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VIBRATION SIMULATOR STUDIES FOR THE DEVELOPMENT OF PASSENGER RIDE COMFORT CRITERIA

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SUMMARY

A test program to determine the total discomfort associated with vehicle vibration is described. The program utilizes a three-degree-of-freedom vibration simulator to determine the effects of multifrequency and multiaxis vibration inputs. The approach to multifrequency vibration includes a separate consideration of the discomfort associated with each frequency component or band of the total spectrum and a subsequent empirical weighting of the discomfort components of these frequency bands when in various random combinations. Mathematically, this may be represented as

$$\mathrm{DISC}_{\mathrm{total}} = \mathrm{DISC}_{\mathrm{max}} + F(\Sigma\mathrm{DISC} - \mathrm{DISC}_{\mathrm{max}})$$

The discomfort (DISC) represents the subjective discomfort associated with the acceleration level of a particular frequency band. The F value or masking factor specifies the fashion in which the discomfort of different frequency bands are added together. Fundamental to this approach is a detailed understanding of human response to discrete frequency inputs. A study has been recently completed that included 186 subjects exposed to frequencies of 1 to 30 Hz and peak acceleration levels from 0.05 to 0.50g. The F value was derived in a second set of tests that systematically explored the passenger discomfort response as a function of various random spectra.

The results are in the form of equal discomfort curves that specify the discomfort associated with discrete frequencies between 1 and 30 Hz and different acceleration levels. These results, in addition to being necessary for the previous equation, provide detailed information of the human discomfort response to increases in acceleration level for each frequency investigated. More importantly, the results provide a method for adding the discomfort associated with separate frequencies to give a total typification of the discomfort of a random spectrum of vibration.

INTRODUCTION

The development of new transportation systems or the modification of existing systems for improved ride quality requires a comprehensive understanding of human response to whole-body vibration. Specifically, what is needed is a scale of discomfort. The scale would necessitate generating extensive experimental data for the development of constant discomfort curves and the associated empirical laws governing the summation of discomfort responses due to multiple-frequency and/or multiple-axis vibration. A recent review and summary (ref. 1) of the criteria literature points out that many differences and contradictions exist in the various reported investigations. For example, it is not unusual for the vibration levels associated with the various proposed criteria to differ from one another by as much as an order o magnitude. The reasons that have been offered for the diversity of results include such factors as poor experimental design, unrealistic laboratory environments, use of inadequate rating scales or adjectives, small subject samples, and lack of information (e.g., ref. 2) regarding the fundamental psychophysical relationship between human comfort response and vibration. Notable exceptions are the studies reported by Shoenberger and Harris (ref. 3 Jones and Saunders (ref. 4), and Miwa (refs. 5 to 11) which were concerned wi the psychophysics of human sensitivity response to whole-body vibration. However, a recent investigation at Langley Research Center (as yet unpublishe demonstrated that sensitivity (intensity) responses of human subjects were different from discomfort type responses at several different frequencies. Consequently, caution needs to be used in applying results (criteria) from studies of intensity (or sensitivity) to problems related to human discomfort. Therefore, the first objective of this investigation is to develop discomfort criteria (equal discomfort curves) in a systematic fashion that removes the limitations of previous investigations.

A second problem that is encountered in the development of a scale of discomfort with accurate information for vehicle design is the total typification of the discomfort of a random vibration. This problem area necessitates the derivation of the total discomfort of a vibration based upon some combination of the discomfort associated with the frequency components of random ride spectra. Previous approaches to the typification of random vibration for prediction of comfort have concentrated upon measures of (1) power spectral density indices (e.g., ref. 12) based upon either unweighte or frequency-weighted power spectra (e.g., ref. 13), (2) amplitude exceedance counts (e.g., ref. 14), and (3) absorbed power (e.g., refs. 15 to 18).

There are several recent reviews (e.g., refs. 19 to 21) which describe the limited applicability of the use of these measures for the prediction of comfort. A major limitation of these measures is that they are based upon frequency weighting obtained for individually applied sinusoidal vibrations. The measures do not account for the effects of masking between frequencies within an axis but apply frequency weights or coefficients to each individual frequency as if it were acting alone. Thus the second objective of the presen investigation is a determination of the empirical relations governing vibratio masking/summation in order to derive the total discomfort of any random-induced ride spectra. The procedure followed for summation of discomfort components of a ride spectra for the total typification of the discomfort of a random vibration is outlined in reference 2. Experimentally, the procedure involves determining how the subjective assessment of the discomfort of a ride varies when many different frequency components are experienced simultaneously The composite weights for specification of the total discomfort of a ride are thus based upon the discomfort of several frequency components in combination rather than an arbitrary summation (usually algebraic) of the discomfort units associated with these components when individually experienced. A specific result of obtaining equal discomfort contours and empirical information for the summation of discomfort units is a scale of discomfort.

In summary the objectives of the present investigation are

(1) To systematically derive "equal vibration discomfort curves"
(2) To determine the influence of vibration masking in order to account for the total discomfort of any random vibration
(3) To develop a scale of total vibration discomfort

METHOD

The objectives of the investigation were achieved through three separate but interconnected studies hereinafter denoted as studies A, B, and C. Study A was directed at obtaining the acceleration levels of different frequencies that produce identical discomfort responses. Study B was used to obtain the empirical relationship between discomfort responses and acceleration level for each separate frequency. Finally, study C, based on sinusoidal and random vibration tests, was used to obtain a method for adding the discomfort associated with separate frequencies (based on the results of study A and B) for a total typification of the discomfort of a random spectrum of vibration. The following sections provide a review of the Langley passenger ride quality apparatus which was used in each investigation, as well as a short description of the subjects, task, and procedure for each study.

Apparatus

The apparatus used was the Langley passenger ride quality apparatus (PRQA). The PRQA is described briefly in this section, and a detailed description can be obtained from references 22 and 23. The PRQA and associated programing and control instrumentation are shown in the photographs of figure 1. Figure 1(a) shows the waiting room where subjects are instructed as to their participation in the experiment, complete questionnaires, and so forth. Shown in figure 1(b) is a model of the PRQA indicating the supports, actuators, and restraints of the three-axis drive system. A photograph of the exterior of the PRQA is shown in figure 1(c) and it should be noted that the actual mechanisms which drive the simulator are located beneath the pictured floor.

An interior view of PRQA with subjects seated in first-class aircraft seats (tourist-class aircraft seats were used in the present study) is presented in figure 1(d). The control console is shown in figure 1(e) and is located at the same level as the simulator to allow the console control operator to constantly monitor subjects within the simulator. Figure 1(f) is a photograph of tourist-class aircraft seats used in the present study.

Subjects

A total of 186 subjects participated in the three studies. The volunteer subjects were undergraduates from Old Dominion University and were paid for their participation in the studies. The pertinent subject demographics for each study are listed in table 1(a).

Subject Task and Procedure

The subjects involved in study A were required to evaluate successive "comparison ride segments" according to a modified method of limits task. Specifically, a subject's task was to determine if a ride segment provided greater or less discomfort than a ride segment termed the "standard ride." The vibration characteristics of the standard and comparison ride segments are provided in table 1(b). Appropriate counterbalancing of frequencies and acceleration levels was performed for these tests.

The task for the subjects of studies B and C was the evaluation of the discomfort of vibrations through a magnitude estimation procedure. The procedure involves applying a standard ride (vibration that was different than that of study A) to the subjects and assigning the standard ride a numerical value of 100. Comparison ride segments (vibrations that were different from those of study A) were then applied and the subjects were asked to evaluate these vibrations relative to the standard ride segment by assigning it an appropriate numerical value. For example, if the discomfort of a ride was felt to be twice the discomfort of the standard ride, the subjects would give the ride a value of 200. The subjects were instructed not to use zero or negative numbers in making their evaluations.

Although the magnitude estimation procedure was used by the subjects in both studies B and C, the vibration characteristics of the standard and comparison ride segments for the two studies differed. The major difference between the vibrations of the two studies was that sinusoidal vibrations were used in study B, whereas both sinusoidal and random vibrations were investigate in study C. A description of these vibrations is provided in table 1(b). Counterbalancing of appropriate factors was done for testing in both studies.

RESULTS AND DISCUSSION

The results of the three investigations conducted to achieve the objectives listed in the introduction are discussed in this section. The results considered collectively culminate in a scale of discomfort. This scale of discomfort requires an anchor point and a brief discussion of the anchor point selection is presented, followed by a detailed discussion of each study.

Anchor Point: Scale of Discomfort

A previous experimental investigation (ref. 24) concluded that 9 Hz should be selected as the anchor (and standard) frequency for development of the scale of discomfort. The primary reason for selecting 9 Hz as the anchor frequency was that it gave less variability of discomfort responses to vibration stimuli as compared with other sinusoidal vibrations. An additional investigation (ref. 25) provided data from which an acceleration level of 0.08g (g = 0.057) was determined to be the approximate threshold of discomfort at the 9 Hz anchor frequency. Consequently, 9 Hz at 0.08g was selected as the anchor point and was assigned a unit value of discomfort (DISC = 1).

Frequency Equating - Study A

As a first step toward derivation of equal discomfort curves, this study determined the acceleration level at different frequencies that produces identical discomfort. Figure 2 presents typical results of study A for a frequency of 5 Hz. (Similar results were obtained for frequencies from 1 to 30 Hz, excluding the standard frequency of 9 Hz.) Figure 2 shows the z-score (standard normal score) transformations of percentage of responses obtained from comparison rides (5 Hz in this case) that were evaluated as having more discomfort than a standard ride as a function of the acceleration level of the comparison rides. The standard ride for this study was a 9 Hz sinusoidal frequency at an acceleration level of 0.15g. The z-score value of 0.0 corresponds to 50 percent of the 5 Hz comparison ride segments evaluated as having more discomfort than the standard ride. Therefore, the acceleration level at the z = 0.0 point of the 5 Hz ride was taken as equal in discomfort to the standard ride. For the example shown in figure 2, an acceleration level of 0.115g at 5 Hz is equal in discomfort to an acceleration level of 0.15 (precisely 0.1528) at 9Hz. Repeating the procedure described above for all other frequencies gives the curve shown in figure 3. The ordinate of figure 3 is the acceleration level corresponding to z = 0.0 (equal discomfort point) for each frequency along the abscissa. Thus the curve of figure 3 is a constant discomfort curve whose absolute level of discomfort must be determined from study B. The discomfort value for the curve of figure 3 will depend upon the subjective discomfort assigned to a ride at 9 Hz and 0.1528g, given that the value of 1 DISC was assigned to 9 Hz at 0.08g.

Equal Discomfort Curves - Study B

The objective of study B was to derive equal discomfort curves that could be assigned absolute levels of discomfort. The results of this study are in the form of magnitude estimates of successive ride segments for a particular frequency. Figure 4 displays an example of these results and provides a connection of these results with those of study A. Figure 4 shows the magnitude estimations of the discomfort of 9 Hz ride segments as a function of acceleration. Since a discomfort value of 1 DISC was specified for a vibration of 9 Hz at 0.08g, an experimental derived value of 2.47 DISC can be obtained for 9 Hz at 0.1528g. This result is important because it represents the discomfort value (DISC) assigned to each acceleration level and frequency of the curve shown in figure 3. It thus provides an adjustment of ride segments of the various frequencies to the same scale of discomfort.

Figure 5 shows the magnitude estimations of discomfort of 5 Hz ride segments as a function of acceleration level. The results for 5 Hz as well as those for the remaining frequencies investigated (1 to 30 Hz) displayed a strong linear relationship between discomfort and acceleration, as shown in as yet unpublished data obtained at Langley Research Center. As previously mentioned, a discomfort (DISC) value of 2.47 was assigned to a ride segment at 5 Hz and 0.115g and served as a basis for adjusting the magnitude estimations of discomfort for the other ride segments of 5 Hz. Similar adjustments were made to the magnitude estimations of discomfort for the other frequencies investigated (1 to 30 Hz, excluding 9 Hz). Then, using data such as that of figure 5 for each frequency, a set of constant discomfort curves was generated and are presented in figure 6. The individual curves of figure 6 indicate the acceleration level of a sinusoidal vibration required to produce a constant level of discomfort. This figure shows constant discomfort curves ranging from a value of one (DISC = 1), which is approximately the discomfort threshold, to values as high as DISC = 12 corresponding to a very high level of discomfort.

ISO Comparisons

The ISO standards document (ref. 13) contains a tabulation of weighting factors intended to reflect the relative influence of individual sinusoidal vibrations on discomfort for a frequency range of 1 to 80 Hz. The magnitude estimation data generated in this study was also formulated in a frequency weighting factor format and used for comparison with the ISO data as illustrated in figure 7. The ISO weighting curve is represented by the solid line and the NASA weighting curve by the dashed line. The ISO weighting curve is a plot of the tabular data contained in reference 14, whereas the NASA weighting curve was obtained by computing, at each frequency, an average weighting factor based upon a normalization of the magnitude estimates of discomfort corresponding to floor acceleration levels ranging from 0.10g to 0.50g. The normalization factor used was the average magnitude estimate of discomfort where the average was taken over all frequencies in the 4 Hz to 8 Hz (flat, equally weighted part of ISO curve) frequency range.

Inspection of figure 7 shows that the basic trend of the NASA weighting curve is similar to that of the ISO weighting curve. However, there are several important differences which should be noted. First, the ISO data tend to weight the lower frequencies (below 4 Hz) and the higher frequencies (above 7 Hz) considerably more than the present data. For example, at a frequency of 15 Hz the NASA weighting factor is approximately 64 percent of the ISO weighting factor. Another difference between the two weighting factor curves is that the NASA data shows that frequencies of 5 Hz and 6 Hz have the largest weighting, with lesser importance attributed to 4, 7, and 8 Hz. These differences may be important when a researcher or designer decides to select a weighting curve for use in obtaining a weighted measure of a ride spectrum (such as a weighted rms level) or for use as a filter characteristic in a "Ride Quality" meter. The NASA set of weighting factors represent an alternative to the weights of the ISO standards. Future studies will resolve differences in prediction accuracy of the two sets of weights.

Vibration Masking - Study C

Study C addresses the question of how the total discomfort of a ride is affected when different frequency components are combined. Such a knowledge is required for application of these data to operational random ride environments. The total discomfort of a ride as specified in reference 1 is represented in the following formula:

$$\mathrm{DISC}_{\mathrm{total}} = \mathrm{DISC}_{\mathrm{max}} + F(\Sigma \mathrm{DISC} - \mathrm{DISC}_{\mathrm{max}})$$

Studies A and B provide the necessary information for computation with the formula, except for F, the masking factor. The derivation of F as a function of bandwidth, center frequency, and acceleration level of vibration is the purpose of study C. At the time this paper was presented for publication, the data analyses for computation of the masking factor(s) were not complete. However, examination of preliminary results for a 10 Hz bandwidth indicated the masking factor to be approximately 0.67. It should be emphasized that this is a rough estimate based upon a single bandwidth and a small portion of the available data. Detailed analyses and results of the masking study will be included in a subsequent publication.

SUMMARY OF RESULTS

The results from this series of interconnected studies can be summarized as follows:

1. Passenger discomfort to whole-body vertical vibration increases linearly with acceleration level for each frequency.
2. A set of constant discomfort curves were generated by accounting for frequency and amplitude effects of vibration upon passenger discomfort.
3. Empirical data from the series of studies provided a mechanism for determining the degree of masking (or summation) of the discomfort of multiple frequency vibration. More importantly, the results, when applied to a mathematical model, provided a method for adding the discomfort associated with separate frequencies to give a total typification of the discomfort of a random spectrum of vibration. Consequently, a scale for the prediction of passenger discomfort was developed.
4. Finally, differences between ISO and NASA derived frequency weighting factors were discussed.

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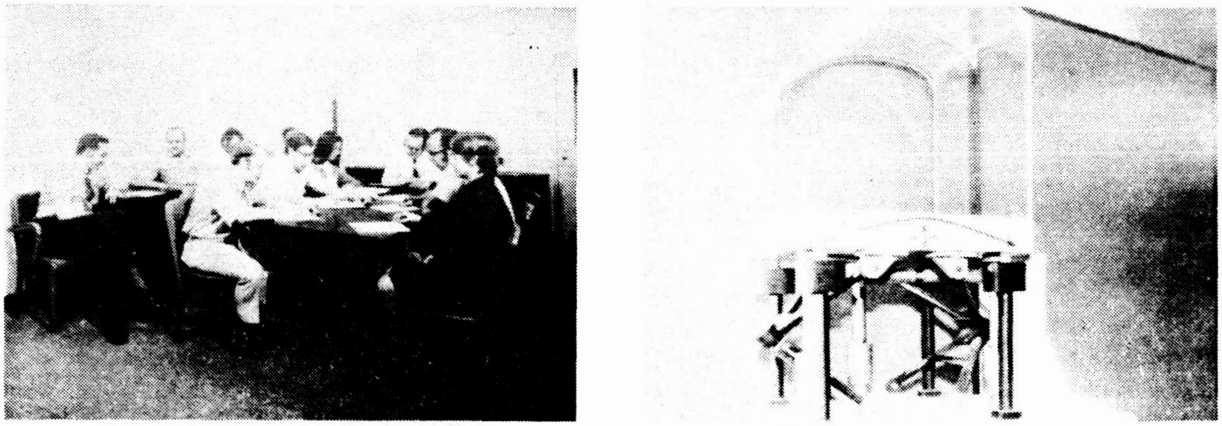
TABLE I.— SUMMARY OF SUBJECT DEMOGRAPHICS AND VIBRATION CHARACTERISTICS OF STANDARD AND COMPARISON RIDE SEGMENTS FOR STUDIES A, B, AND C

(a) Subject demographics

	Number of subjects			Age, yr		Weight, kg (lb)		Subjective task
	Males	Females	Total	Median	Range	Mean	Standard deviation	
Study A	12	42	54	18	18 to 31	60.2 (132.8)	10.3 (22.8)	Method of limits
Study B	41	55	96	21	18 to 55	67.0 (147.8)	14.2 (31.4)	Magnitude estimation
Study C	15	21	36	20	18 to 57	61.2 (135.0)	11.3 (25.0)	Magnitude estimation

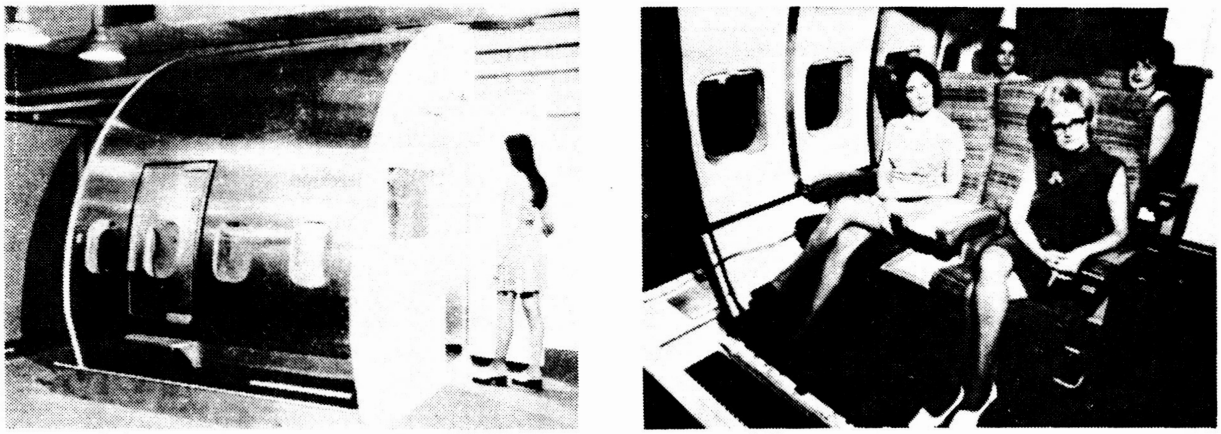
(b) Vibration characteristics

	Axis	Type	Frequency, Hz	Acceleration, g	Onset and offset, sec	Duration, sec	No. of vib.	Time between vibrations, sec
Standard ride								
Study A	Vert.	Sinusoidal	9	0.15	5	10	50	5
Study B	Vert.	Sinusoidal	Variable	Variable	5	10	30	5
Study C	Vert.	Sinusoidal	9	0.10 (rms)	5	20	48	5
Comparison rides								
Study A	Vert.	Sinusoidal	1 to 30	0.05 to 0.475	5	10	100	5
Study B	Vert.	Sinusoidal	1 to 30	0.05 to 0.475	5	10	90	5
Study C	Vert.	Random (2,5, and 10 Hz BW)	Center frequency at 1 to 9 and 13 Hz	0.03 to 0.12 (rms)	5	20	144	5



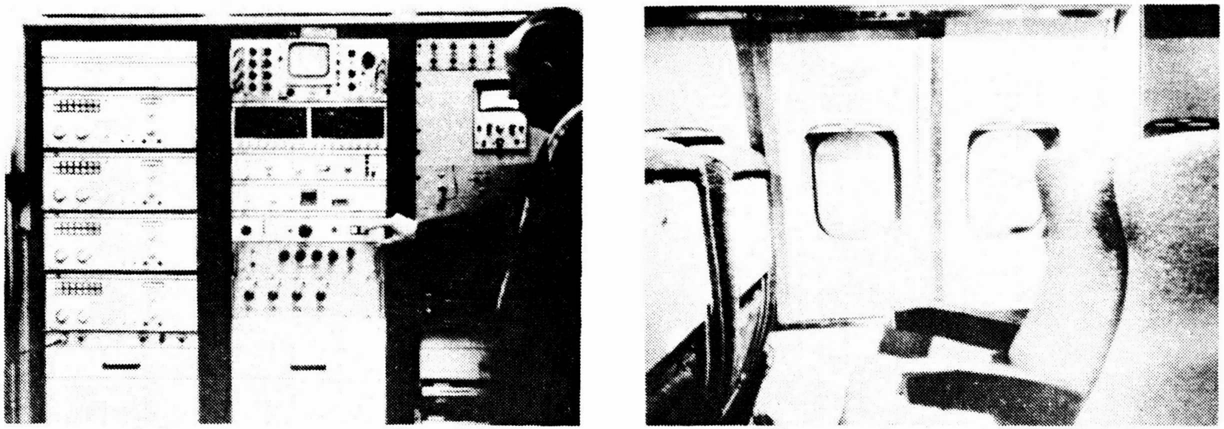
(a) Waiting room.

(b) Model of PRQA.



(c) Simulator exterior.

(d) Simulator interior.



(e) Control console.

(f) Tourist type seats.

Figure 1.- Langley passenger ride quality apparatus.

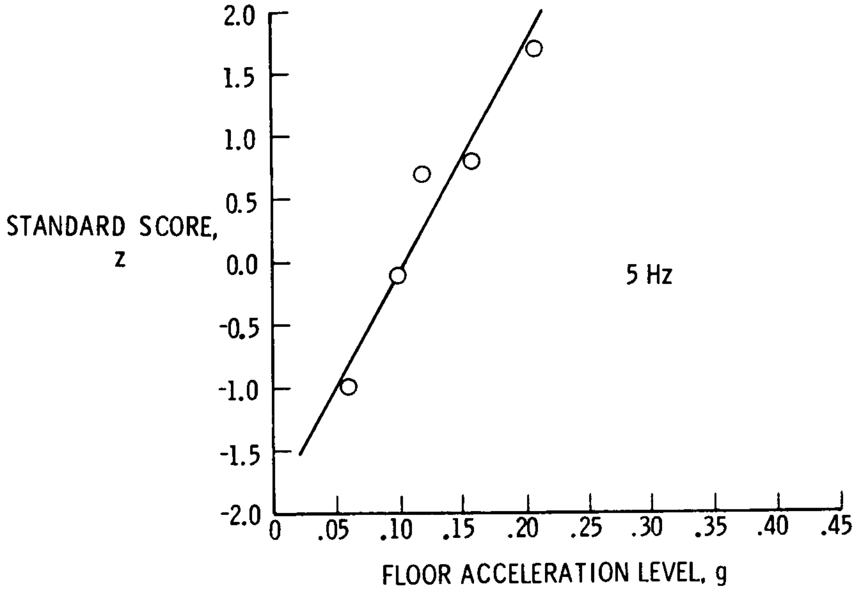


Figure 2.- The z-score transformations of the percentage of comparison rides at 5 Hz evaluated as having greater discomfort than standard ride at 9 Hz and 0.15 g as a function of acceleration level of comparison rides.

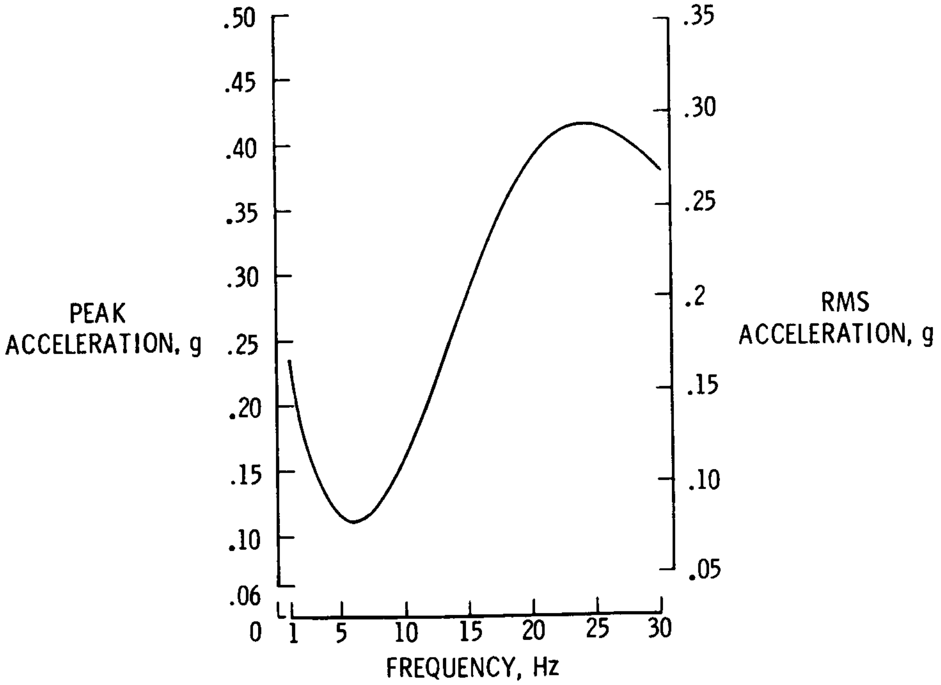


Figure 3.- Peak and rms acceleration levels required to produce equal discomfort as a function of frequency.

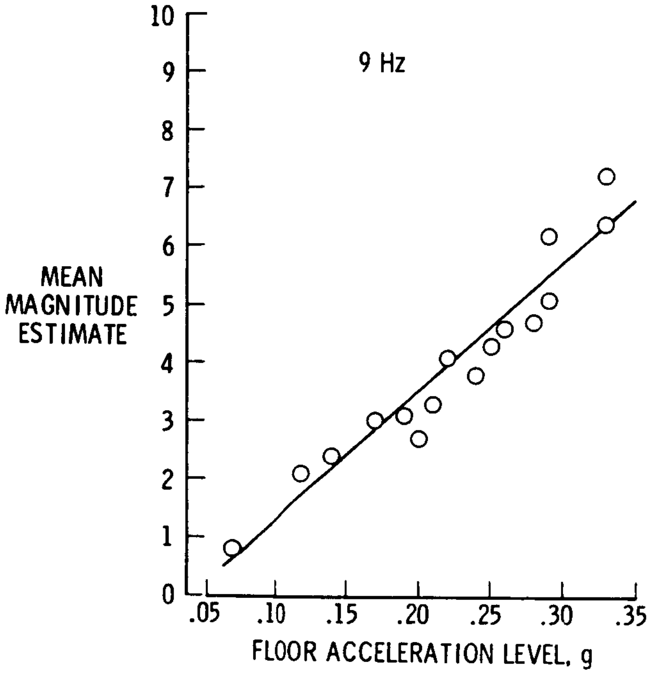


Figure 4.- Mean magnitude estimate of discomfort as a function of floor acceleration level for a 5 Hz sinusoidal vibration.

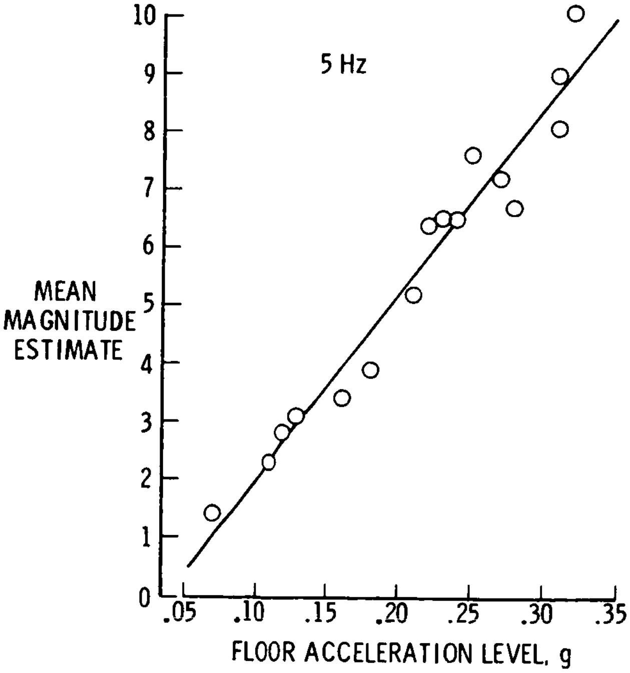


Figure 5.- Mean magnitude estimate of discomfort as a function of floor acceleration level for a 5 Hz sinusoidal vibration.

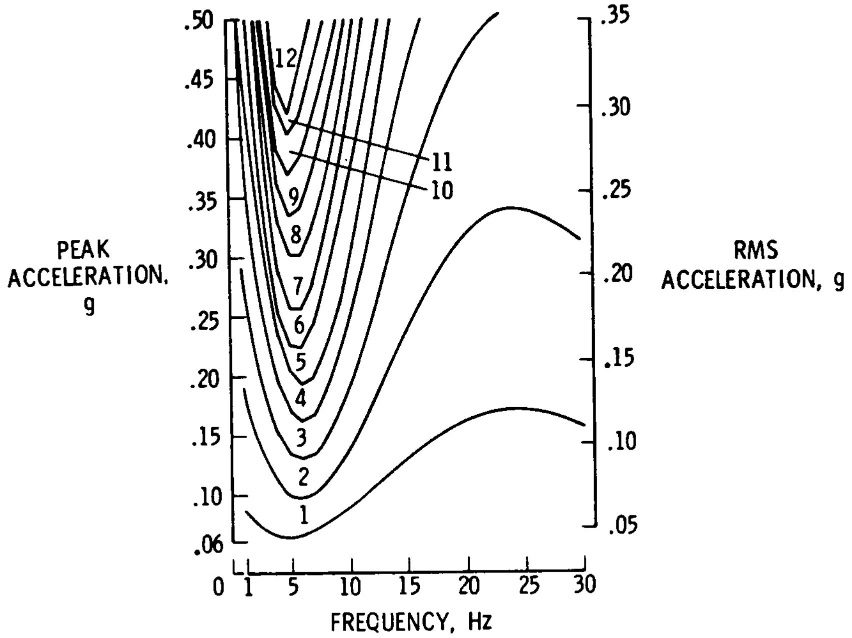


Figure 6.- Peak and rms acceleration levels required to produce successive equal discomfort curves (DISC = 1 to 12) as a function of frequency.

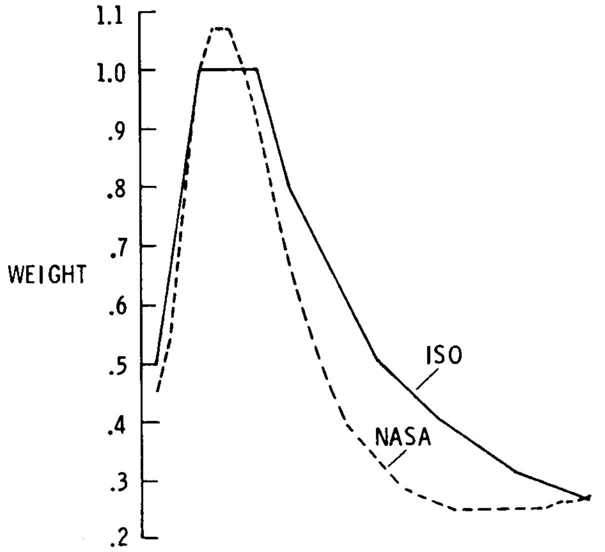


Figure 7.- Comparison of ISO and NASA frequency weighting factors as a function of floor input frequency.