied to the cabin. You are to make yourself as comfortable and relaxed as possible while the test is being conducted; however, you must keep your feet on the floor and keep your seatbelts fastened at all times. During the tests you will at all times be in two-way communication with the test conductor.

You have the option at any time and for any reason to terminate the tests in any of three ways: (1) by pressing overhead button labeled "STOP," (2) by voice communication with the test conductor, or (3) by pressing downward on the toggle switch located at the front of each right-hand armrest. Because of individual differences in people, there is always the possibility that someone may find the motions objectionable and may not wish to continue. If this should happen to you, please do not hesitate to stop the tests by one of the above methods.

Simulator Instructions

(Upon entering the simulator, the subject should be told:) Please be seated and fasten your seatbelt. (Waiting until all the subjects are ready.) The mirror you see in front of you is a two-way mirror to allow the operator to monitor any discomfort you may have during a ride. In addition, as I told you before, the test conductor will be able to hear everything you say. Also, if you wish to end the test, you can push the toggle switch, press one of these little buttons (point to both), or you can ask the test conductor to stop the test and let you out.

Dichotomous Comfort Evaluations

The task you will now be required to perform is to evaluate the comfort associated with a series of ride segments. Specifically, you will be asked to rate each ride segment as being either "comfortable" or "uncomfortable." Each ride segment will be presented for approximately 15 seconds. At the beginning of each segment you are to rate, the test conductor will say "start," and at the end of the ride segment, he will say "stop." Immediately after the word "stop," you are to evaluate the ride segment just experienced by placing an appropriate mark on the rating sheet. For example, if you feel that the ride segment just experienced is "comfortable," then you should mark the appropriate place on the rating sheet with a "C." If you feel that the ride is "uncomfortable," then you should mark the rating sheet with an "X," i.e.,

Comfortable = C

Uncomfortable = X

Evaluation marks.- You should record your evaluation (letter) of the ride segment on the blank space next to the ride segment number. For example, the data sheet for you to record your evaluation of a ride segment will look something like the following:

Ride Segment

1 C

2 X

3 X

4 ___

Evaluations.- There are two requirements you should use in your evaluations. First, your evaluations should be based upon vibration. Certainly you could evaluate a ride based on other factors such as temperature and pressure. However, restrict your evaluations of a ride segment to variations of vibration.

Second, base your evaluation of a ride upon comfort of a vibration, not only upon variations of vibration. In other words, rate a ride segment in terms of comfort of a vibration, not on whether you notice differences of vibration. This requirement is important because we are interested in differences of comfort, not merely your ability to detect differences of vibrations.

Consistency.- It is typical for participants in the study to "try and be consistent." Instead of trying to be consistent with previous ride segments, try and evaluate each segment without looking at evaluations of previous ride segments. Please do not be concerned about whether your ratings agree with the others in the simulator with you. Remember we want to know how different people feel about the ride. You may talk between the segments you are to rate, but please do not talk during them. It is also typical for participants to feel that they are not doing well at this task. It is usually true, however, that participants are doing better than they think they are, so don't be discouraged if you find the task difficult or monotonous at times.

Remember.-

1. Listen for the words "start" and "stop."

2. Evaluate only the comfort of vibrations.

3. Place your evaluation in the appropriate blank: C to indicate comfortable and X to indicate uncomfortable.

Are there any questions?

Constant Stimuli

The task you will now be required to perform is to indicate whether you think the discomfort of a ride segment is "greater" or "less" than the discomfort of a standard ride segment. This means that your discomfort evaluation of a particular ride will always be in comparison to the standard ride segment. I will specify the start of a ride segment with the word "start," and I will specify the end of a ride segment with the word "stop." After you hear the word "stop," you are to evaluate the ride segment in comparison to the standard ride segment. I will present the ride segment, termed the standard ride, at the beginning, and intermittently throughout your evaluations.

Evaluation marks.- You should record your evaluation of a ride segment, greater or less, on the blank space next to the ride segment number. For example, the data sheet for you to record your evaluation of a ride segment will look like the following:

Ride Segment

1 G

2 L

3 L

Evaluations.- There are two requirements you should use in your evaluations. First, your evaluations should be based upon vibration. Certainly you could evaluate a ride based on other factors such as temperature and pressure. However, restrict your evaluations of a ride segment to variations of vibration.

Second, base your evaluation of a ride upon comfort of a vibration, not only upon variations of vibration. In other words, rate a ride segment in terms of comfort of a vibration, not on whether you notice differences of vibration. This requirement is important because we are interested in differences of comfort, not merely your ability to detect differences of vibrations.

Consistency.- It is typical for participants in the study to "try and be consistent." Instead of trying to be consistent with previous ride segments, try and evaluate each segment without looking at evaluations of previous ride segments. Please do not be concerned about whether your ratings agree with the others in the simulator with you. Remember we want to know how different people feel about the ride. You may talk between the segments you are to rate, but please do not talk during them. It is also typical for participants to feel that they are not doing well at this task. It is usually true, however, that participants are doing better than they think they are, so don't be discouraged if you find the task difficult or monotonous at times.

Remember.-

1. Listen for the words "start" and "stop."

2. Evaluate only the discomfort of vibrations.

3. Place your evaluation, greater or less discomfort on the appropriate blank.

Are there any questions?

Magnitude Estimation

The task you will now be required to perform is to evaluate the discomfort of ride segments. I will present one type of ride segment, termed the standard, at the beginning and intermittently throughout your evaluations. The standards will be the same within each session but differ from session to session. The discomfort of the standard ride segment is to be assigned the number 100. I will also present ride segments termed comparison ride segments that provide both less or more discomfort than the standard 100. Your task will be to assign numbers to each of these comparison ride segments above and below the standard 100. Try to assign the appropriate number to each ride segment regardless of what you may have called the previous ride segment. If, for example, the ride segment seems to provide twice the discomfort as the standard, say 200. If the ride segment provides one-tenth the discomfort, say 10. If the ride segment provides one-fourth the discomfort of the standard, say 25. As you know, there are infinite numbers above as well as below the standard of 100. You may use decimals, fractions, or whole numbers. Do not use zero or negative numbers in your evaluations.

Evaluation marks.- You should record your evaluation (number) of the ride segment on the blank space next to the ride segment number. For example, the data sheet for you to record your evaluation of a ride segment will look like the following:

Ride Segment

1 23

2 200

3 25

4 ____

Evaluations.- There are two requirements you should use in your evaluations. First, your evaluations should be based upon vibration. Certainly, you could evaluate a ride based on other factors such as temperature or pressure. However, restrict your evaluations of a ride segment to variations of vibration.

Second, base your evaluation of a ride upon comfort of a vibration, not only upon variations of vibration. In other words, rate a ride segment in terms of comfort of a vibration, not on whether you notice differences of vibration. This requirement is important because we are interested in differences of comfort, not merely your ability to detect differences of vibrations.

Consistency.- It is typical for participants in the study to "try and be consistent." Instead of trying to be consistent with previous ride segments, try and evaluate each segment without looking at evaluations of previous ride segments. Please do not be concerned about whether your ratings agree with the others in the simulator with you. Remember we want to know how different people feel about the ride. You may talk between the segments you are to rate, but please do not talk during them. It is also typical for participants to feel that they are not doing well at this task. It is usually true, however, that participants are doing better than they think they are, so don't be discouraged if you find the task difficult or monotonous at times.

Remember.-

1. Listen for the words "start" and "stop."

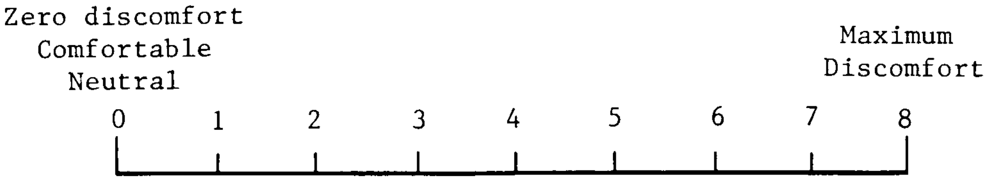
2. Evaluate only the discomfort of vibrations.

3. Place your evaluation number on the appropriate blank.

Are there any questions?

Category Scale Evaluations

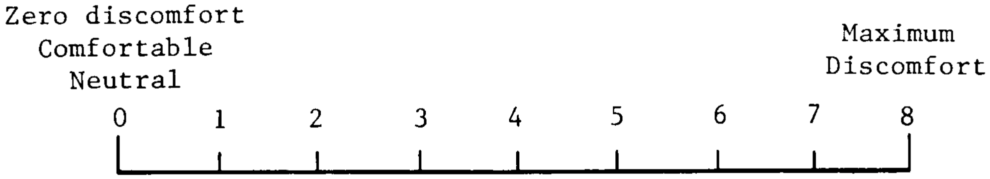
The task you will be required to perform is to evaluate the discomfort associated with various ride segments. Each ride segment, to be evaluated by yourself, will be presented to you for a total of 15 seconds. I will specify the start of a ride segment with the word "start," and I will specify the end of a ride segment with the word "stop." Evaluate the discomfort of a vibration contained in a ride segment in terms of the following scale:



There will be several seconds between successive ride segments to allow you to mark your evaluation.

Evaluation marks.- You should record your evaluation of the discomfort associated with the vibration of each ride segment by placing a checkmark (✓) upon the scale. Try to be careful in recording your evaluations because the point of the checkmark (✓) will be used for interpretation of distance along the scale.

Scale interpretation.-



The discomfort scale should be interpreted as if equal numerical distances represented equal discomfort. For example, the magnitude of discomfort between 1 and 2 is equal to the magnitude of discomfort between 5 and 6. The total continuum should be conceived as representing increasing discomfort values (smallest to greatest) you may associate with vibration.

There are two requirements you should use in your evaluations. First, your evaluations should be based upon vibration. Certainly, you could evaluate a ride based on other factors such as temperature and pressure. However, restrict your evaluations of a ride segment to variations of vibration.

Second, base your evaluation of a ride upon comfort of a vibration, not only upon variations of vibration. In other words, rate a ride segment in terms of comfort of a vibration, not on whether you notice differences of vibration. This requirement is important because we are interested in differences of comfort, not merely your ability to detect differences of vibrations.

Consistency.- It is typical for participants in the study to "try and be consistent." Instead of trying to be consistent with previous ride segments, try and evaluate each segment without looking at evaluations of previous ride segments. Please do not be concerned about whether your ratings agree with the others in the simulator with you. Remember we want to know how different people feel about the ride. You may talk between the segments you are to rate, but please do not talk during them. It is also typical for participants to feel that they are not doing well at this task. It is usually true, however, that participants are doing better than they think they are, so don't be discouraged if you find the task difficult or monotonous at times.

Remember.-

1. Listen for the words "start" and "stop."

2. Evaluate the vibration of each ride segment in terms of the discomfort you associated with such a ride.

3. Interpret the discomfort scale as if equal numerical distances represent equal discomfort magnitudes.

4. Carefully place your evaluation mark on the continuum.

Are there any questions?

APPENDIX B

VIBRATION TESTING ORDER

The order of presentation of vibration ride segments varied with the type of test conducted. For the scale anchoring test only 9-Hz vertical vibrations were investigated and successive ride segments within a session consisted of randomizations (twice, without replacement) of the nine acceleration levels. The order of presentation for frequency equating and sinusoidal dose vibration tests was similar since both types of tests involved the use of sinusoidal standard and comparison ride segments. The frequencies of vibration within an axis were randomized to determine the frequency content of comparison rides in a session. The five or seven acceleration levels investigated for each frequency (number of acceleration levels depended on the test) were then randomized twice, without replacement, to determine successive comparison ride segments of a session.

The ride-segment order for each session consisted of a standard ride segment followed by either two or three comparison ride segments. It should be noted that for criteria-development investigations of the vertical axis of vibration, the frequency range of 1 to 30 Hz was divided into equal thirds prior to the randomizations and presentation of these vibrations to subjects. This procedure was necessitated to maintain an overall testing period of less than 2 1/2 hours for each subject. In addition, two different test procedures were used for vertical vibration testing, because previous research (ref. 21), indicated subjective responses (i.e., magnitude estimations) for this type of task could vary with the manner in which stimuli (vibrations) were presented to subjects. The procedural differences consisted of using two acceleration levels at each vibration frequency for standard ride segments, as well as two ranges of acceleration levels for comparison ride segments of a select frequency.

The order of presentation for tests of response to random vibration and axis equating was identical with previous tests of frequency equating and sinusoidal dose tests. The difference between these tests and previous tests was the physical vibration characteristics that were randomized.

APPENDIX C

TYPICAL TEST RESULTS

Figures C1 to C5 show examples of some typical test results. Figure C1 shows one example of the standard normal score z as a function of the vertical floor acceleration and C2 shows the corresponding mean magnitude estimations of discomfort. Figure C3 shows standard normal score z for lateral acceleration levels. Figure C4 shows representative data of discomfort as a function of vertical acceleration for two bandwidths of frequency. Figure C5 shows similar data for lateral acceleration.

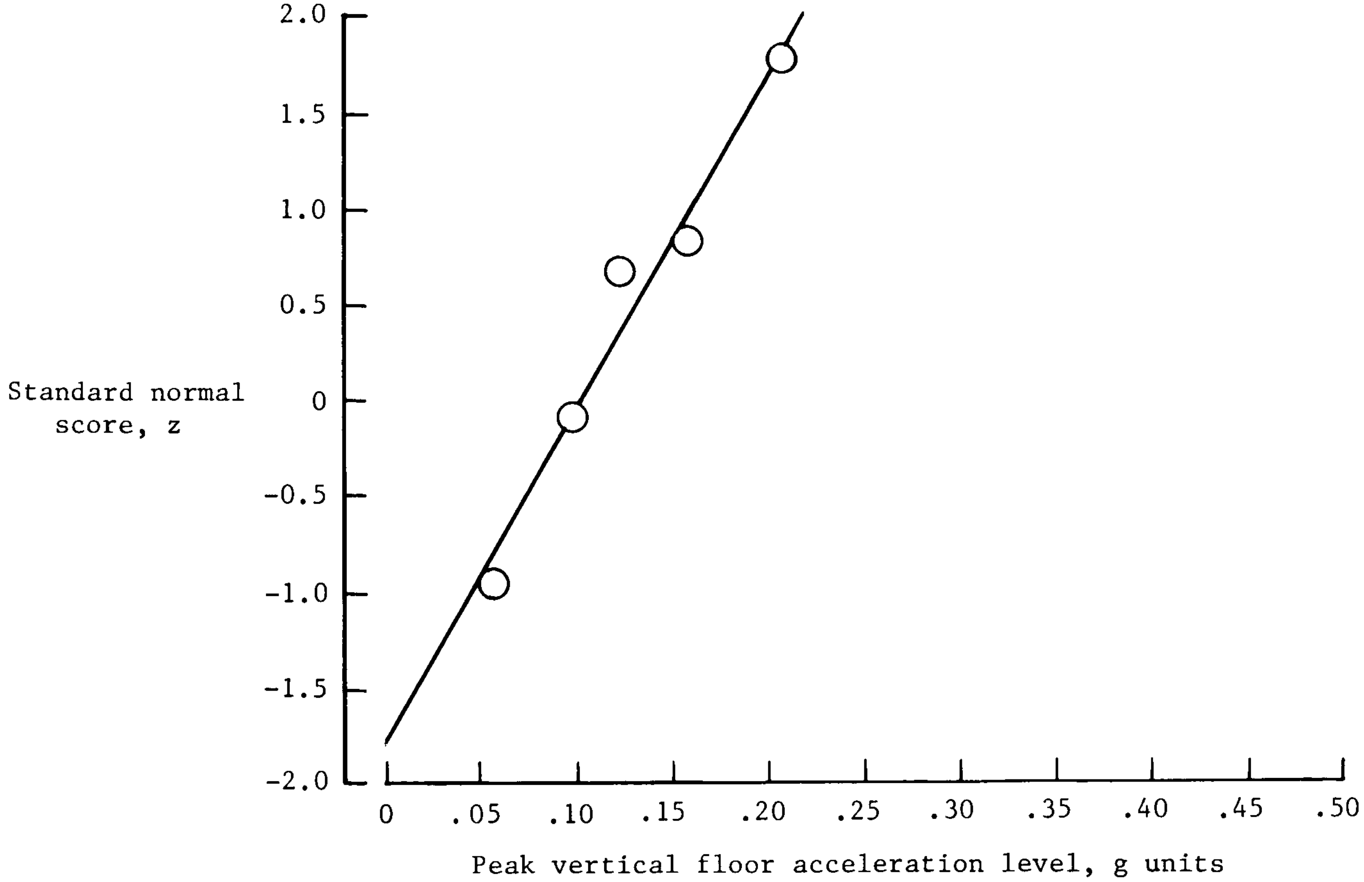


Figure C1.- The z-score transformations of percent of comparison ride segments of 5-Hz vertical vibration evaluated as having greater discomfort than standard ride segments of 9-Hz vertical vibration (peak acceleration level, 0.153g) as a function of peak floor acceleration level of 5-Hz vertical vibration.

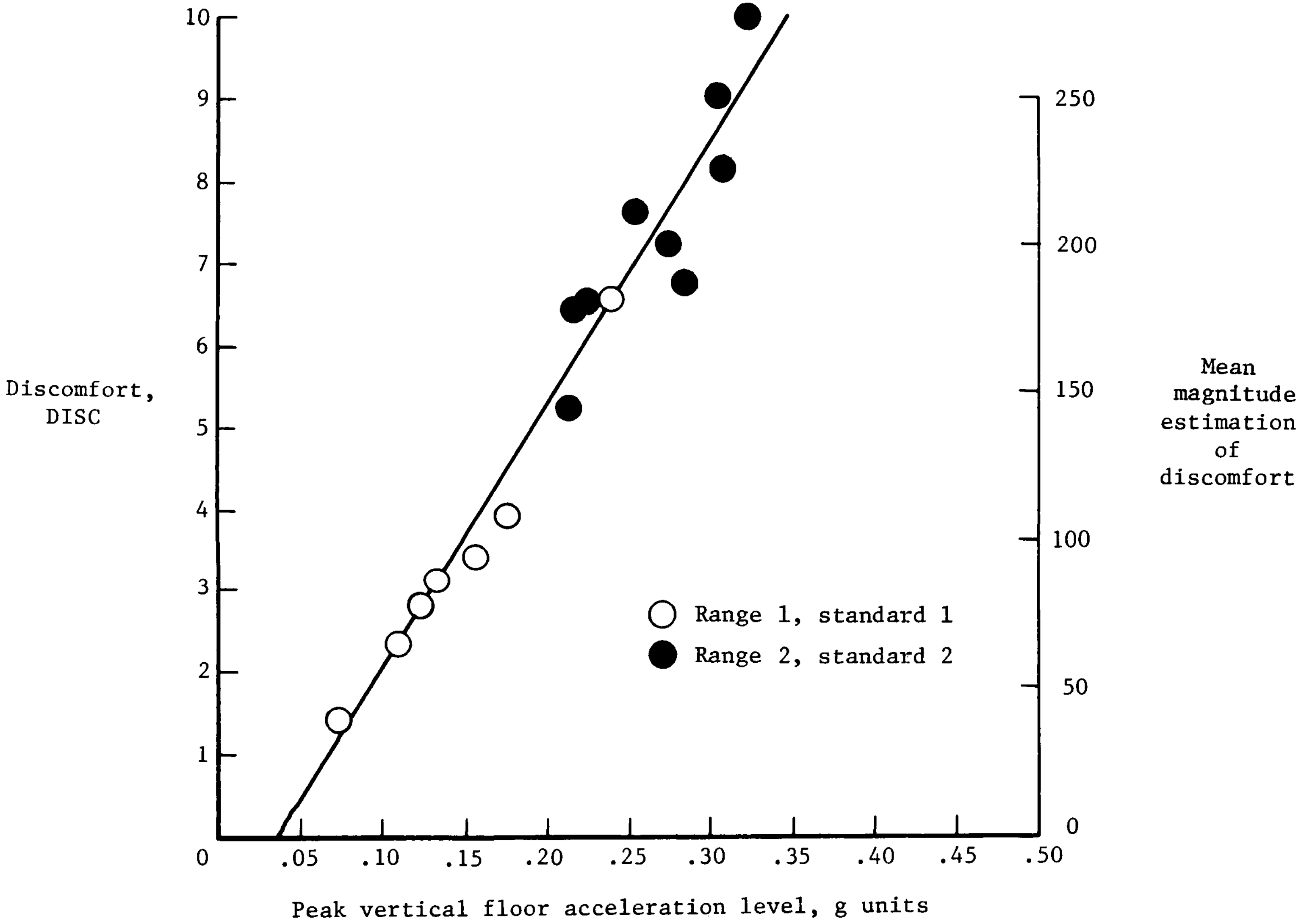


Figure C2.- Discomfort and mean magnitude estimations of discomfort as a function of the peak floor acceleration level of 5-Hz vertical vibration, investigated for two ranges of acceleration level.

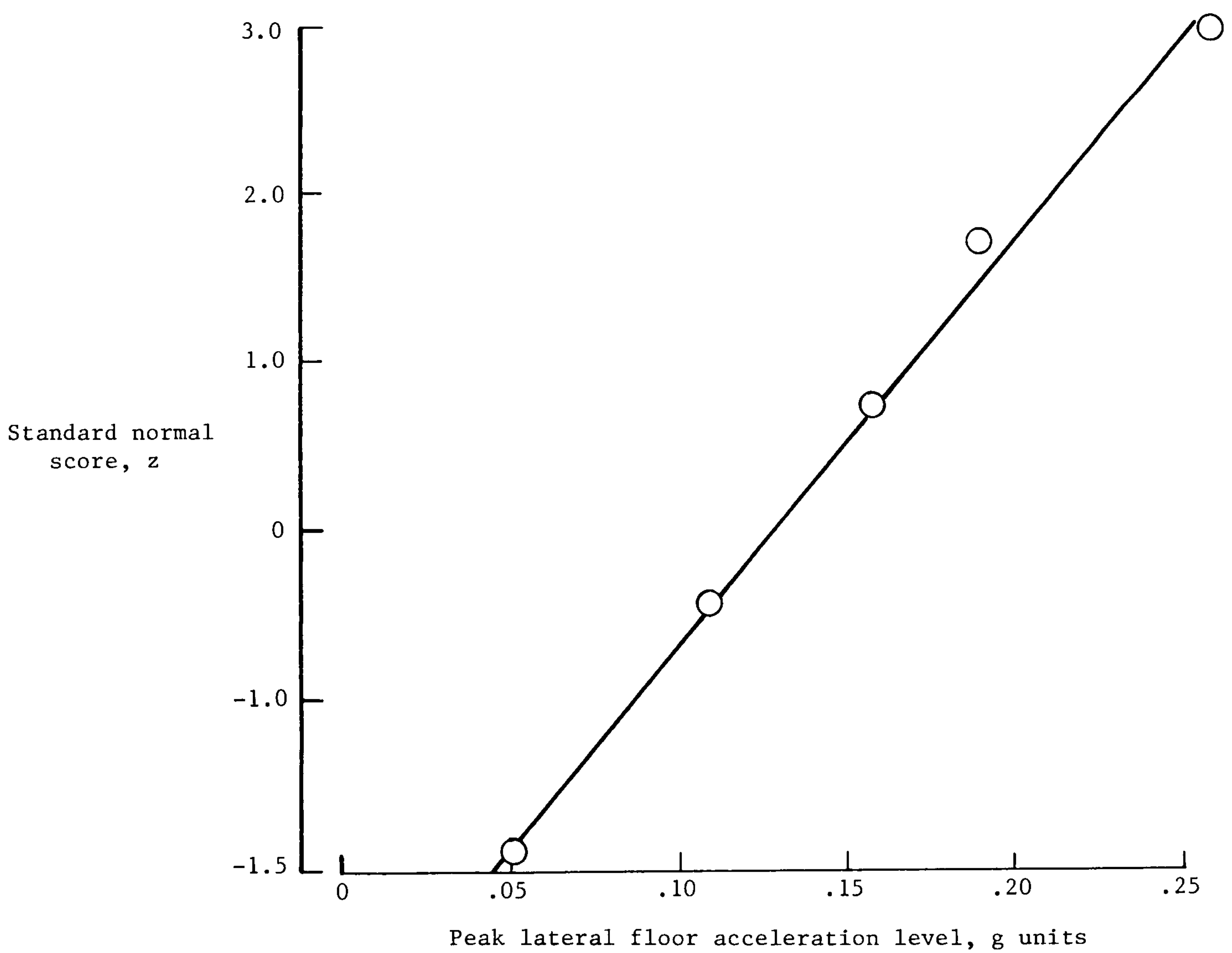


Figure C3.- The z-score transformations of percentage of comparison ride segments of 5-Hz lateral vibration evaluated as having greater discomfort than standard ride segments of 9-Hz vertical vibration (peak acceleration level, 0.136g) as a function of peak floor acceleration level of 5-Hz lateral vibration.

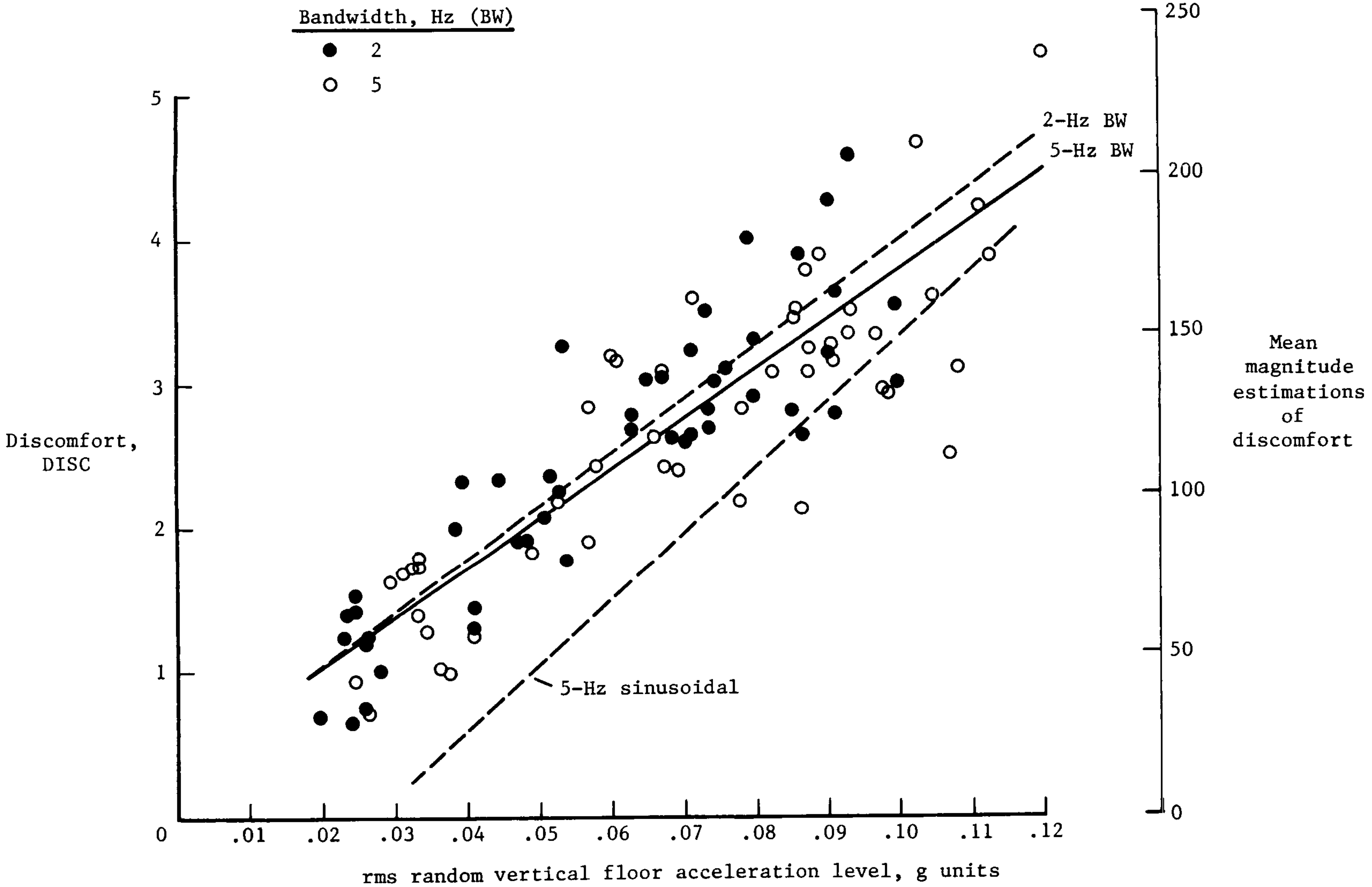


Figure C4.- Discomfort and mean magnitude estimations of discomfort for 2- and 5-Hz bandwidth vertical vibrations centered at 5 Hz as well as similar responses for 5-Hz sinusoidal vibration, as a function of random vertical floor acceleration level.

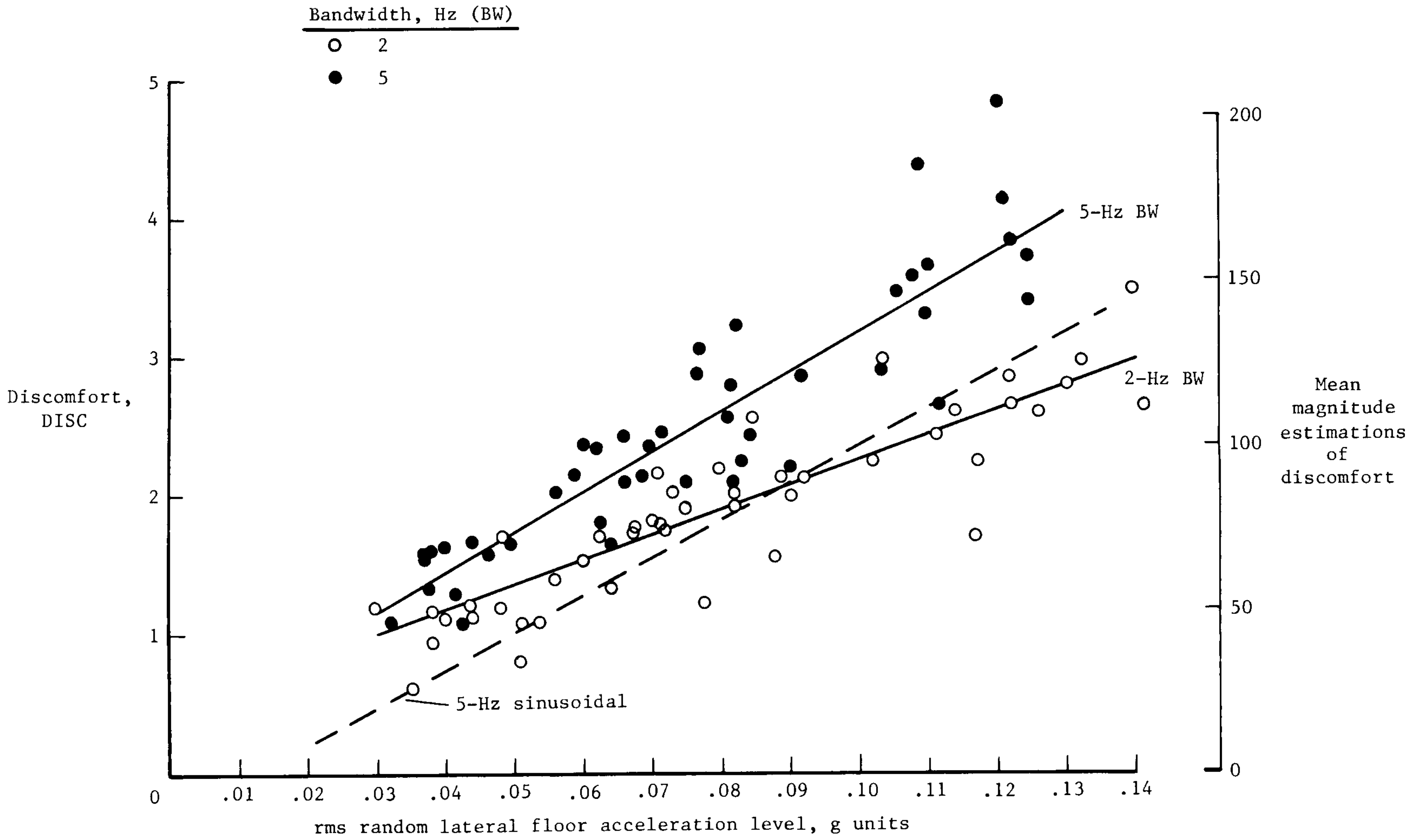


Figure C5.- Discomfort for 2- and 5-Hz bandwidth lateral vibrations centered at 5 Hz, as well as 5-Hz sinusoidal lateral vibration, as a function of random lateral floor acceleration level.

REFERENCES

1. Symposium on Vehicle Ride Quality. NASA TM X-2620, 1972.
2. 1975 Ride Quality Symposium. NASA TM X-3295, DOT-TSC-OST-75-40, 1975.
3. Dempsey, Thomas K.: A Model and Predictive Scale of Passenger Ride Discomfort. NASA TM X-72623, 1974.
4. Leatherwood, Jack D.; and Dempsey, Thomas K.: A Model for Prediction of Ride Quality in a Multifactor Environment. NASA TM X-72842, 1976.
5. Dempsey, Thomas K.; and Leatherwood, Jack D.: Prediction of Passenger Ride Quality in a Multifactor Environment. NASA TM X-73945, 1976.
6. Hanes, R. M.: Human Sensitivity to Whole-Body Vibration in Urban Transportation Systems: A Literature Review. APL JHU-TPR 004, Johns Hopkins Univ., May 1970.
7. Jones, A. J.; and Saunders, D. J.: Equal Comfort Contours for Whole Body Vertical Pulsed Sinusoidal Vibration. J. Sound & Vib., vol. 23, no. 1, July 1972, pp. 1-14.
8. Miwa, Toshisuke: Evaluation Methods for Vibration Effect. Part 1. Measurements of Threshold and Equal Sensation Contours of Whole Body for Vertical and Horizontal Vibrations. Ind. Health, vol. 5, 1967, pp. 183-205.
9. Shoenberger, Richard W.; and Harris, C. Stanley: Psychophysical Assessment of Whole-Body Vibration. Hum. Factors, vol. 13, no. 1, Feb. 1971, pp. 41-50.
10. Leatherwood, Jack D.; and Dempsey, Thomas K.: Psychophysical Relationships Characterizing Human Response to Whole-Body Sinusoidal Vertical Vibration. NASA TN D-8188, 1976.
11. Guide for the Evaluation of Human Exposure to Whole-Body Vibration. Draft Int. Stand. ISO/DIS 2631, Int. Organ. Stand., 1972.
12. Clevenson, Sherman A.; and Leatherwood, Jack D.: On the Development of Passenger Vibration Ride Acceptance Criteria. Shock & Vib. Bull. 43, Pt. 3, U.S. Dep. Def., June 1973, pp. 105-111.
13. Stephens, David G.; and Clevenson, Sherman A.: The Measurement and Simulation of Vibration for Passenger Ride Quality Studies. Proceedings of the Technical Program, NOISEXPO - National Noise and Vibration Control Conference, c.1974, pp. 86-92.
14. Dempsey, Thomas K.; and Leatherwood, Jack D.: Methodological Considerations in the Study of Human Discomfort to Vibration. Proceedings Addendum - International Conference on High Speed Ground Transportation, Arizona State Univ., Jan. 1975, pp. A67-A88.

15. Dempsey, Thomas K.; and Leatherwood, Jack D.: Experimental Studies for Determining Human Discomfort Response to Vertical Sinusoidal Vibration. NASA TN D-8041, 1975.

16. Leatherwood, Jack D.: Vibrations Transmitted to Human Subjects Through Passenger Seats and Considerations of Passenger Comfort. NASA TN D-7929, 1975.

17. Dempsey, Thomas K.; and Leatherwood, Jack D.: Vibration Simulator Studies for the Development of Passenger Ride Comfort Criteria. 1975 Ride Quality Symposium, NASA TM X-3295, DOT-TSC-OST-75-40, 1975, pp. 601-614.

18. Leatherwood, Jack D.; Dempsey, Thomas K.; and Clevenson, Sherman A.: An Experimental Study for Determining Human Discomfort Response to Roll Vibration. NASA TN D-8266, 1976.

19. Dempsey, Thomas K.; and Leatherwood, Jack D.: Vibration Ride Comfort Criteria. Proceedings 6th Congress of the International Ergonomics Association "Old World, New World, One World" and Technical Program of the 20th Annual Meeting of the Human Factors Society, c.July 1976, pp. 260-266.

20. Dempsey, Thomas K.; Coates, Glynn D.; and Leatherwood, Jack D.: An Investigation of Ride Quality Rating Scales. NASA TP-1064, 1977.

21. Poulton, E. C.: The New Psychophysics: Six Models for Magnitude Estimation. Psychol. Bull., vol. 69, no. 1, Jan. 1968, pp. 1-19.

TABLE I.- SUMMARY OF SUBJECT DEMOGRAPHICS

Test	Number			Age		Weight	
	Males	Females	Total	Median, yrs	Range, yrs	Mean, kg (lb)	Standard deviation, kg (lb)
Scale anchoring	51	81	132	23	18 to 57	66.0 (145.5)	13.8 (30.5)
Scale transformation	37	149	186	31	18 to 52	64.8 (142.8)	13.3 (29.3)
Criteria development:							
Vertical axis:							
Frequency equating	12	42	54	18	18 to 31	60.2 (132.8)	10.3 (22.8)
Sinusoidal dose response	41	55	96	21	18 to 55	67 (147.8)	14.2 (31.4)
Random dose response	15	21	36	20	18 to 57	61.2 (135.0)	11.3 (25.0)
Lateral axis:							
Frequency equating	12	24	36	33	18 to 55	69.8 (153.9)	13.6 (29.9)
Sinusoidal dose response	12	36	48	24	18 to 63	64.4 (141.9)	13.5 (29.8)
Random dose response	18	30	48	25	18 to 57	63.6 (140.2)	12.7 (28.0)
Axis equating	12	24	36	33	18 to 55	69.8 (153.9)	13.6 (29.9)
Roll axis:							
All tasks	18	54	72	25	18 to 45	64.8 (142.8)	15.2 (33.6)
Longitudinal axis:							
Random-vibration response	14	94	108	30	18 to 63	63.4 (139.7)	10.4 (23.0)
Pitch axis:							
Random-vibration response	14	94	108	30	18 to 63	63.4 (139.7)	10.4 (23.0)

TABLE II.- EXPERIMENTAL DESIGN[a]

Axis of vibration	Evaluation procedure for test area and specific test -					
	Scale anchoring	Criteria development				Scale transformation[b]
	Threshold of discomfort	Frequency equating	Sinusoidal dose response	Random dose response	Axis equating	Equating of scales
Vertical	Dichotomous comfort response	Constant stimuli	Magnitude estimation	Magnitude estimation		Category scale and magnitude estimation
Lateral		Constant stimuli	Magnitude estimation	Magnitude estimation	Constant stimuli	
Roll		Constant stimuli	Magnitude estimation	Magnitude estimation	Constant stimuli	
Pitch				Magnitude estimation		
Longitudinal				Magnitude estimation		

[a] Entries in the table indicate the type of subjective evaluation.

[b] Random vibrations of vertical and lateral, vertical and roll, and vertical, lateral, and roll, as well as these vibrations combined with noise were investigated.

TABLE III.- SUMMARY OF VIBRATION CHARACTERISTICS FOR STANDARD AND COMPARISON RIDE SEGMENTS FOR SCALE ANCHORING AND SCALE TRANSFORMATION TESTS

Characteristic	Scale anchoring tests	Scale transformation tests
Standard ride segments		
Axis of vibration		Vertical
Type of vibration		Sinusoidal
Frequency, Hz		9
rms acceleration[a]		0.11
Onset-offset, sec		10
Number of vibrations[c] . .		56
Time between vibrations, sec		5
Comparison ride segments		
Axis of vibration	Vertical	Multiple[b]
Type of vibration	Sinusoidal	Random
Frequency, Hz	9	------------
Center frequency, Hz . .	------------	2, 3, 5, 7
Bandwidth, Hz	------------	2, 5, 10
rms acceleration[a]	0.02 to 0.12	0.02 to 0.10
Onset-offset, sec	5	5
Duration, sec	10	15
Number of vibrations[c] . .	180	168
Time between vibrations, sec	5	5

[a] Units are in g units for vertical, lateral, and longitudinal axes, and units are in radians per second squared for roll or pitch axes.

[b] Random vibrations of vertical, vertical and lateral, vertical and roll, and vertical, lateral, and roll.

[c] Total number of vibrations per subject.

TABLE IV.- SUMMARY OF VIBRATION CHARACTERISTICS

DIFFERENT CRITERIA DEVELOPMENT TESTS

Characteristic	Vertical axis tests			Longitudinal axis tests	Pitch axis tests
	Frequency equating	Sinusoidal dose response	Random dose response	Random dose response	Random dose response
Standard ride					
Axis of vibration	Vertical	Vertical	Vertical	Vertical	Vertical
Type of vibration	Sinusoidal	Sinusoidal	Sinusoidal	Sinusoidal	Sinusoidal
Frequency, Hz	9	Variable	9	9	9
rms acceleration[a]	0.11	Variable	0.10	0.09	0.09
Onset-offset, sec	5	5	5	5	5
Duration, sec	10	10	10	10	10
Number of vibrations[b] . .	50	30	48	24	12
Time between vibrations, sec	5	5	5	5	5
Comparison					
Axis of vibration	Vertical	Vertical	Vertical	Longitudinal	Pitch
Type of vibration	Sinusoidal	Sinusoidal	Random	Random	Random
Frequency, Hz	1-30	1-30	----------	----------	----------
Center frequency, Hz . .	----------	----------	2-9, 13	5	3
Bandwidth, Hz	----------	----------	2, 5, 10	5, 10	5
rms acceleration[a]	0.04-0.34	0.04-0.34	0.03-0.12	0.03-0.15	0.20-1.1
Onset-offset, sec	5	5	5	5	5
Duration, sec	10	10	15	15	15
Number of vibrations[b] . .	100	90	144	72	36
Time between vibrations, sec	5	5	5	5	5

[a] Units are in g units for vertical, lateral, and longitudinal axes. Units are

[b] Total number of vibrations per subject.

OF STANDARD AND COMPARISON RIDE SEGMENTS FOR

WITHIN THE VARIOUS AXES OF VIBRATION

Lateral axis tests				Roll axis tests			
Frequency equating	Sinusoidal dose response	Random dose response	Axis equating	Frequency equating	Sinusoidal dose response	Random dose response	Axis equating
segments							
Lateral	Lateral	Lateral	Vertical	Roll	Roll	Roll	Vertical
Sinusoidal	Sinusoidal	Sinusoidal	Sinusoidal	Sinusoidal	Sinusoidal	Sinusoidal	Sinusoidal
5	Variable	5	9	2	Variable	3	9
0.10	Variable	0.10	0.10	0.32	Variable	0.57	0.10
5	5	5	5	5	5	5	5
10	10	10	10	10	10	10	10
45	30	32	10	30	24	6	10
5	5	5	5	5	5	5	5
ride segments							
Lateral	Lateral	Lateral	Lateral	Roll	Roll	Roll	Roll
Sinusoidal	Sinusoidal	Random	Sinusoidal	Sinusoidal	Sinusoidal	Random	Sinusoidal
1-10	1-10	----------	5	1-4	1-4	----------	3
----------	----------	2-9	----------	----------	----------	3	----------
----------	----------	2, 5, 10	----------	----------	----------	5	----------
0.04-0.28	0.04-0.34	0.03-0.12	0.04-0.18	0.23-0.62	0.23-0.62	0.18-1.54	0.11-0.57
5	5	5	5	5	5	5	5
10	10	15	10	10	10	15	10
90	90	96	20	60	72	18	20
5	5	5	5	5	5	5	5

in radians per second squared for pitch and roll axes.

TABLE V.- SUMMARY OF INTERCEPT AND SLOPE COEFFICIENTS FOR LEAST-SQUARES LINEAR FUNCTIONS BETWEEN DISCOMFORT AND PEAK VERTICAL FLOOR ACCELERATION LEVELS FOR EACH SINUSOIDAL VERTICAL FREQUENCY INVESTIGATED

Frequency, Hz	Intercept	Slope
1	0.3946	8.8296
2	-.3713	15.2731
3	-.7685	21.4441
4	-1.0028	27.1273
5	-1.2352	32.2146
6	-.7592	28.8279
7	-.7188	27.4856
8	-.0576	19.8988
9	-.8919	21.9987
10	-1.2718	22.9530
11	-.6912	16.9931
12	-.4937	14.0437
13	-.3695	12.0297
14	-.3470	10.7501
15	-.5220	10.4234
16	-0.1406	8.3656
17	.1650	6.8997
18	-.2190	7.5948
19	-.3326	7.5326
20	.0986	6.1421
21	-.1989	6.7045
22	-.1769	6.5021
23	.0345	5.9102
24	-.0465	6.0773
25	.0494	5.8456
26	.0010	6.0208
27	-.0684	6.2664
28	-.1695	6.6472
29	-.0324	6.4483
30	-.0766	6.7358

TABLE VI.- SUMMARY OF INTERCEPT AND SLOPE COEFFICIENTS FOR LEAST-SQUARES LINEAR FUNCTIONS BETWEEN DISCOMFORT AND PEAK LATERAL FLOOR ACCELERATION LEVELS FOR EACH SINUSOIDAL LATERAL FREQUENCY INVESTIGATED

Frequency, Hz	Intercept	Slope
1	-0.8322	26.7849
2	-1.1106	52.2679
3	-.3586	32.1940
4	.0217	19.9130
5	-.3163	19.0267
6	-.7048	19.8629
7	-.7024	16.3704
8	-.4184	14.8952
9	-.0636	11.6969
10	-.3307	8.9291

TABLE VII.- SUMMARY OF INTERCEPT AND SLOPE COEFFICIENTS FOR LEAST-SQUARES LINEAR FUNCTIONS BETWEEN DISCOMFORT AND PEAK ROLL ACCELERATION LEVEL FOR EACH SINUSOIDAL ROLL FREQUENCY INVESTIGATED

Frequency, Hz	Intercept	Slope
1	-2.3302	5.8994
2	-.1455	4.6724
3	.2830	2.4946
4	.3405	2.3532

TABLE VIII.- SUMMARY OF INTERCEPT AND SLOPE COEFFICIENTS FOR LEAST-SQUARES LINEAR FUNCTIONS BETWEEN DISCOMFORT AND RANDOM VERTICAL FLOOR ACCELERATION LEVELS FOR RANDOM VIBRATIONS OF SELECT CENTER FREQUENCIES OF VIBRATION

Center frequency, Hz	Intercept	Slope
2	-0.2737	25.6976
3	-.0434	36.3625
4	-.1456	44.7799
5	.2270	36.0383
6	.2912	39.4716
7	.2217	38.0780
8	.1433	37.6770
9	.3367	31.7515
10	.3141	28.7898
11	.4608	26.0990
12	.4413	22.1400
13	.4217	18.1807

TABLE IX.- SUMMARY OF INTERCEPT AND SLOPE COEFFICIENTS FOR LEAST-SQUARES LINEAR FUNCTIONS BETWEEN DISCOMFORT AND RANDOM LATERAL FLOOR ACCELERATION LEVELS FOR RANDOM LATERAL VIBRATIONS OF SELECT CENTER FREQUENCIES AND BANDWIDTHS

Center frequency, Hz	Bandwidth, Hz	Intercept	Slope
2	2	0.5384	37.8339
3	2	.2954	32.3312
3	5	-.2149	49.0092
4	2	.7221	21.5835
4	5	-.1565	39.3229
5	2	.4785	17.8407
5	5	.2816	29.1386
5	10	-.5531	39.8261
6	2	.3101	18.2296
6	5	.2292	28.3390
7	2	.3830	17.4845
7	5	.2190	22.6535
8	2	.0784	20.7663
8	5	.3585	20.7794
9	2	.0558	19.9090

L-78-600

Figure 1.- Passenger ride quality apparatus (PRQA) at the Langley Research Center.

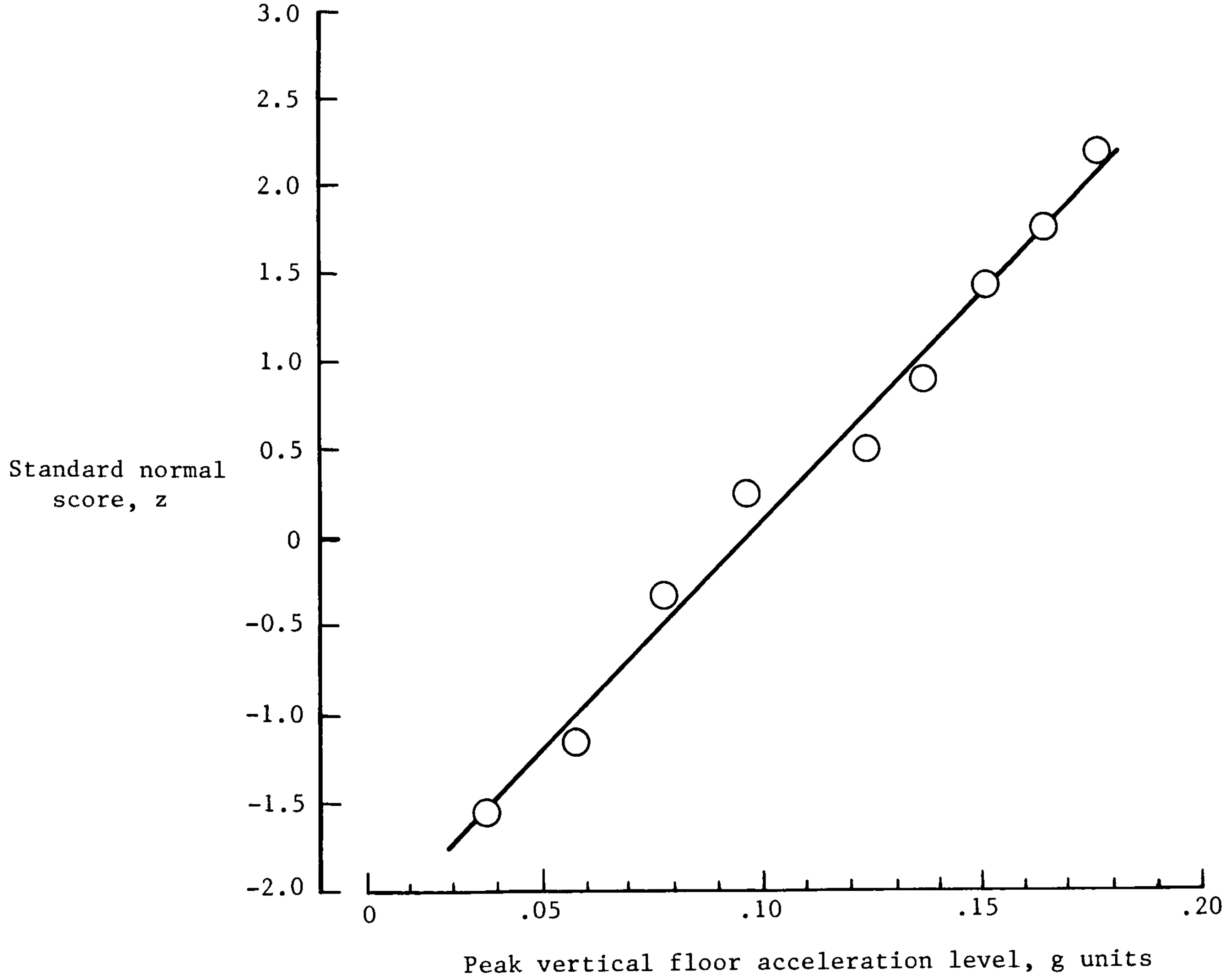


Figure 2.- Standard normal score z transformations of percentage of 9-Hz vertical vibrations evaluated as uncomfortable as a function of peak vertical floor acceleration level.

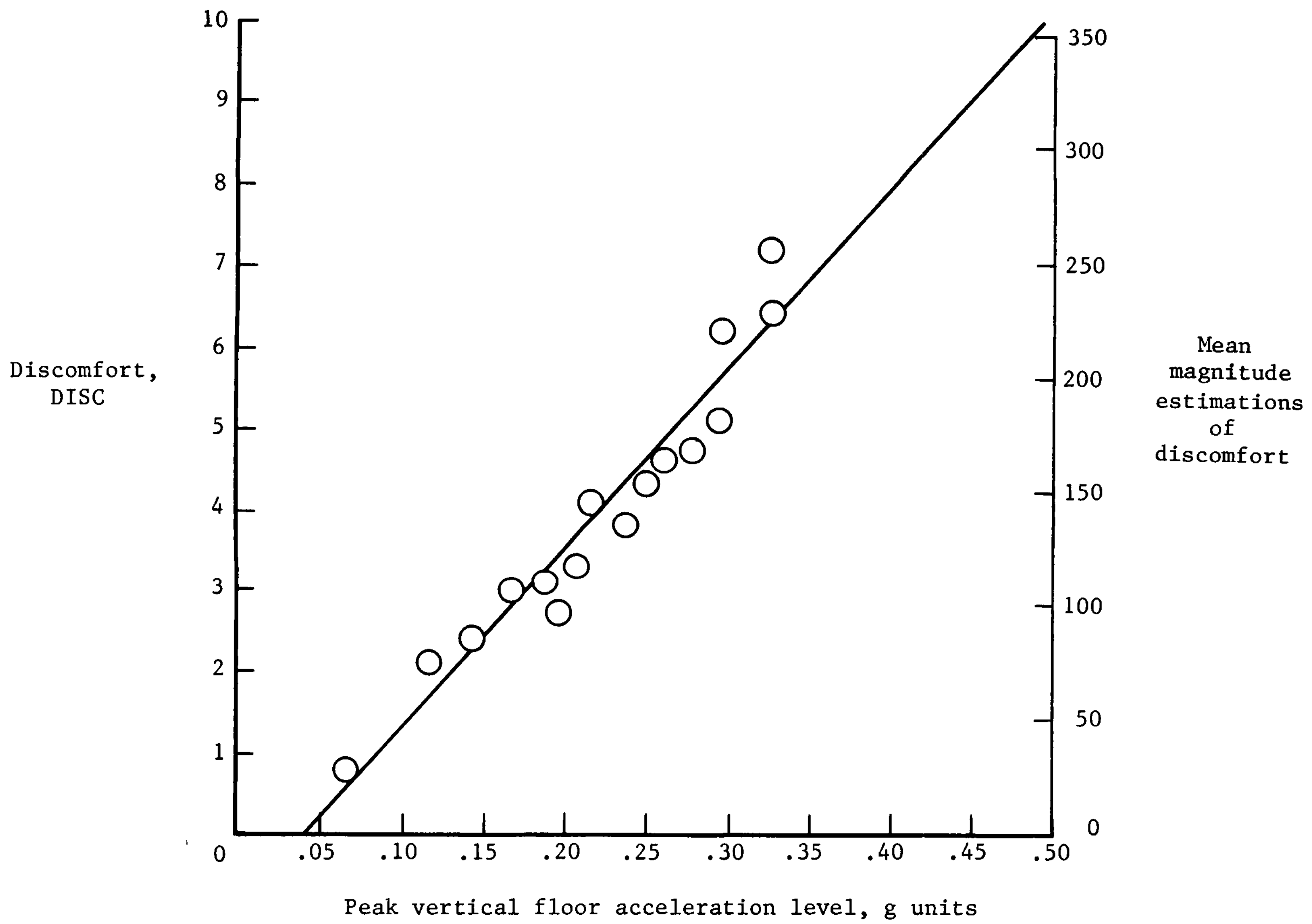


Figure 3.- Discomfort and mean magnitude estimations of discomfort as a function of peak vertical floor acceleration level of 9-Hz vertical vibration.

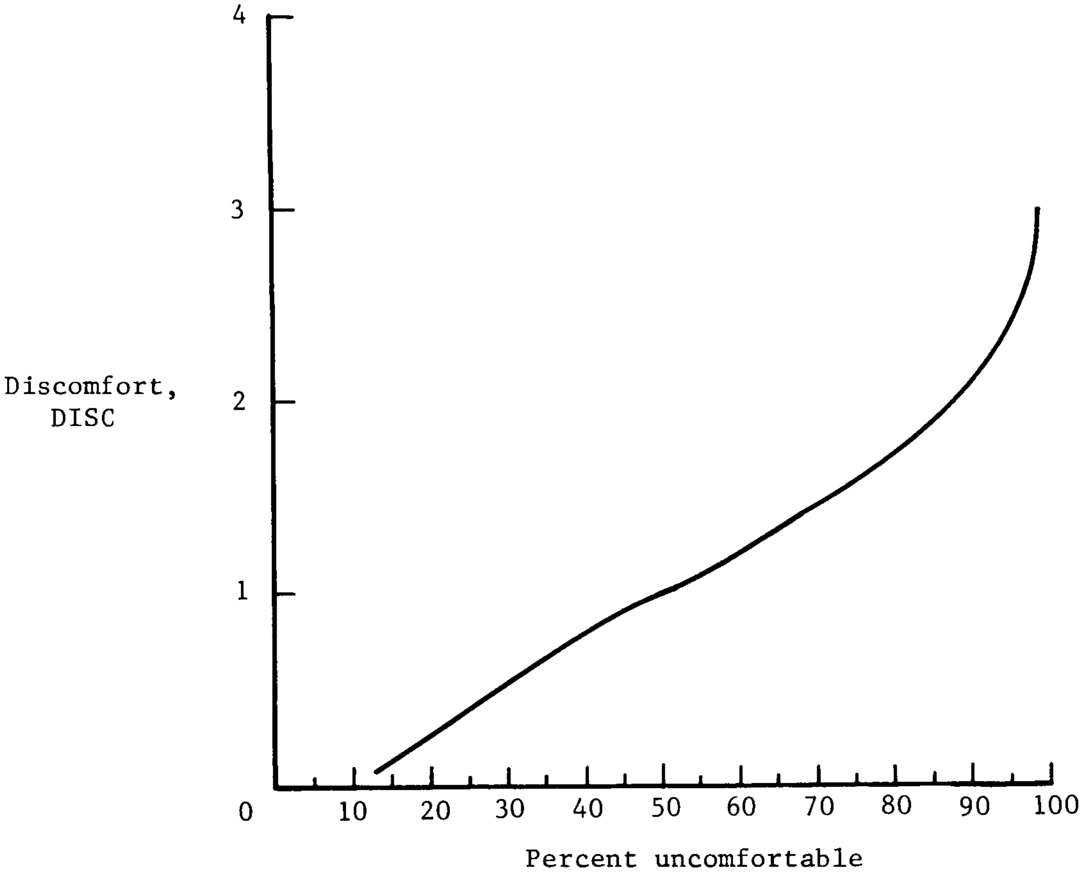


Figure 4.- Discomfort as a function of percent of passengers uncomfortable.

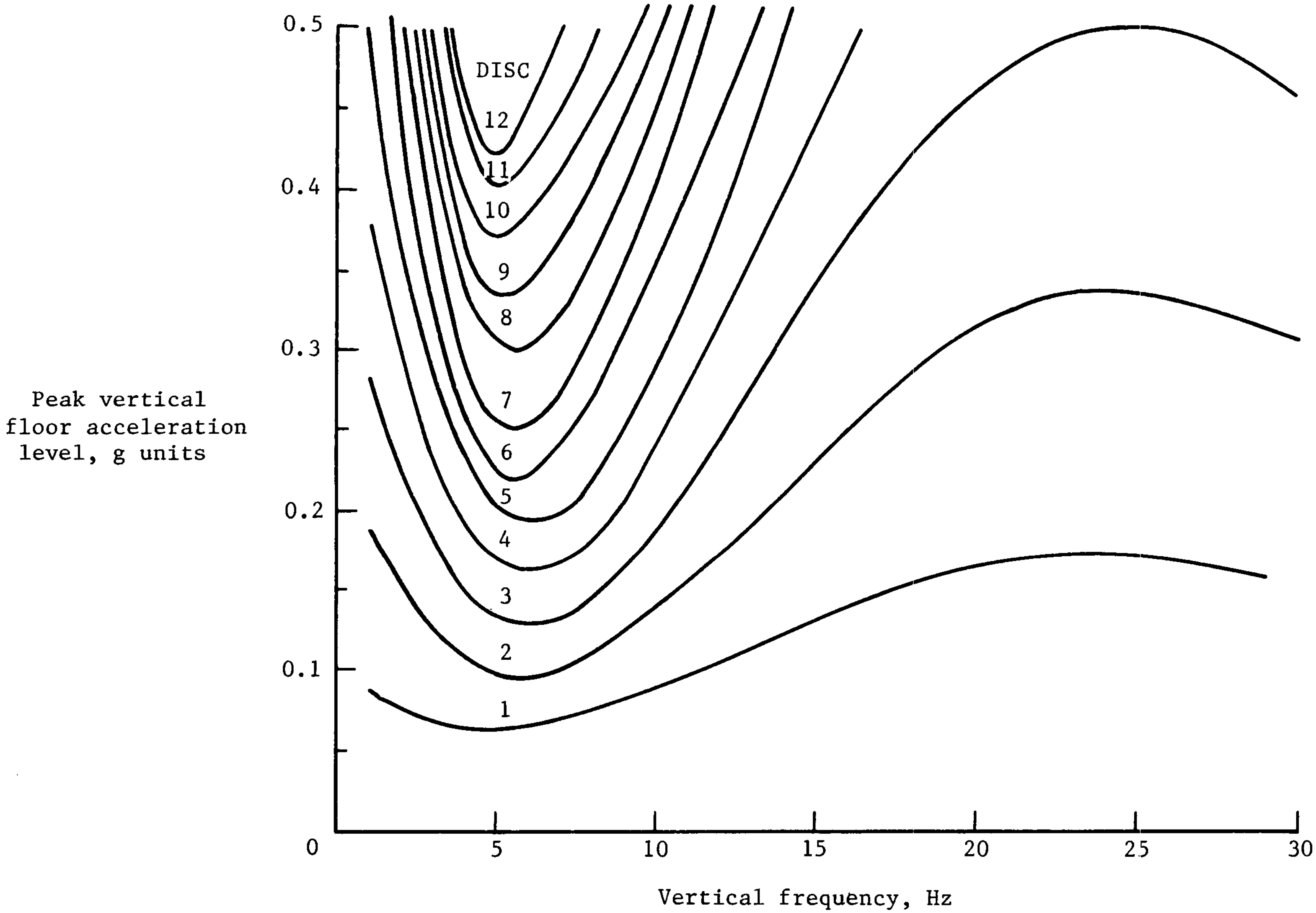


Figure 5.- Peak vertical floor acceleration levels required to produce successive equal-discomfort curves (DISC = 1 to 12) as a function of vertical frequency.

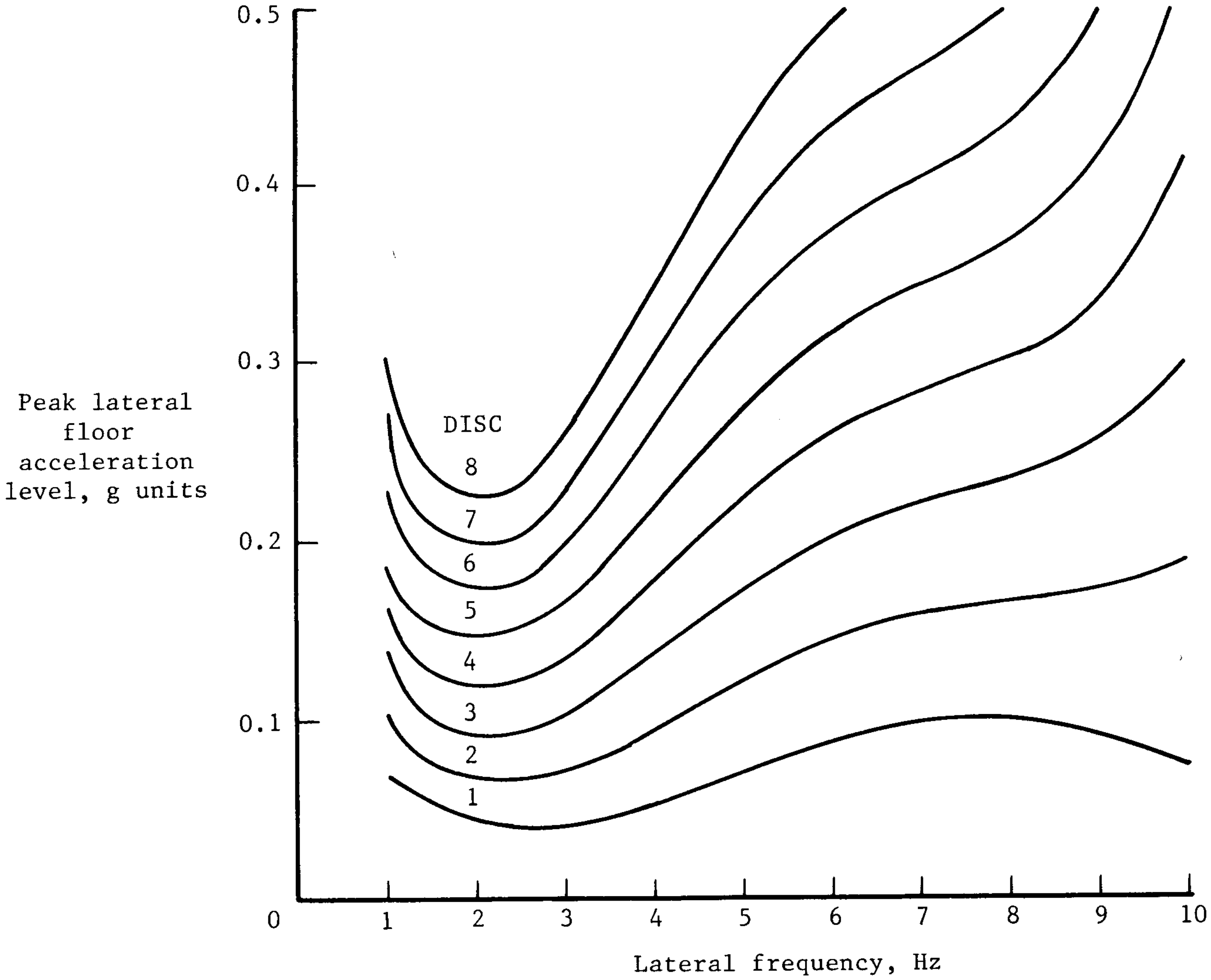


Figure 6.- Peak lateral floor acceleration level required to produce successive equal-discomfort curves (DISC = 1 to 8) as a function of lateral frequency.

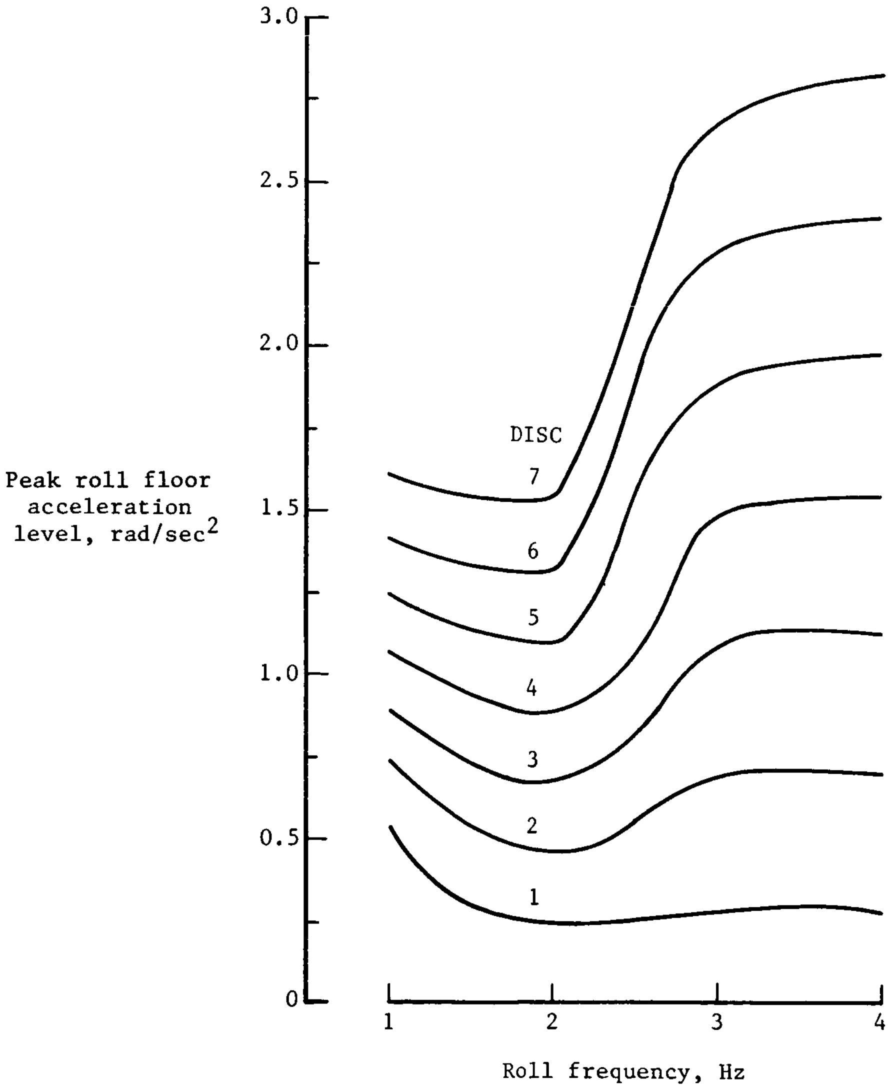


Figure 7.- Peak roll floor acceleration level required to produce successive equal-discomfort curves (DISC = 1 to 7) as a function of roll frequency.

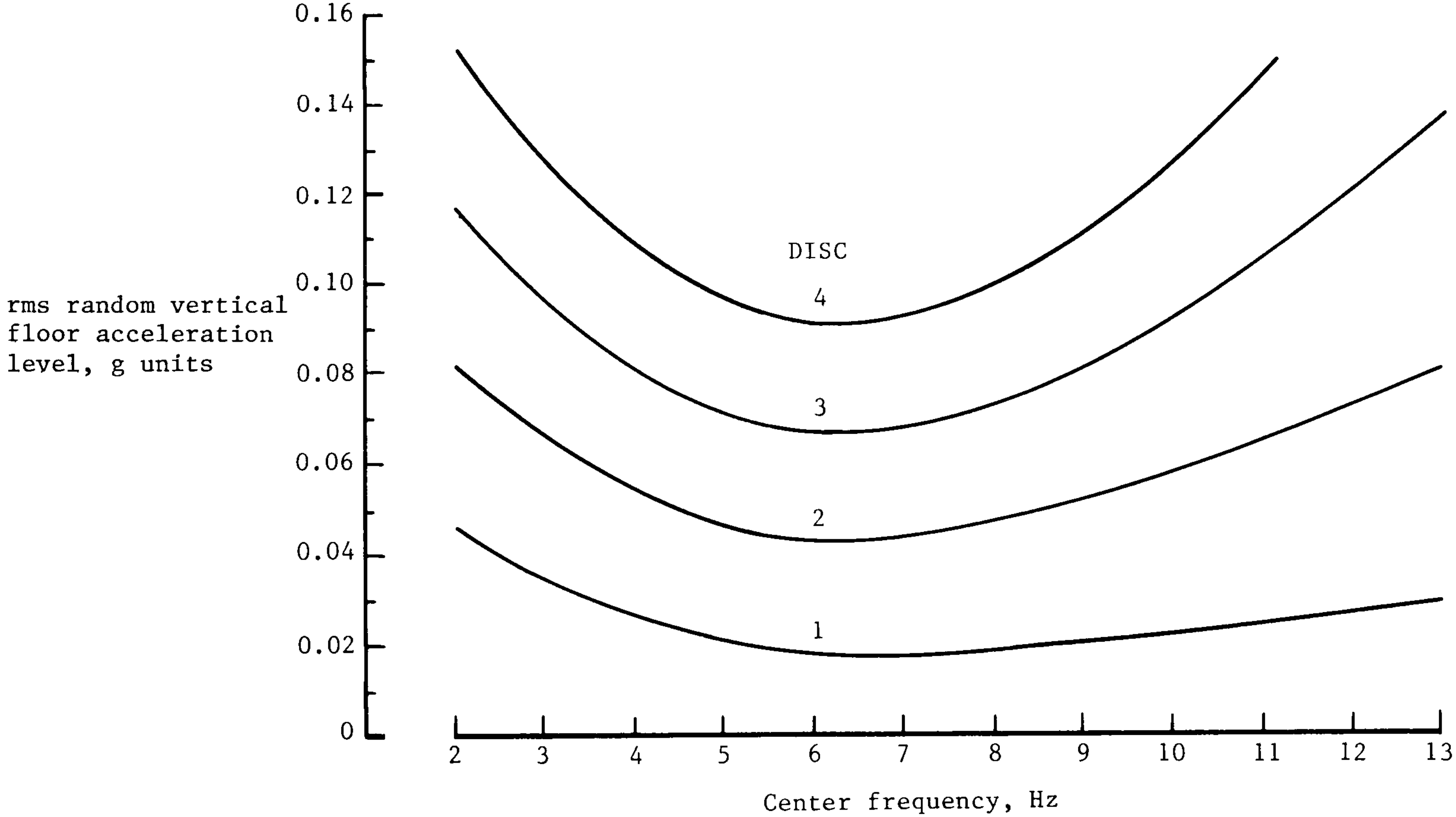
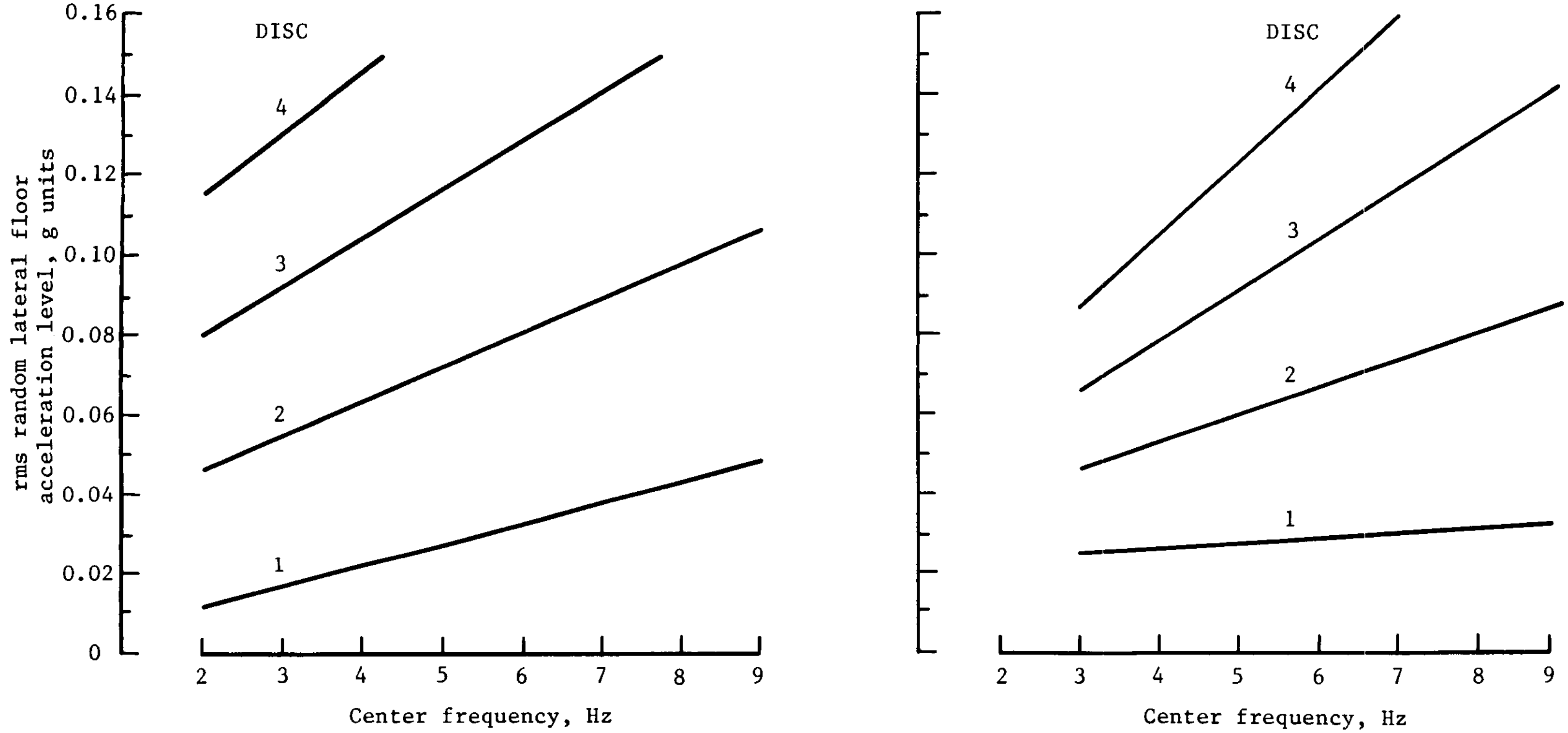


Figure 8.- Random vertical floor acceleration level required to produce successive equal-discomfort curves (DISC = 1 to 4) as a function of center frequency of random vibration.



(a) Bandwidth: 2 Hz.

(b) Bandwidth: 5 Hz.

Figure 9.- Random lateral floor acceleration vibration level required to produce successive equal-discomfort curves (DISC = 1 to 4) as a function of center frequency for: 2-Hz bandwidth and 5-Hz bandwidth vibration.

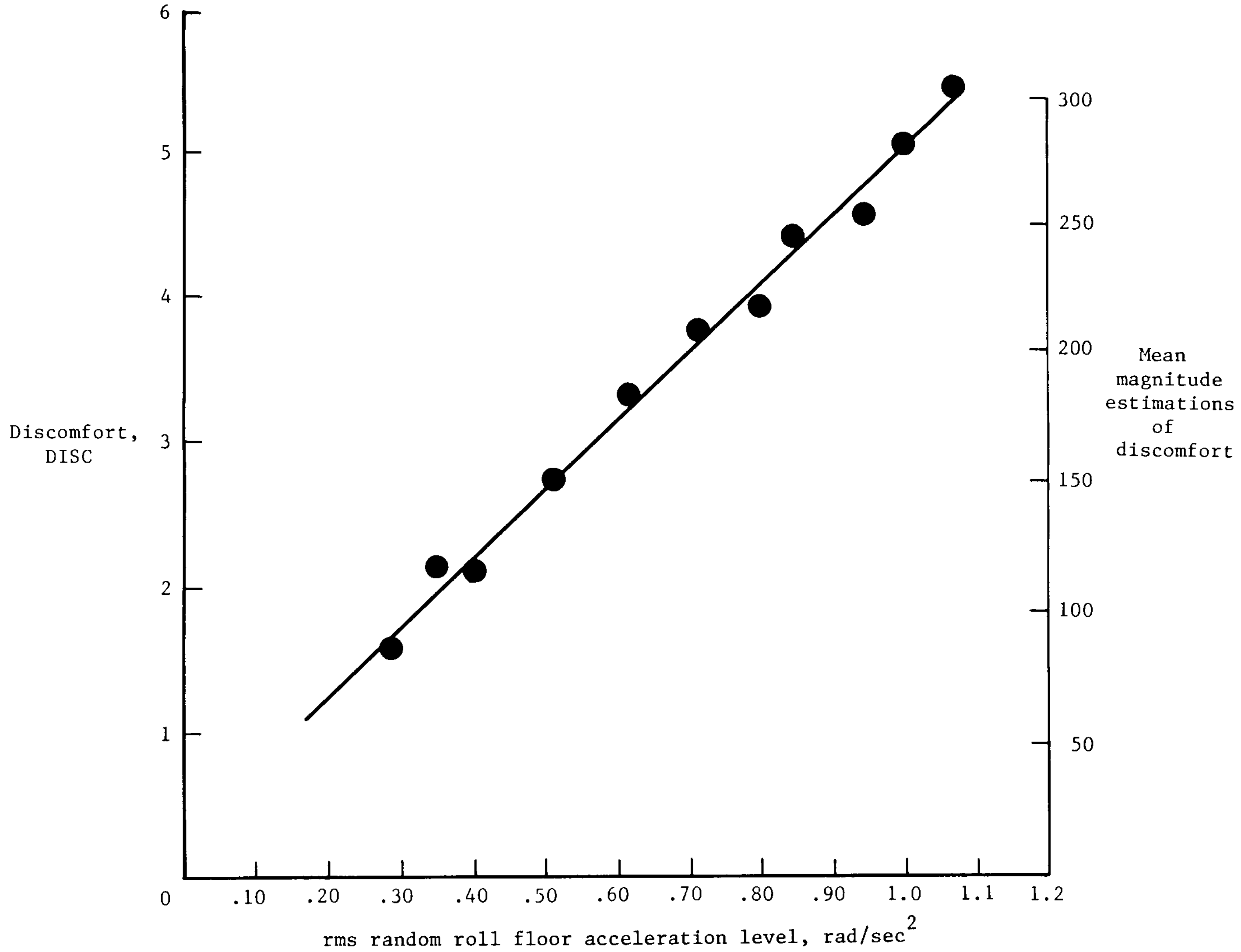


Figure 10.- Discomfort and mean magnitude estimations of discomfort for a bandwidth of 5 Hz with a 3-Hz center frequency as a function of random roll acceleration level.

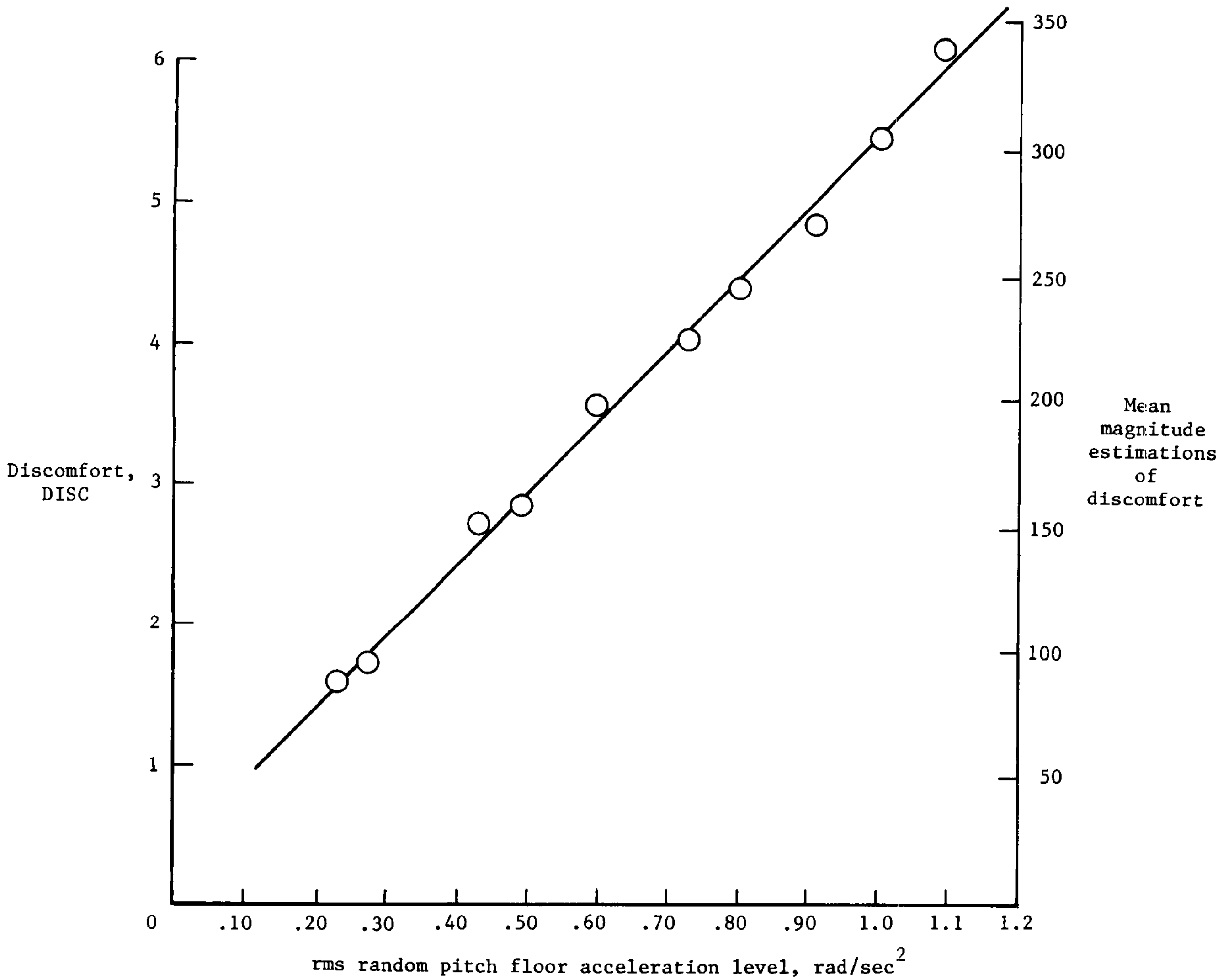


Figure 11.- Discomfort and mean magnitude estimations of discomfort for a bandwidth of 5 Hz with a 3-Hz center frequency as a function of random pitch acceleration level.

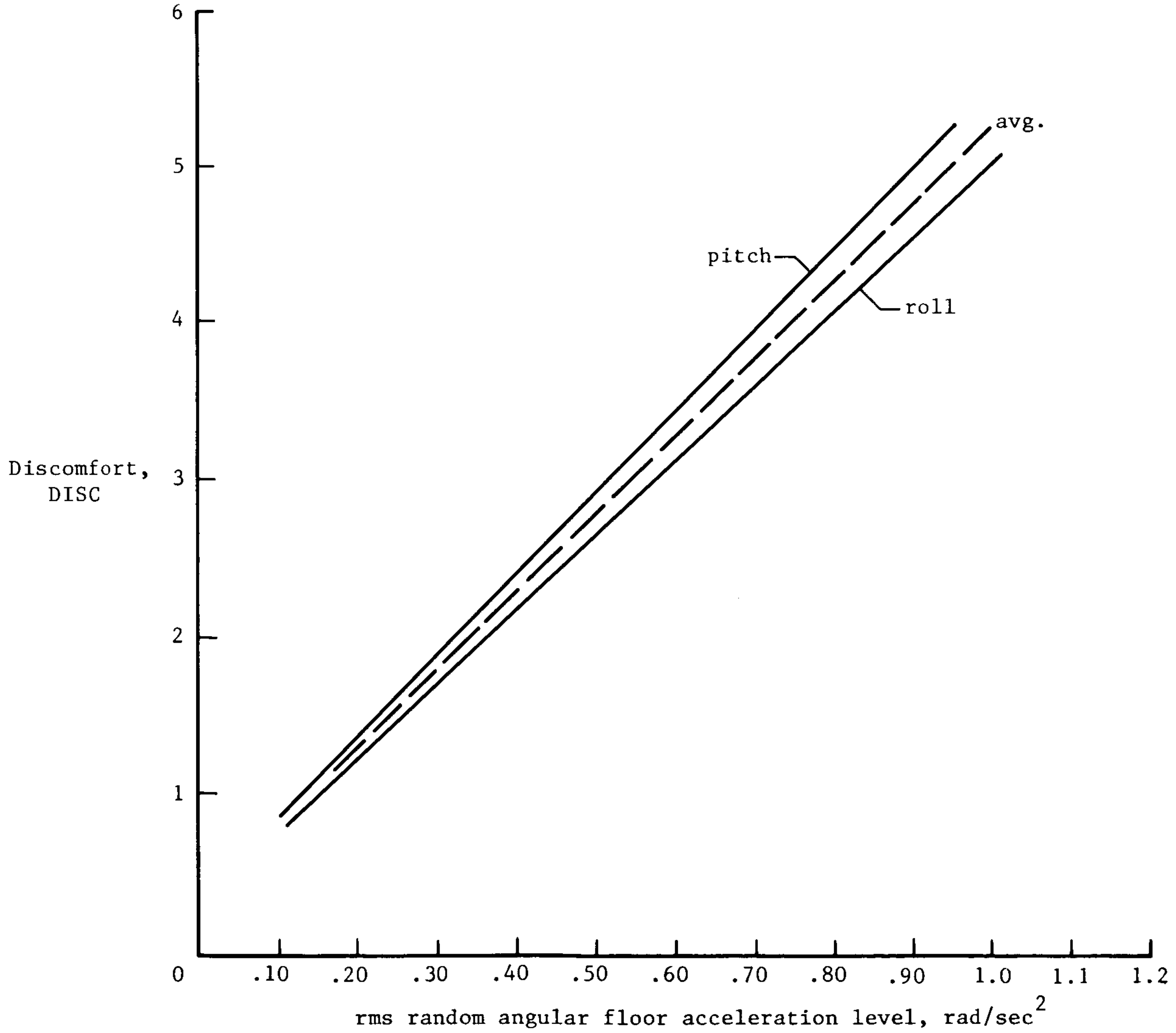


Figure 12.- Discomfort for pitch and roll vibrations as a function of random angular acceleration level.

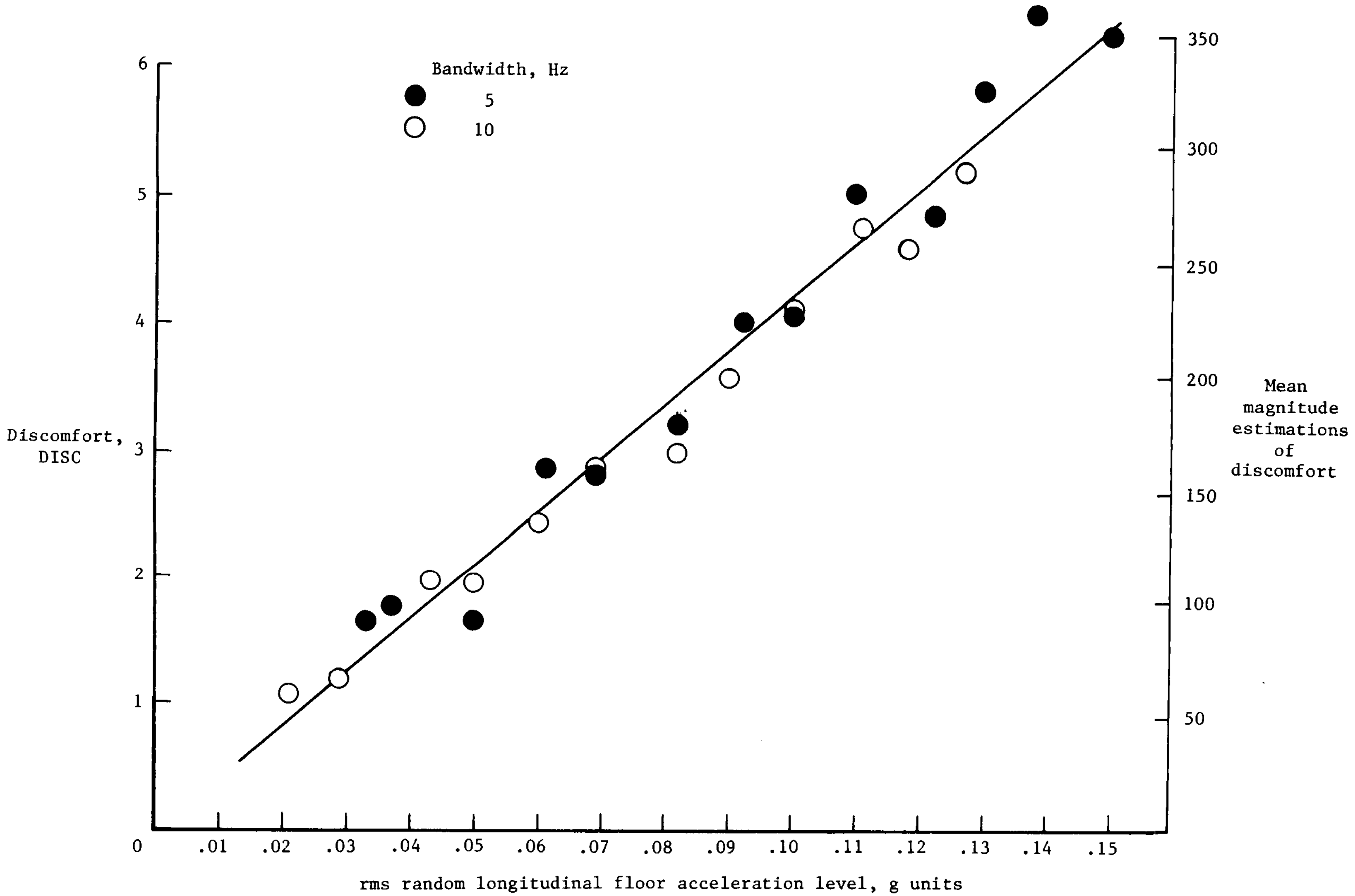
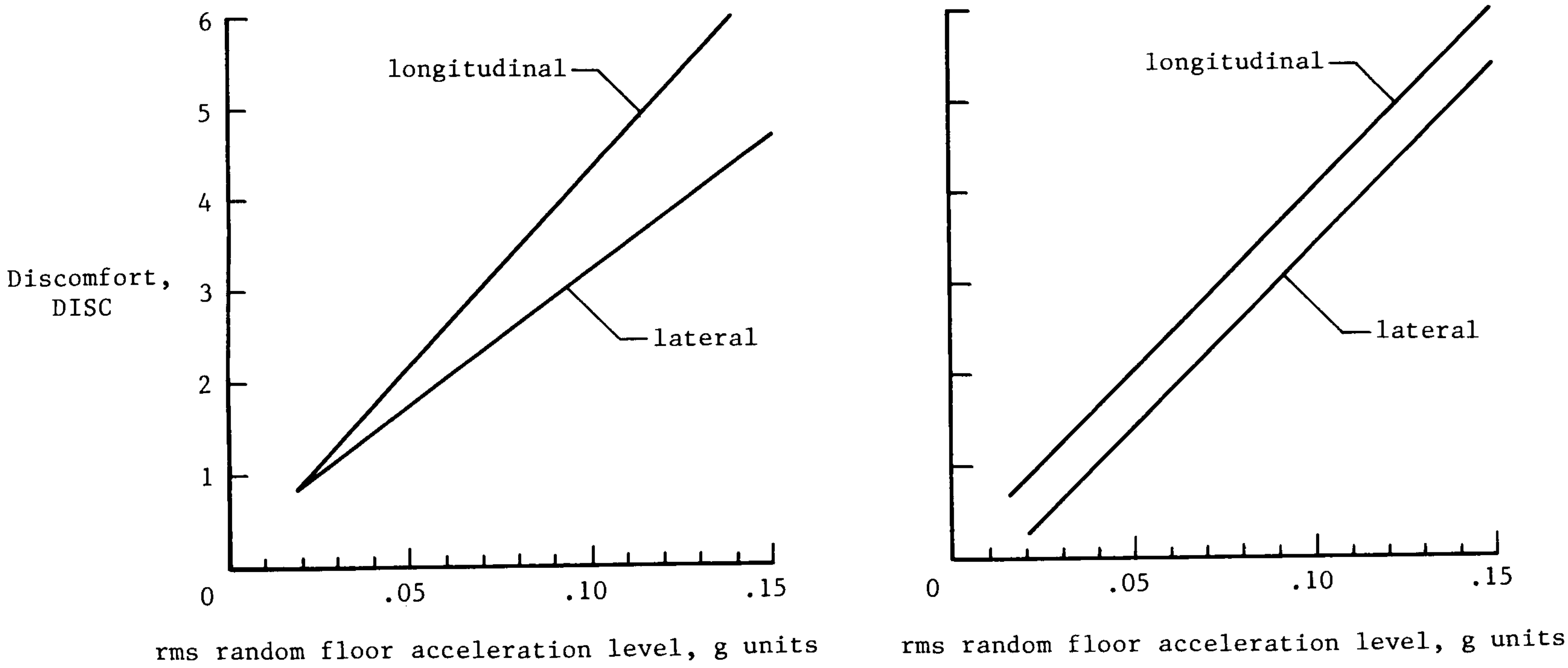


Figure 13.- Discomfort and mean magnitude estimations of discomfort as a function of random longitudinal floor acceleration level for 5- and 10-Hz bandwidth vibrations with a center frequency of 5 Hz.



(a) Random vibrations with bandwidth of 5 Hz and center frequency of 5 Hz.

(b) Random vibrations with bandwidth of 10 Hz and center frequency of 5 Hz.

Figure 14.- Discomfort as a function of random floor acceleration level of lateral and longitudinal vibration for a center frequency of 5 Hz and two different bandwidths.

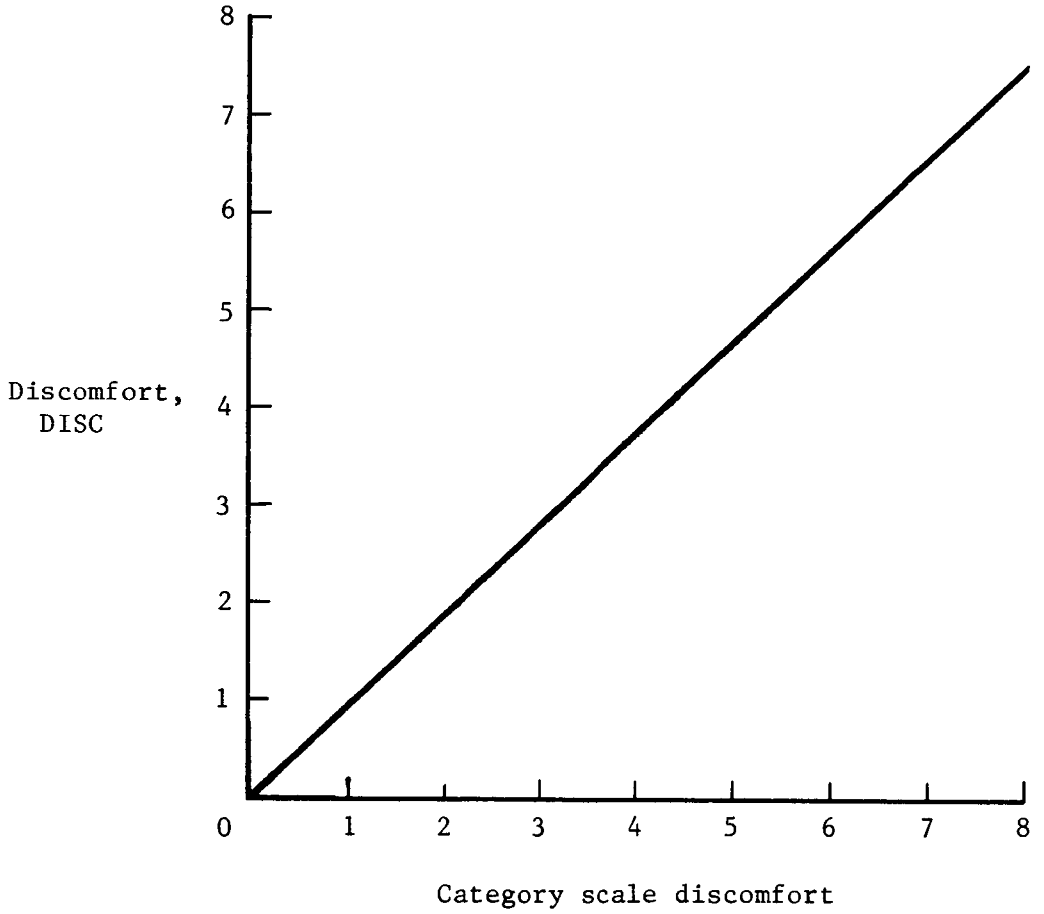


Figure 15.- Discomfort as a function of a discomfort evaluation on a unipolar, continuous, nine-point category scale.

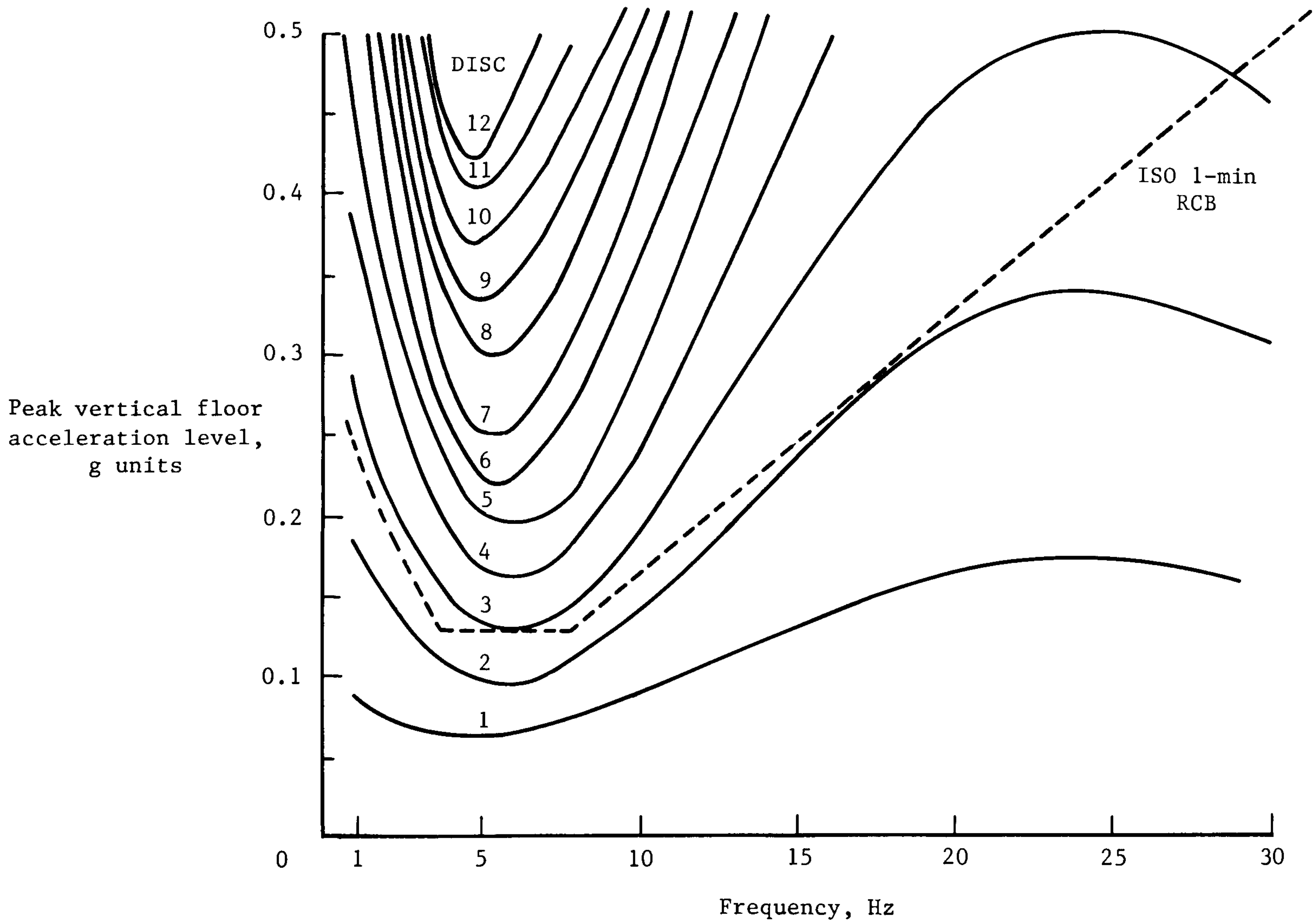


Figure 16.- Sinusoidal vertical-vibration equal-discomfort curves compared with ISO 1-min reduced-comfort boundary (RCB) recommendation.

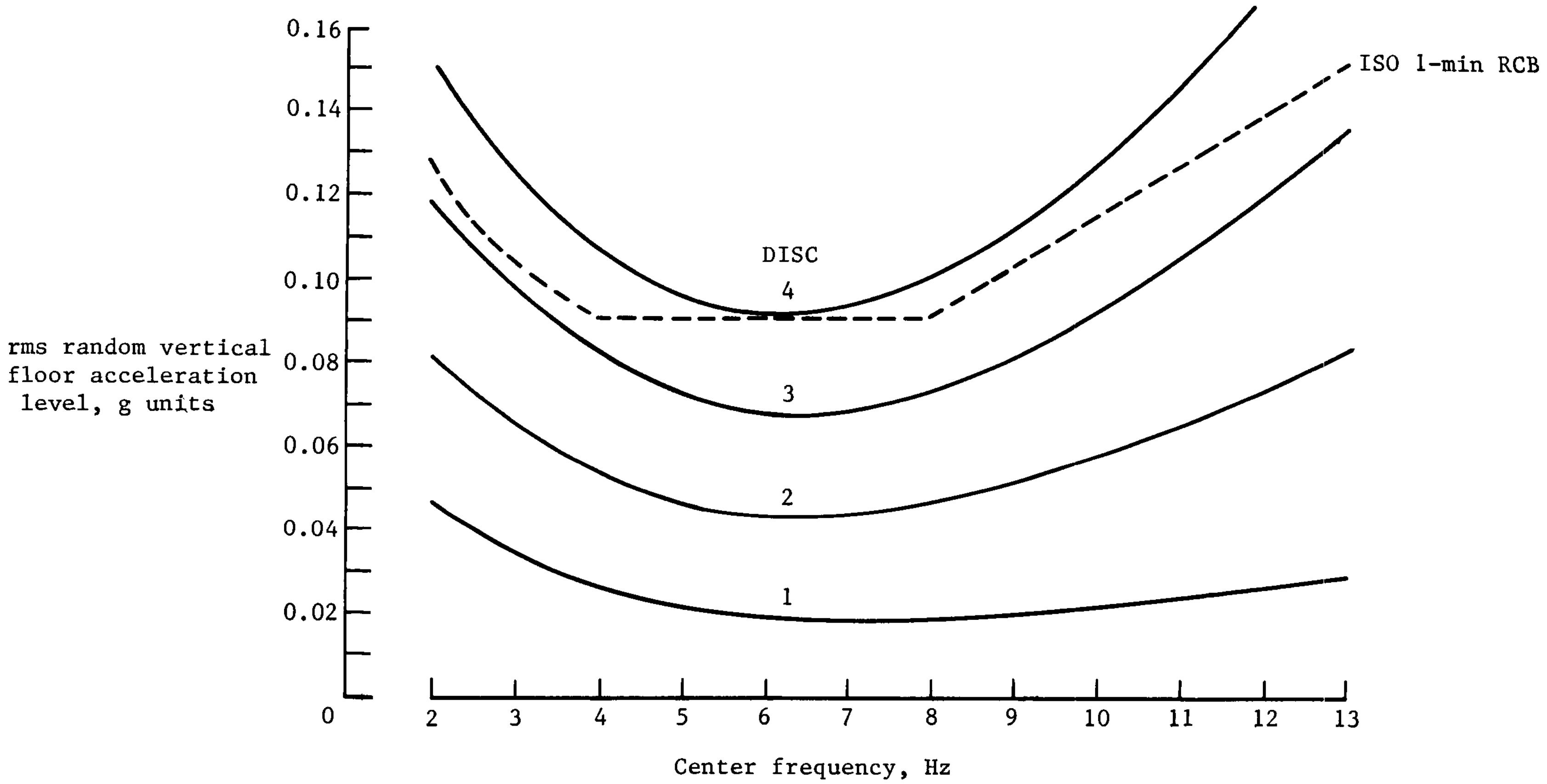


Figure 17.- Random vertical-vibration equal-discomfort curves compared with ISO 1-min reduced comfort boundary (RCB) recommendation.

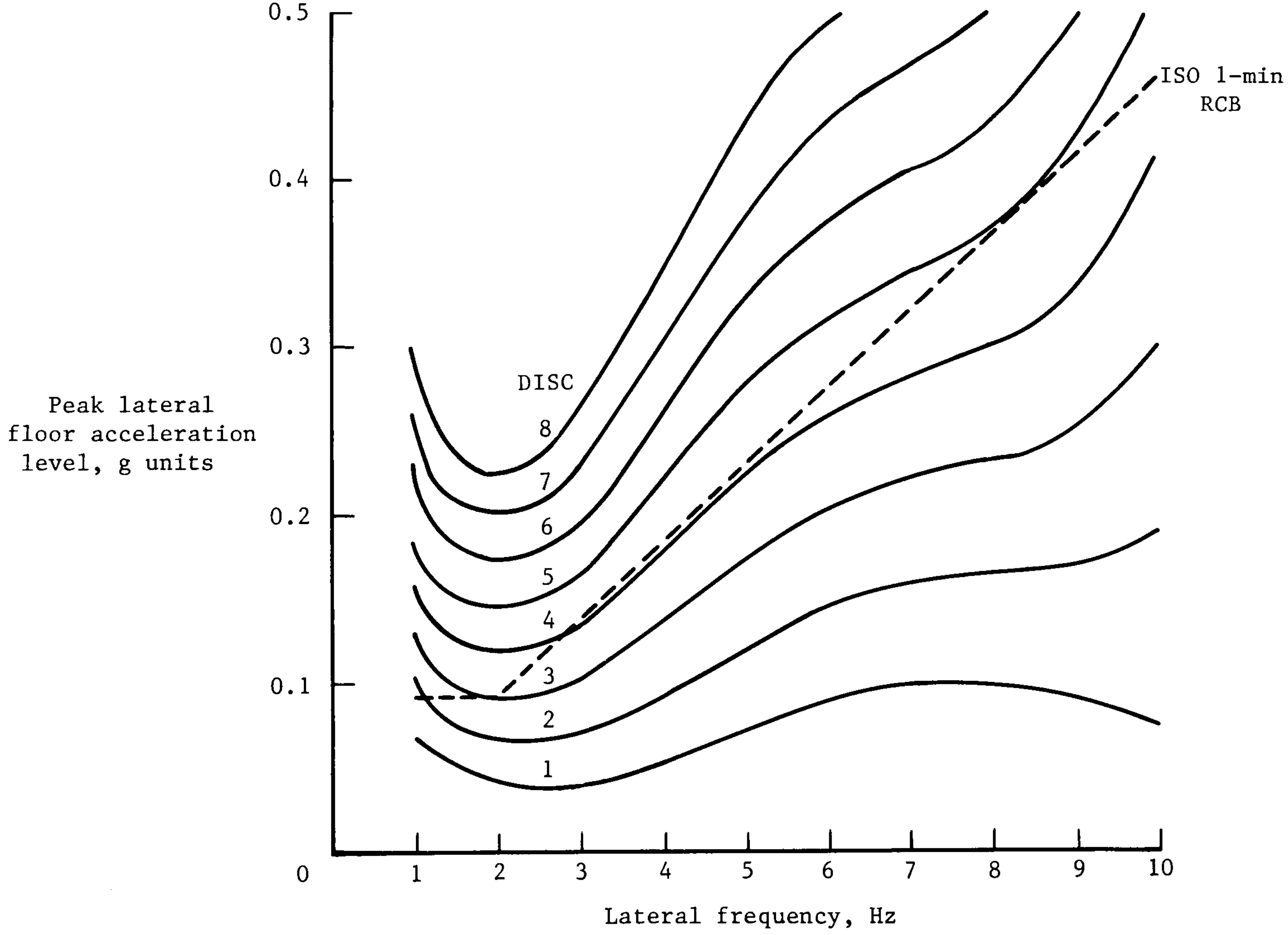
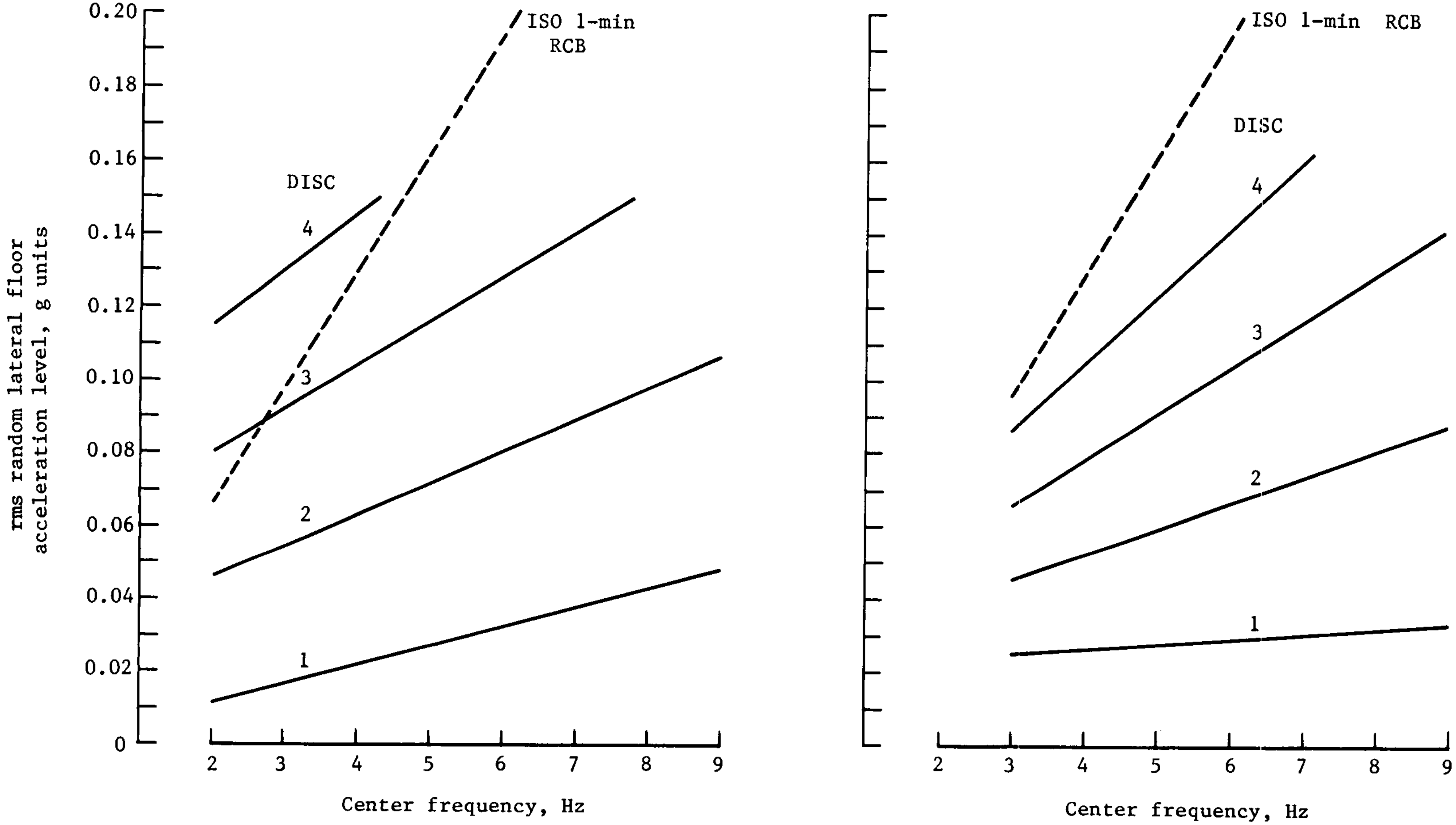


Figure 18.- Sinusoidal lateral-vibration equal-discomfort curves compared with ISO 1-min reduced comfort boundary (RCB) recommendation.



(a) Bandwidth: 2 Hz. **(b) Bandwidth: 5 Hz.**

Figure 19.- Random lateral-vibration equal-discomfort curves for 2- and 5-Hz bandwidth vibrations compared with ISO 1-min reduced comfort boundary (RCB) recommendation.

1. Report No. NASA TP-1422	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle DISCOMFORT CRITERIA FOR SINGLE-AXIS VIBRATIONS		5. Report Date May 1979
		6. Performing Organization Code
7. Author(s) Thomas K. Dempsey, Jack D. Leatherwood, and Sherman A. Clevenson		8. Performing Organization Report No. L-12681
9. Performing Organization Name and Address NASA Langley Research Center Hampton, VA 23665		10. Work Unit No. 505-09-13-11
		11. Contract or Grant No.
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, DC 20546		13. Type of Report and Period Covered Technical Paper
		14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

A number of experimental investigations have been conducted to determine the fundamental relationships governing human subjective discomfort response to single-axis vibrations. The axes investigated were vertical, lateral, longitudinal, roll, and pitch, and the vibrations used were both sinusoidal and random in nature. Results of these investigations have provided the basis for (1) development of a scale of passenger discomfort that is common to all axes of vibration and (2) generation of discomfort criteria for each axis of vibration. The discomfort criteria are in the form of discomfort curves for each axis and for both types of vibration. Furthermore, empirical equations describing discomfort responses within each axis of vibration are included. These equations can be used to estimate passenger discomfort for single-axis ride environments and/or as a design tool for trade-off analyses between discomfort and vibration characteristics. Comparisons of the various single-axis criteria curves obtained in these studies as well as comparisons of these curves with the International Standards Organization (ISO) recommendations are discussed. Finally, a transformation is presented that relates the discomfort scale to a measure of passenger acceptance (percent of passengers finding the ride environment uncomfortable).

17. Key Words (Suggested by Author(s)) Ride quality Human response Vibration Discomfort Ride comfort	18. Distribution Statement Unclassified - Unlimited Subject Category 53

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 57	22. Price* $5.25

* For sale by the National Technical Information Service, Springfield, Virginia 22161

NASA-Langley, 1979