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Human Discomfort Response to Noise Combined With Vertical Vibration

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SUMMARY

An experimental investigation was conducted (1) to determine the effects of combined environmental noise and vertical vibration upon human subjective discomfort response, (2) to develop a model for the prediction of passenger discomfort response to the combined environment, and (3) to develop a set of noise-vibration curves for use as criteria in ride quality design. Judgments of subjective discomfort were obtained from a total of 60 subjects who were exposed to parametric combinations of noise and vibrations through the use of a realistic laboratory simulator. Results of this investigation indicated that accurate prediction of passenger ride comfort requires knowledge of both the level and frequency content of the noise and vibration components of a ride environment as well as knowledge of the interactive effects of combined noise and vibration. A design tool in the form of an empirical model of passenger discomfort response to combined noise and vertical vibration was developed and illustrated by several computational examples. Finally, a set of noise-vibration criteria (constant discomfort) curves were generated to illustrate the fundamental design trade-off possible between passenger discomfort and the noise-vibration levels that produce the discomfort.

INTRODUCTION

The design and development of advanced air and surface transportation systems require a fundamental understanding of passenger discomfort which occurs in response to the noise and vibration environments produced by such systems. In particular, the design engineer needs valid and reliable methods for (1) estimating passenger discomfort resulting from an environment which combines noise and vibration (combined environment) and (2) determining the trade-offs between passenger acceptance and the levels of noise and vibration present in the combined environment. Many studies (see refs. 1 to 9, for example) have been conducted to explore the separate effects of noise or vibration upon human comfort and annoyance, but only a few studies (e.g., refs. 10 to 12) have dealt with the effects of these two variables acting in combination. These latter studies, however, were limited in scope and hence lack sufficient generality to be useful as design tools for estimating passenger discomfort response within diverse transportation systems.

Recently a comprehensive effort has been undertaken at the NASA Langley Research Center to develop a predictive model for use in the estimation of passenger discomfort caused by combined vibration and noise. To date, the NASA studies (refs. 13 to 20) have resulted in the development of a ride comfort model based upon a fundamental understanding of human discomfort response to vibration only. The effects of noise and the possible interaction of noise with vibration have not yet been accounted for in the NASA model development program. Consequently, the objectives of this study are (1) to determine the effects of combined noise and vibration stimuli upon human discomfort, (2) to develop a general model for predicting human discomfort response to combined noise and vibration environments, and (3) to develop a set of noise-vibration criteria curves.

SYMBOLS

A	vibration discomfort level, DISC
a_i	intercept of linear psychophysical function relating vibration discomfort level to peak acceleration level for the ith frequency of vertical sinusoidal vibration, DISC
a_k	intercept of least-square line relating incremental discomfort due to presence of noise to vibration discomfort level D_V, DISC
b_i	slope of linear psychophysical function relating vibration discomfort level to peak acceleration level for the ith frequency of vertical sinusoidal vibration, DISC/g unit
b_k	slope of the least-square line relating incremental discomfort due to presence of noise to vibration discomfort level D_V
D_I	incremental discomfort due to presence of noise in a vibration environment, DISC
$D_{I,j}$	incremental discomfort due to presence of noise in the jth octave band, corrected for octave-band effect, DISC
$D_{I,Y}$	incremental discomfort due to presence of noise at a level of Y dB(A) in the presence of vibration discomfort level D_V uncorrected for octave-band effect, DISC
$D_{I,max}$	incremental discomfort due to presence of noise associated with the octave band that produces maximum incremental discomfort, corrected for octave-band effect, DISC
D_{N+V}	total discomfort response to combined noise and vibration environment, DISC
D_V	level of discomfort due to applied vibration spectrum, DISC
$D_{V,i}$	vibration discomfort level due to vertical sinusoidal vibration applied at the ith frequency, DISC
f	octave-band center frequency, Hz
f_c	center frequency of applied random vibration spectrum, Hz
f_v	vibration frequency, Hz
g	acceleration level normalized by acceleration due to gravity ($1g = 9.81$ m/sec^2)

i	vibration frequency, Hz ($i = 1$ corresponds to 1 Hz, $i = 2$ corresponds to 2Hz, etc.), $i = 1, \ldots, 30$
j	octave-band frequency index ($j = 1$ corresponds to 63-Hz band, $j = 2$ corresponds to 125-Hz band, etc.), $j = 1, \ldots, 6$
L_A	octave-band A-weighted sound pressure level, dB(A)
N	number of decibels above reference level, $20 \log (p/p_{ref})$
p	root-mean-square sound pressure
p_{ref}	reference rms pressure, 0.00002 N/m^2
S	loudness, sones
S_m	loudness of loudest band of noise spectrum, sones
S_t	loudness of total noise spectrum, sones
ΣS	sum of loudness of all bands of noise spectrum, sones
s	subjects
Y	denotes dB(A) level within one octave band
α	level of statistical significance

Abbreviation:

rms	root mean square

EXPERIMENTAL METHOD

Selection of Variables

The independent variables selected for use in this study were noise level (A-weighted), noise octave-band center frequency, vibration discomfort level (measured in terms of discomfort units), and vibration frequency. The dependent variable was the subjective discomfort experienced by passenger subjects when exposed to various parametric combinations of the independent variables. The method used to obtain subjective discomfort is discussed later in this section.

The meanings of the independent variables are evident except for the term "vibration discomfort level." It is therefore useful to discuss this variable briefly and the reasons for using it as an independent variable. Previous studies (refs. 18 and 19) in the NASA ride quality model research program determined that, for each discrete frequency of vertical sinusoidal vibration, a linear relationship existed between subjective discomfort and vibration acceleration level. (See appendix A.) This determination led to the development of a ratio scale of discomfort for each frequency of vertical vibration that was adjusted to have a value of unity at discomfort threshold; i.e., the amount of discomfort experienced at discomfort threshold for each frequency was defined as 1 discomfort unit (1 DISC). The resultant ratio scale provided a measure of vibration discomfort that was common to all frequencies of vertical vibration. It was, therefore, possible to specify various combinations of vibration frequency and acceleration that produce equivalent levels of subjective discomfort. Since one of the objectives of the present study was to develop a model of passenger discomfort response to the combined environment, specific combinations of vibration frequency and vibration acceleration level that produce known levels of vibration discomfort were selected as vibration stimuli. For this reason vibration discomfort level was selected as an independent variable. In this manner the increment in discomfort response resulting from the presence of noise could be determined. It should be noted, furthermore, that the use of vibration discomfort level as an independent variable had the important additional advantage of minimizing the effect of vibration frequency, thereby permitting the focus of this study to be the determination of the effects of the added noise without the confounding effect of vibration frequency.

Experimental Apparatus

The apparatus used in this study was the Langley Research Center Passenger Ride Quality Apparatus (PRQA) as shown in figure 1. The PRQA is a unique electrohydraulic three-degree-of-freedom motion simulator capable of exposing passenger subjects to complex vibration and noise inputs over a wide range of frequencies and amplitudes. The simulator is described in detail in reference 14 and the reader is referred to that document for details of the simulator operating characteristics, etc. It should be mentioned, however, that the interior of the PRQA is configured to resemble a modern jet transport closely. It contains six aircraft tourist-class seats which permitted simultaneous testing of six subjects.

Subjects

A total of 60 subjects (49 female and 11 male) obtained from the general public through the use of an NASA contractual subject pool were used in this study. The ages of the subjects ranged from 18 to 62 years; the median age was 30 years. Each subject was required to undergo audiometric screening to insure that only subjects with normal hearing were used in the study. In addition, each subject was screened medically to insure that no subject was used who had a medical condition or injury that could be aggravated by exposure to noise and vibration.

The use of a large number of female subjects resulted from the fact that testing was done during normal working hours, and male subjects were more difficult to obtain during these hours. This is not considered a serious limitation, however, since results of previous research (refs. 16 and 17) indicated that no significant differences in discomfort responses occurred as a function of gender or age.

Experimental Design

The experimental design for this study is presented in table I. The design is a 4 × 4 × 4 × 6 factorial design with repeated measures on each factor. The factors used in this study consisted of four values of vibration frequency (3, 6, 9, and 12 Hz), four levels of vibration discomfort (1, 2, 3, and 4 DISC), four levels of A-weighted noise (76, 82, 88, and 94 dB(A)), and six octave bands of noise (63, 125, 250, 500, 1000, and 2000 Hz). Table II gives the actual acceleration levels corresponding to each combination of vibration frequency and vibration discomfort level of table I.

Scaling Method and Procedure

The scaling method selected for use in this study was magnitude estimation. This method allowed measurements of subjective discomfort within the combined environment to be made along the same scale used to measure subjective discomfort to vibration alone. The magnitude estimation procedure involved numbering standard stimuli; subjects were then asked to assign numbers to comparison stimuli that reflected their judgments of the magnitude of the comparison stimuli in relation to the standard modulus. Details of the application of the magnitude estimation procedure are given in the subject instructions (appendix B).

Table III gives the four standard stimulus conditions used in this study. The standards consisted of vibration stimuli only and were selected to provide a vibration discomfort level of 2 discomfort units (2 DISC) at each of the four frequencies of vertical vibration. The comparison stimuli consisted of ride segments corresponding to the parametric combinations of the vibration and noise factors of table I. For example, each cell of table I represented a unique comparison ride segment that contained both noise and vibration. The total number of ride segments experienced by each subject was the 384 parametric combinations given in table I, plus a total of 128 standard ride segments. The comparison ride segments were applied in random order and were organized into 32 sessions with each session containing 4 standards and 12 comparison rides. The vibration frequency of the standard and comparison rides within a session was constant and was determined by random assignment of sessions to the four levels of vibration frequency. All standard ride segments were assigned a discomfort value of 100. Furthermore, each ride segment consisted of a 5-sec onset, 10-sec duration, and a 5-sec offset with interstimulus intervals of 5 sec.

Prior to beginning actual testing, the subjects were thoroughly instructed in the use of the magnitude estimation procedure as well as other pertinent information related to test procedures and protocol. Instructions given to the subjects are presented in appendix B. The subjects were provided rating sheets upon which to mark their evaluations; a sample rating sheet is presented in appendix C. Because of the large number of stimuli, the testing of each group of six subjects required 2 days. The procedure used was to apply one-half of the stimuli (16 sessions) on the first day; the remaining stimuli followed approximately 1 week later.

Data Analysis

The presence (or absence) of statistically significant main effects and interactions of the independent variables with the ratings of discomfort was tested by computing a four-factor analysis of variance for the repeated measures design. The level of significance for testing the main effects and interactions of the vibration and noise stimuli in the analysis of variance was chosen to be $\alpha = 0.05$. It should be noted that the term "main effect" is used in a statistical sense and does not necessarily imply that the effect of a particular independent variable is of engineering significance. In this regard, a post hoc multiple comparison procedure (Scheffé method, ref. 21) was used to examine selected comparisons between factor level means, or treatment means, whenever application of such a procedure appeared to be necessary in order to interpret the results adequately. The level of significance for the post hoc tests was selected to be $\alpha = 0.005$. The reason for selecting a more stringent level of significance for the post hoc tests arose from the fact that the results of this study were to be interpreted with respect to their practical implications relative to engineering design applications in the area of vehicle ride quality. The use of a repeated measures design, appropriate from the standpoint of efficiency and achievement of the primary goals of this paper, did result in a more sensitive analysis in terms of finding statistical significance. Thus the indication of statistical significance did not necessarily imply practical significance. However, the use of a very small significance level in association with the post hoc tests tended to make statistical and "practical" significance correspond more closely.

RESULTS AND DISCUSSION

The experimental design used in this investigation resulted in the collection of a very large quantity of data describing the main effects and interactions of the four independent variables. This section presents only those results considered to be directly relevant to the three objectives stated in the Introduction. Consequently, the following paragraphs are restricted to the discussion of the four main effects, the two interactive effects with most practical importance (vibration discomfort level × noise level and noise level × octave band), and the method used to develop a ride comfort model based upon these results.

Principal Effects

The raw data collected in this study consisted of 23 040 individual magnitude estimates of discomfort corresponding to the evaluations of each of the 384 stimuli conditions by 60 subjects. Thus each cell of the factorial design (table I) contained 60 magnitude estimates of discomfort, one for each subject. An analysis of variance as shown in table IV was used to summarize these results. For purposes of further discussion the factors were defined by the following symbols:

f_V	vibration frequency, Hz
A	vibration discomfort level, DISC
L_A	octave-band A-weighted sound pressure level, dB(A)
f	octave-band center frequency, Hz
s	subjects

Examination of the results in table IV indicates that the main effects of factors f_V, A, f, and L_A as well as all interactions of these four factors were statistically significant ($\alpha = 0.05$).

Vibration frequency.- The main effect of vibration frequency is displayed in figure 2 where the total discomfort responses (averaged over factors f, L_A, and A) are presented as a function of vibration frequency. The total discomfort responses of figure 2 are presented in terms of discomfort units (or DISC) which were obtained by multiplying each magnitude estimate by the discomfort level of the standard (2 DISC) and dividing by 100.

The results of the analysis of variance and inspection of figure 2 lead to the implication that the discomfort due to the 6-Hz vibration frequency may have been slightly greater than the discomfort associated with the other three frequencies. However, application of the Scheffé method (ref. 21) to the comparisons between the discomfort response of 6 Hz and the three discomfort responses at 3, 9, and 12 Hz indicated the contrasts to be nonsignificant ($\alpha = 0.005$). Thus the use of vibration discomfort level as a factor in the experimental design effectively controlled for the effect of vibration frequency and thereby permitted the major focus of this paper to be directed toward the main effects and interactions of the other three factors.

Noise octave-band frequency.- The main effect of noise octave-band frequency is illustrated in figure 3. The discomfort responses for this effect have been averaged over factors f_V, A, and L_A. The data of figure 3 indicate that both the lowest and highest octave bands resulted in substantially increased levels of discomfort as compared to the intermediate octave bands. Post hoc tests verified that the discomfort produced by the lowest and highest octave bands differed significantly ($\alpha = 0.005$) from the discomfort produced by the intermediate octave bands. This difference implies that passenger comfort may be more adversely affected in transportation systems that operate in a noise regime characterized by very low or very high frequencies. The detrimental effect of low-frequency noise is particularly important from the standpoint of noise control since low-frequency noise is difficult to control effectively.

Vibration discomfort level.- The main effect of vibration discomfort level is indicated by the solid curve in figure 4. The discomfort ratings for this case have been averaged over factors f_V, L_A, and f. Also shown in this figure (dashed curve) is the discomfort that would be contributed by vibration acting alone. Examination of this figure indicates that total discomfort response to the combined environment increased in an approximate linear fashion with increasing vibration discomfort level. However, the presence of such a strong main effect due to vibration discomfort level is not surprising since this effect was built into the analysis by virtue of the experimental design. Of particular interest is the effect of the added noise upon discomfort response. This effect is illustrated by the difference between the total discomfort due to the combined environment (solid curve) and the discomfort due to vibration only (dashed curve). The addition of noise provided an increase in total discomfort of approximately 2 DISC at the lowest level of vibration discomfort and about 1/2 DISC at the highest level of vibration discomfort. Thus the overall effect of the added noise upon total discomfort response decreased as the level of applied vibration discomfort increased. Data such as that displayed in figure 4 can be used to obtain crude estimates of the effect of adding noise to a vibration environment. Better estimates of the noise effects, however, can be obtained by considering the interactions between noise and vibration. This is discussed in detail later in this paper.

Noise level.- The main effect of noise level is shown in figure 5. In this case the total discomfort responses were averaged over factors f_v, A, and f. Figure 5 indicates that total discomfort response increased by almost 2 DISC as noise level increased from 76 to 94 dB(A). Post hoc comparisons between the consecutive factor level means indicated that all comparisons were significant ($\alpha = 0.005$). Thus this main effect is a strong one and is very important from an engineering applications viewpoint.

Interactions

The two interactions of practical importance for vehicle ride quality are considered to be the one between vibration discomfort level and noise level and the one between noise level and octave-band center frequency. These are discussed in the following sections.

Vibration discomfort level × noise level.- The most important interaction affecting ride quality modeling is the one between the level of vibration discomfort (equivalent to a physical acceleration level) and noise level. These two factors in the vehicle design or modification process are those most easily controlled by the systems designer. This interaction is illustrated in figure 6 where the total discomfort response is presented as a function of applied vibration discomfort level for each level of noise. Also shown (by the dashed line) is the discomfort that would be present if the vibration were acting alone. The results presented in figure 6 show several interesting features. First, it is obvious that increasing the noise level within each level of vibration discomfort generally resulted in an increase in total discomfort response. Furthermore, the relative increase in total discomfort in the presence of the added noise was large at the low levels of vibration discomfort and decreased as vibration discomfort increased. For example, at the highest level of applied vibration discomfort, the presence of noise at either 76 or 82 dB(A) contributed only minimally to total discomfort, whereas at the threshold of discomfort for vibration, these same noise levels produced discomfort increments of 1 and 1.5 DISC, respectively. In addition, for a noise level of 94 dB(A), a decrease in vibration discomfort level from $D_V = 4$ to $D_V = 1$ produced only a modest improvement in overall discomfort response. On the other hand, for a noise level of 76 dB(A), a reduction of vibration discomfort level over the same range produced substantial reductions in total discomfort response. These results illustrate quite well the fundamental trade-off between noise and vibration when both are present in a ride environment and provide the basis for modeling passenger discomfort within the combined environment.

Noise level × octave band.- The interaction between noise level and octave-band center frequency ($L_A \times f$ interaction) is presented in figure 7. It is apparent from this figure that total discomfort response was highly dependent upon the particular combination of noise level and octave band experienced by subjects, with the lowest and highest octave bands producing maximum discomfort within each noise level. An obvious implication shown by the results given in both figures 6 and 7 is that the accurate prediction of passenger discomfort in the combined environment requires knowledge of the interactive effects of noise level, noise frequency, and vibration discomfort level. These effects must be incorporated into the prediction procedure together with knowledge of the spectrum characteristics of the two physical variables.

Ride Comfort Modeling

This section discusses the procedure used to develop an empirical model of passenger discomfort response to combined noise and vertical vibration based upon the results presented in this paper. The approach used was to derive a set of empirical equations describing the incremental discomfort produced when noise is added to a vibration environment. As mentioned earlier, empirical functions for estimating discomfort responses to vibration alone were determined in previous NASA research investigations (for example, ref. 19). These functions are summarized in appendix A. For the present study the incremental discomfort response attributable to the presence of noise is defined by the following equation:

$$D_I = D_{N+V} - D_V \tag{1}$$

where D_{N+V} is the total discomfort response to the combined environment, D_V is the discomfort response that would be produced if the vibration were acting alone, and D_I is the incremental discomfort response resulting from the presence of noise. The data of figure 6 were used to determine D_I and its functional dependence upon both the level of applied vibration discomfort and the level of applied noise. Figure 8 illustrates this functional dependence in terms of the variation of incremental noise discomfort response D_I as a function of noise level and vibration level. Least-square parabolic regression curves were computed for each value of vibration discomfort level shown in figure 8 and are indicated by the solid lines.

The resultant set of four parabolic functions allows the computation of the incremental discomfort due to the presence of noise as a function of dB(A) noise level for each of the levels of vibration discomfort used in this study. The next step involved the development of a set of relationships that allows the computation of incremental discomfort due to noise for any combination of noise level and vibration discomfort level. This development was accomplished by use of the four parabolic functions to compute the four values of noise discomfort at each dB(A) level over the range of 65 to 100 dB(A) and then fitting a least-square line to each set of four values thus obtained. This resulted in the following general equation for noise discomfort:

$$D_{I,Y} = a_k + b_k D_V \tag{2}$$

where $D_{I,Y}$ is the incremental discomfort due to the presence of noise at a level of Y dB(A) (note that $D_{I,Y}$ replaces D_I in eq. (1)), a_k is the intercept of the least-square line, b_k is the slope of the least-square line, and D_V is the level of vibration discomfort produced by the vibration spectrum present in the combined environment. Values of a_k and b_k for each noise level are given in table V.

Corrections for octave-band effect.- The data used to develop equation (2) consisted of subjective ratings of discomfort that were averaged over the six octave bands at each noise level. As a result, the effect of octave-band frequency was not directly accounted for in these equations. A reasonable means of incorporating the octave-band effect in the development of the ride quality model was to compute a set of weighting factors to be applied to the incremental discomfort values calculated by equation (2) in order to correct for the octave-band effect. These weighting factors were obtained by (a) computing the overall incremental discomfort contribution due to noise for each of the separate octave bands, (b) computing the mean (over octave-band frequency) of the six incremental noise discomfort contributions, and (c) normalizing the incremental noise discomfort response within each of the octave bands by the mean obtained in step (b). This gave a set of frequency-dependent weighting factors that can be applied to the values of incremental noise discomfort produced by equation (2) if it is known that a single octave band provides the dominant noise source. These weighting factors are given in table VI.

Continuous spectrum noise.- Since this investigation dealt only with discomfort responses obtained from exposure to noise within a single octave band, the results are strictly applicable to the condition where the dominant source is limited to a single octave band. However, a reasonable and logical approach for estimating incremental discomfort due to broad spectrum noise (contiguous octave bands) was developed by applying the results obtained by S. S. Stevens (ref. 22) for the computation of the loudness of complex noise. The reader is referred to appendix D for a detailed discussion of the rationale and justification for applying Stevens' method.

Stevens' approach gives the following relationship to compute the incremental noise discomfort contribution to the total discomfort response for the case where the noise source consists of more than one octave band:

$$D_I = D_{I,\max} + 0.3\left(\sum_j D_{I,j} - D_{I,\max}\right) \qquad (j = 1, \ldots, 6) \tag{3}$$

where D_I is the incremental discomfort resulting from the presence of noise when the noise spectrum contains two or more octave bands of sufficient level to affect discomfort response, $D_{I,max}$ is the incremental discomfort associated with the octave band that produces maximum discomfort, $\sum_j D_{I,j}$ is the sum of the incremental discomfort values contributed by each of the octave bands (i.e., the $D_{I,Y}$ corrected for octave band, and j is the octave-band index (e.g., $j = 1$ corresponds to 63 Hz, etc.). Note that $D_{I,j}$ is computed by using equation (2) together with the values of a_k and b_k from table V and then correcting for the octave-band main effect by applying the appropriate weighting factors given in table VI.

In summary, equations (2) and (3) together with tables V and VI can be used to obtain estimates of incremental noise discomfort (for a given level of vibration discomfort) due to the presence of contiguous octave bands in the combined environment. For environments in which the major noise source is confined to a single octave band, it is sufficient to use equation (2) with tables V and VI to compute incremental noise discomfort. For convenience the incremental discomfort values due to added noise for selected combinations of noise level and vibration discomfort level were computed, and the resulting values of noise discomfort are presented in table VII. The use of table VII in conjunction with the octave-band weighting factors given in table VI is sufficient to determine the incremental noise discomfort due to single octave bands. Total subjective discomfort is then obtained by applying equation (1). The exact procedures for computing estimates of total discomfort for single octave-band noise and/or continuous spectra noise combined with vibration are given in detail in appendix A.

Noise-Vibration Criteria

Equations (1) and (2) were used to compute a set of constant total discomfort curves. These curves are presented in figure 9 for total discomfort levels of 1, 2, 3, and 4 DISC. The solid curves represent the total discomfort response averaged over octave bands for each of the four DISC levels. The dashed portions are extrapolations of each curve to the condition of zero vibration discomfort ($D_V = 0$), and the shaded area surrounding each curve represents the range of values that each curve can take on when corrected for the octave-band effect.

The application of the data presented in figure 9 is completely general with respect to the range of vibration parameters used in this study. In other words, the discomfort due to vibration (plotted along the abscissa of fig. 9) can result from applied vibrations consisting of single or multiple discrete frequencies or from completely random vibrations. The noise levels, however, correspond to those within a single dominant octave band. If the noise characteristics satisfy this condition, then the curves of figure 9 can be treated as criteria curves. For example, if the plotted values of vibration discomfort level and noise level obtained from measurements on a specific vehicle produce a point that falls below the DISC = 1 curve, then the ride can be said to be below discomfort threshold and therefore would be acceptable to the majority of passengers. In this sense the curves provide the design engineer with a means of obtaining quick estimates of the trade-offs available between noise and vibration for a specified level of discomfort. If the noise spectrum is continuous, however, recourse can be made to the equations and procedures developed in the preceding sections for handling this situation.

CONCLUDING REMARKS

This paper has presented the results of a research investigation to determine the effects of combined noise and vertical vibration upon human subjective discomfort response, to develop a ride comfort model that will allow prediction of discomfort response to the combined environment, and to generate tentative noise-vibration criteria curves. The more important conclusions and implications derived from the results of this experimental investigation are summarized as follows.

Accurate prediction of passenger ride comfort in a combined noise and vibration environment will require knowledge of the levels and frequency content of each of these factors. Furthermore, a predictive model of passenger discomfort will have to incorporate these factors and their interactive effects into the prediction procedure.

Subjective discomfort response was highly dependent upon noise octave-band frequency with maximum subjective discomfort occurring for noises applied within the 63-Hz and 2000-Hz octave bands. Consequently, the effect of noise octave band cannot be neglected and must be incorporated into the predictive model of ride comfort. Furthermore, the relatively large values of discomfort produced by noise applied at the lower octave bands indicate that transportation vehicles characterized by similar low-frequency interior noise spectra may be prone to serious ride quality problems since such low-frequency noise is particularly difficult to control.

The relative importance of either noise or vibration to passenger discomfort was found to depend upon the particular levels of each factor present in a vehicle environment. For example, if the vibration levels associated with a vehicle were of sufficient intensity to generate large discomfort values, then the addition of noise produced relatively small additional increments in discomfort. On the other hand, if the vibration levels were small, then noise became the principal determiner of discomfort. This basic relationship defined the fundamental design trade-off that must be considered by a systems designer in the attempt to achieve adequate passenger comfort within a transportation vehicle.

The results presented in this study were used to develop a general model of human discomfort response to combined noise and vibration environments. The resultant model provides the design engineer with a comprehensive tool for estimating subjective comfort over a broad spectrum of vehicles, diagnosing ride comfort problems, and evaluating compromises available between passenger comfort and the complexity and/or costs of noise and vibration control techniques. Such a tool has heretofore been unavailable to the design community.

A set of noise-vibration criteria curves were developed that enable a design engineer to make quick estimates of the relative effects upon human discomfort of noise and vibration within a vehicle. These criteria curves were in the form of constant discomfort curves and are useful as a preliminary design tool for determining whether a specified level of discomfort (or comfort) can be met.

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APPENDIX A

COMPUTATIONAL PROCEDURE FOR TOTAL DISCOMFORT

An example best illustrates the computational procedure. For this purpose two separate cases may be considered. In the first case, consider the vibration spectrum given in figure 10 to act simultaneously with the noise spectrum shown in figure 11(a). This particular noise spectrum contains a single dominant octave band. In the second case, the same vibration spectrum is combined with the continuous octave-band spectrum shown in figure 11(b). Computational steps required to compute the total discomfort response for these two cases are presented below.

Case 1: Vibration and Single Dominant Noise Octave Band

Step 1.- Compute the discomfort level attributable to the vibration components of the total ride environment. This involves the use of the techniques and empirical equations developed in earlier studies in the NASA ride comfort research program. If the vibration can be characterized as single frequency (sinusoidal), then the following equation is used to compute the vibration discomfort:

$$D_{V,i} = a_i + b_i g_{peak} \tag{A1}$$

where $D_{V,i}$ is the vibration discomfort (in DISC) produced by a peak vertical acceleration level g_{peak} applied at the ith frequency and a_i and b_i are the intercept and slope, respectively, of the linear psychophysical relationship between subjective discomfort and sinusoidal vertical vibration. Values of a_i and b_i for each frequency of vibration from 1 to 30 Hz are given in table VIII.

If the vertical vibration is random in nature, the following equation can be used to estimate vibration discomfort:

$$D_V = -1.75 + 33.35 g_{rms} + 0.857(f_c) - 0.102(f_c)^2 + 0.00346(f_c)^3 \tag{A2}$$

where g_{rms} is the overall root-mean-square acceleration level of the vertical vibration spectrum and f_c is the center frequency of the dominant spectral component of the vibration. Equation (A2) has been derived in prior NASA research (ref. 23) and is valid for vibration spectra whose dominant frequency component has a bandwidth in the range from 2 to 10 Hz and whose associated center frequency is in the range from 2 to 13 Hz. For the present example (see fig. 10) the bandwidth is 10 Hz, center frequency is 6 Hz, and the overall rms acceleration level is $0.100g_{rms}$. Substituting these values into equation (A2) gives

$$D_V = 3.80 \text{ DISC}$$

Step 2.- Incremental discomfort due to noise for the vibration discomfort level obtained in step 1 should now be computed. Equation (2), in section entitled "Ride Comfort Modeling," can be used with the appropriate coefficients from table V, or it can be used with table VII directly. Using equation (2) gives

$$D_{I,90} = 3.2968 - 0.6547D_V$$

or

$$D_{I,90} = 3.2968 - 0.6547(3.80)$$

$$D_{I,90} = 0.807 \text{ DISC (uncorrected for octave band)}$$

Step 3.- The appropriate weighting factor from table VI to account for the octave-band frequency effect should be applied. Since the dominant octave band for this noise spectrum is the 250-Hz band, the required correction factor is 0.786. Thus the noise discomfort, corrected for octave band, is

$$D_{I,90} = 0.807(0.786) = 0.634 \text{ DISC (corrected for octave band)}$$

Step 4.- The final step is the computation of the total discomfort produced by the combined environment using equation (1).

$$D_{N+V} = D_{I,90} + D_V$$

or

$$D_{N+V} = 0.634 + 3.80 = 4.43 \text{ DISC}$$

Case 2: Vibration and Continuous Noise Spectrum

Step 1.- Compute vibration discomfort as in step 1 of "Case 1."

$$D_V = 3.80 \text{ DISC}$$

Step 2.- Compute the discomfort due to the presence of noise for each octave band of the continuous noise spectra. The octave-band levels are listed in the following table:

Octave-band center frequency, Hz	dB(A)
63	65
125	85
250	75
500	85
1000	80
2000	75

Using equation (2) with the appropriate coefficients from table V and correcting for octave band gives the following set of computations for the noise discomfort within each octave band.

63-Hz octave band:

$$D_{I,65} = 0.3447 - 0.1219(3.80) = -0.118 = 0 \text{ DISC}$$

If $D_{I,Y} < 0$, set it equal to zero.

125-Hz octave band:

$$D_{I,85} = 2.5164 - 0.5533(3.80) = 0.414 \text{ DISC}$$

and applying the octave-band weighting factor gives

$$D_{I,85} = (0.414)(0.963) = 0.399 \text{ DISC}$$

250-Hz octave band:

$$D_{I,75} = 1.2408 - 0.3429(3.80) = -0.062 = 0 \text{ DISC}$$

500-Hz octave band:

$$D_{I,85} = 2.5164 - 0.5533(3.80) = 0.414 \text{ DISC}$$

and applying the octave-band weighting factor

$$D_{I,85} = (0.414)(0.646) = 0.267 \text{ DISC}$$

1000-Hz octave band:

$$D_{I,80} = 1.8311 - 0.4494(3.80) = 0.123 \text{ DISC}$$

and applying the octave-band weighting factor gives

$$D_{I,80} = (0.123)(0.688) = 0.085 \text{ DISC}$$

2000-Hz octave band:

$$D_{I,75} = 1.2408 - 0.3429(3.80) = -0.062 = 0 \text{ DISC}$$

These calculations are summarized in the following table:

Octave band	dB(A)	$D_{I,j}$
63	65	0
125	85	.399
250	75	0
500	85	.267
1000	80	.085
2000	75	0

Step 3.- The total discomfort due to noise can be computed by using equation (3), which is

$$D_I = D_{I,\max} + 0.3\left(\sum_j D_{I,j} - D_{I,\max}\right)$$

Using the computed values of $D_{I,j}$ obtained in step 2 gives

$$D_{I,\max} = 0.399 \text{ DISC}$$

$$\sum_{j} D_{I,j} = 0.399 + 0.267 + 0.085 = 0.751 \text{ DISC}$$

Thus,

$$D_I = 0.399 + 0.3(0.751 - 0.399)$$

$$D_I = 0.505 \text{ DISC}$$

Step 4.- The total discomfort due to the combined environment can be computed by using equation (1), which can be written

$$D_{N+V} = D_I + D_V$$

$$D_{N+V} = 0.505 + 3.80 = 4.30 \text{ DISC}$$

APPENDIX B

SUBJECT INSTRUCTIONS

The instructions given to the test subjects are presented in this appendix.

Instructions

You have volunteered to participate in a research program to investigate the ride quality of transportation vehicles. Specifically, we wish to identify the types of vibration and noises in transportation vehicles which most influence a person's sense of well-being. To assess the influence of these vibrations and noises, we have built a simulator which can expose passengers to realistic ride environments. The simulator essentially provides no risk to passengers. The system has been designed to meet stringent safety requirements so that it cannot expose subjects to motions or noises 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 and noises that you will receive today are representative of the vibrations and noises 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 and noises 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 one of three ways: (1) press overhead button labeled "STOP," (2) by voice communication with the test conductor, or (3) by pressing downward on the switch lever located at the front of each armrest. Because of individual differences in people, there is always the possibility that someone may find a ride objectionable and may not wish to continue. If this should happen to you, please do not hesitate to stop the tests by one of these methods.

Instructions for Ride Estimations

The task you will now be required to perform is to <u>evaluate</u> the discomfort associated with a series of ride segments. The discomfort evaluation you make of a particular ride segment will always be in comparison to a standard ride segment. Each ride segment will be presented for approximately 10 seconds. The start of a ride segment will be indicated by a red light in the upper left corner of the front mirror. The red light will be on during each of the ride segments you are to evaluate. Immediately after the light goes off, you are to evaluate the ride segment just experienced in comparison with the standard ride segment.

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Task.- I will present a 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 present ride segments that provide both less or more discomfort than the standard 100. Your task will be to assign numbers to each of these 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.

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 something 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 the vibration and noise experienced during the ride segment that you are rating. Certainly, you could evaluate a ride based on other factors such as temperature, pressure, etc. However, restrict your evaluations of a ride segment to the comfort associated with various vibrations and noises and not upon variations of vibration or noise. In other words, rate a ride segment in terms of comfort of a vibration and noise, not on whether you notice differences of vibration and noise. This requirement is important because we are interested in differences of comfort, not merely in your ability to detect differences of vibrations and noises.

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 to 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.

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Remember.-

(1) Watch for the red light.

(2) Evaluate only the discomfort of vibrations and noises.

(3) Place your evaluation number on the appropriate blank.

Are there any questions?

Simulator Instructions

(Upon entering the simulator, the subject should be told:)

Please be seated and fasten your seatbelt. (Wait until all the subjects are ready.) Now, 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 press the armrest 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. This first test will take about one hour.

APPENDIX C

SAMPLE RATING SHEET

The sample rating sheet given to each test subject is as follows:

SUBJECT NO. ____________ SEX ______ DATE ________

SEAT NO. ____________ AGE ______ TIME ______ AM

WEIGHT _____ PM

RIDE	SESSION 1
S	100
1	
2	
3	
S	100
4	
5	
6	
S	100
7	
8	
9	
S	100
10	
11	
12	

RIDE	SESSION 2
S	100
1	
2	
3	
S	100
4	
5	
6	
S	100
7	
8	
9	
S	100
10	
11	
12	

RIDE	SESSION 3
S	100
1	
2	
3	
S	100
4	
5	
6	
S	100
7	
8	
9	
S	100
10	
11	
12	

RIDE	SESSION 4
S	100
1	
2	
3	
S	100
4	
5	
6	
S	100
7	
8	
9	
S	100
10	
11	
12	

RIDE	SESSION 5
S	100
1	
2	
3	
S	100
4	
5	
6	
S	100
7	
8	
9	
S	100
10	
11	
12	

RIDE	SESSION 6
S	100
1	
2	
3	
S	100
4	
5	
6	
S	100
7	
8	
9	
S	100
10	
11	
12	

RIDE	SESSION 7
S	100
1	
2	
3	
S	100
4	
5	
6	
S	100
7	
8	
9	
S	100
10	
11	
12	

RIDE	SESSION 8
S	100
1	
2	
3	
S	100
4	
5	
6	
S	100
7	
8	
9	
S	100
10	
11	
12	

APPENDIX D

INCREMENTAL DISCOMFORT CAUSED BY NOISE FOR CONTINUOUS SPECTRUM NOISE

Using direct loudness matches, Stevens (ref. 22) found that the loudnesses in octave bands can be combined according to the following formula:

$$S_t = S_m + 0.3(\Sigma S - S_m) \qquad \text{(D1)}$$

where S_t is the loudness (in sones) of the total noise spectrum, S_m is the loudness of the loudest band, and ΣS is the sum of the loudness of all the bands. The empirical relationship defined by equation (D1) provides a basis for computing the total discomfort due to a continuous noise spectrum (in the presence of vibration) provided that subjective loudness and subjective discomfort can be shown to be similar psychological quantities and to obey similar psychophysical laws. It would certainly be reasonable to assume that loudness and discomfort response to noise are closely related quantities since one would expect discomfort and/or annoyance to increase as the perceived loudness of the noise increases. Evidence supportive of the assumption that subjective loudness and subjective discomfort are closely related was found by considering the relationship between noise stimulus level and subjective magnitude of each of these psychological quantities. Stevens found that loudness is related to noise stimulus intensity by a power-law relationship of the form

$$\log L = 0.03N - 1.2 \qquad \text{(D2)}$$

where S is the loudness in sones and N is the number of decibels above the reference level ($N = 20 \log (p/p_{ref})$). For comparison purposes the logarithms of the values of incremental discomfort due to noise obtained in this study were used to compute the power-law relationship between noise discomfort and noise stimulus level within each of the octave bands, and the resulting power-law coefficients were then averaged over octave bands. This resulted in the following power-law relationship:

$$\log D_I = 0.0337(\text{dB(A)}) - 2.867 \qquad \text{(D3)}$$

Comparison of equation (D3) with the power-law equation for loudness (eq. (D2)) obtained by Stevens indicates that the power-law exponent for discomfort is very close to the power-law exponent obtained for loudness. Thus the growth of loudness and discomfort caused by noise is defined by very similar power relationships, and it would be reasonable to assume that these two psychophysical quantities will correlate quite highly with one another. This correlation leads to the further implication that noise discomfort responses produced by two or more contiguous octave bands of noise will summate in a manner similar to the summation of loudness as determined by Stevens. It is therefore assumed that the Stevens masking-summation relationship can be tentatively applied to the problem of predicting discomfort response to noise. Of course, the validity of this assumption should be examined by means of appropriately designed experiments.

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TABLE I.- EXPERIMENTAL DESIGN, REPEATED MEASURES

Vibration frequency, Hz	Vibration discomfort level, DISC	Noise level, dB(A)																							
		76						82						88						94					
		Octave-band center frequency, Hz																							
		63	125	250	500	1000	2000	63	125	250	500	1000	2000	63	125	250	500	1000	2000	63	125	250	500	1000	2000
3	1 2 3 4																								
6	1 2 3 4	Total number of cells: 384 Total number of subjects: 60 Repeated measures on all factors																							
9	1 2 3 4																								
12	1 2 3 4																								

TABLE II.- ACCELERATION LEVELS CORRESPONDING TO EACH COMBINATION OF VIBRATION FREQUENCY AND VIBRATION DISCOMFORT LEVEL

Vibration frequency, Hz	Peak acceleration levels, g units, for vibration discomfort level, DISC, of -			
	1	2	3	4
3	0.082	0.129	0.176	0.222
6	.061	.096	.130	.165
9	.086	.131	.177	.222
12	.106	.178	.249	.320

TABLE III.- STANDARD RIDE AT EACH FREQUENCY FOR DISC = 2

Standard ride	Frequency, Hz	Acceleration level, g_{peak}
1	3	0.130
2	6	.096
3	9	.131
4	12	.178

TABLE IV.- SUMMARY OF ANALYSIS OF VARIANCE

Source	Degrees of freedom	Sum of squares	Mean square	Error term	F-ratio
Vibration frequency, f_v	3	231 242	77 080	$f_v \times s$	[a]3.98
Vibration discomfort level, A	3	14 407 910	4 802 638	$A \times s$	[b]211.08
Noise level, L_A	3	23 517 490	7 839 163	$L_A \times s$	[b]165.50
Octave-band frequency, f	5	10 007 320	2 001 464	$f \times s$	[b]78.86
Subjects, s	59	41 526 940	703 846		
$f_v \times A$	9	711 695	79 077	$f_v \times A \times s$	[b]15.95
$f_v \times L_A$	9	116 617	12 957	$f_v \times L_A \times s$	[b]3.09
$A \times L_A$	9	1 439 414	159 934	$A \times L_A \times s$	[b]26.80
$f_v \times f$	15	375 693	25 046	$f_v \times f \times s$	[b]5.08
$A \times f$	15	249 080	16 605	$A \times f \times s$	[b]3.62
$L_A \times f$	15	4 113 500	274 233	$L_A \times f \times s$	[b]35.71
$f_v \times s$	177	3 427 099	19 362		
$A \times s$	177	4 027 156	22 752		
$L_A \times s$	177	8 383 614	47 365		
$f \times s$	295	7 486 828	25 379		
$f_v \times A \times L_A$	27	311 700	11 544	$f_v \times A \times L_A \times s$	[b]2.62
$f_v \times A \times f$	45	622 519	14 722	$f_v \times A \times f \times s$	[b]3.69
$f_v \times L_A \times f$	45	631 933	14 042	$f_v \times L_A \times f \times s$	[b]2.74
$A \times L_A \times f$	45	778 831	17 307	$A \times L_A \times f \times s$	[b]4.00
$f_v \times A \times s$	531	2 632 349	4 957		
$f_v \times L_A \times s$	531	2 225 938	4 191		
$A \times L_A \times s$	531	3 167 727	5 965		
$f_v \times f \times s$	885	4 367 598	4 935		
$A \times f \times s$	885	4 054 147	4 580		
$L_A \times f \times s$	885	6 796 392	7 679		
$f_v \times A \times L_A \times f$	135	2 126 576	15 752	$f_v \times A \times L_A \times f \times s$	[b]3.58
$f_v \times A \times L_A \times s$	1593	7 031 274	4 413		
$f_v \times A \times f \times s$	2655	10 587 800	3 987		
$f_v \times L_A \times f \times s$	2655	13 630 630	5 133		
$A \times L_A \times f \times s$	2655	11 496 860	4 330		
$f_v \times A \times L_A \times f \times s$	7965	35 094 950	4 406		

[a] $\alpha = 0.05$.
[b] $\alpha = 0.01$.

TABLE V.- VALUES OF SLOPE AND INTERCEPT FOR FUNCTION OF $D_{I,Y} = a_k + b_k D_V$

Noise level, dB(A) (a)	Intercept, a_k	Slope, b_k
65	0.3447	-0.1219
66	.4172	-.1445
67	.4935	-.1669
68	.5736	-.1893
69	.6575	-.2116
70	.7452	-.2337
71	.8368	-.2558
72	.9320	-.2777
73	1.0312	-.2995
74	1.1340	-.3212
75	1.2408	-.3429
76	1.3512	-.3644
77	1.4654	-.3858
78	1.5835	-.4071
79	1.7055	-.4284
80	1.8311	-.4494
81	1.9605	-.4704
82	2.0938	-.4913
83	2.2294	-0.5118
84	2.3718	-.5329
85	2.5164	-.5533
86	2.6649	-.5738
87	2.8172	-.5942
88	2.9732	-.6145
89	3.1330	-.6346
90	3.2968	-.6547
91	3.4642	-.6746
92	3.6354	-.6944
93	3.8104	-.7142
94	3.9893	-.7338
95	4.1720	-.7533
96	4.3574	-.7724
97	4.5486	-.7921
98	4.7426	-.8113
99	4.9404	-.8304
100	5.1421	-.8494

[a] For noise levels below 65 dB(A), values of a_k and b_k are assumed to be zero.

TABLE VI.- OCTAVE-BAND WEIGHTING FACTORS

Octave-band center frequency, Hz	Weighting factor
63	1.470
125	.963
250	.786
500	.646
1000	.688
2000	1.448

TABLE VII.- VALUES OF INCREMENTAL DISCOMFORT DUE TO PRESENCE OF NOISE FOR VARIOUS COMBINATIONS OF NOISE AND VIBRATION DISCOMFORT LEVELS

(UNCORRECTED FOR OCTAVE-BAND EFFECT)

(a) 65 to 75 dB(A)

Vibration discomfort, DISC	Incremental discomfort for noise level, dB(A), of -										
	65	66	67	68	69	70	71	72	73	74	75
0.5	0.284	0.345	0.410	0.479	0.552	0.628	0.709	0.793	0.881	0.973	1.069
.6	.272	.330	.393	.460	.530	.605	.683	.765	.852	.941	1.035
.7	.259	.316	.377	.441	.509	.582	.658	.738	.822	.909	1.001
.8	.247	.302	.360	.422	.488	.558	.632	.710	.792	.877	.966
.9	.235	.287	.343	.403	.467	.535	.606	.682	.762	.845	.932
1.0	.223	.273	.327	.384	.446	.512	.581	.654	.732	.813	.898
1.1	.211	.258	.310	.365	.425	.488	.555	.626	.702	.781	.864
1.2	.198	.244	.293	.346	.404	.465	.530	.599	.672	.748	.829
1.3	.186	.229	.276	.328	.382	.441	.504	.571	.642	.716	.795
1.4	.174	.215	.260	.308	.361	.418	.479	.543	.612	.684	.761
1.5	.162	.200	.243	.290	.340	.395	.453	.515	.582	.652	.726
1.6	.150	.186	.226	.271	.319	.371	.428	.488	.552	.620	.692
1.7	.137	.172	.210	.252	.298	.348	.402	.460	.522	.588	.658
1.8	.125	.157	.193	.233	.277	.324	.376	.432	.492	.556	.624
1.9	.113	.143	.176	.214	.255	.301	.351	.404	.462	.524	.589
2.0	.101	.128	.160	.195	.234	.278	.325	.377	.432	.492	.555
2.1	.089	.114	.143	.176	.213	.254	.300	.349	.402	.459	.521
2.2	.076	.099	.126	.157	.192	.231	.274	.321	.372	.427	.486
2.3	.064	.085	.110	.138	.171	.208	.248	.293	.342	.395	.452
2.4	.052	.070	.093	.119	.150	.184	.223	.266	.312	.363	.418
2.5	.040	.056	.076	.100	.128	.161	.197	.238	.282	.331	.384
2.6	.028	.042	.060	.081	.107	.138	.172	.210	.252	.299	.349
2.7	.016	.027	.043	.062	.086	.114	.146	.182	.222	.267	.315
2.8	.003	.013	.026	.044	.065	.091	.120	.154	.193	.235	.281
2.9			.009	.025	.044	.067	.095	.127	.163	.202	.246
3.0				.006	.023	.044	.069	.099	.133	.170	.212
3.1					.002	.021	.044	.071	.103	.138	.178
3.2							.018	.043	.073	.106	.144
3.3								.016	.043	.074	.109
3.4									.013	.042	.075
3.5										.010	.041
3.6											.006
3.7											
3.8											
3.9											
4.0											

TABLE VII.- Continued

(b) 76 to 86 dB(A)

Vibration discomfort, DISC	Incremental discomfort for noise level, dB(A), of -										
	76	77	78	79	80	81	82	83	84	85	86
0.5	1.169	1.272	1.380	1.491	1.606	1.725	1.848	1.974	2.105	2.240	2.378
.6	1.132	1.234	1.339	1.448	1.561	1.678	1.799	1.922	2.052	2.184	2.321
.7	1.096	1.195	1.298	1.406	1.516	1.631	1.750	1.871	1.999	2.129	2.263
.8	1.060	1.157	1.258	1.363	1.472	1.584	1.701	1.820	1.945	2.074	2.206
.9	1.023	1.118	1.217	1.320	1.427	1.537	1.652	1.769	1.892	2.018	2.148
1.0	.987	1.080	1.176	1.277	1.382	1.490	1.602	1.718	1.839	1.963	2.091
1.1	.950	1.041	1.136	1.234	1.337	1.443	1.553	1.666	1.786	1.908	2.034
1.2	.914	1.002	1.095	1.191	1.292	1.396	1.504	1.615	1.732	1.852	1.976
1.3	.877	.964	1.054	1.148	1.247	1.349	1.455	1.564	1.679	1.797	1.919
1.4	.841	.925	1.014	1.106	1.202	1.302	1.406	1.513	1.626	1.742	1.862
1.5	.805	.887	.973	1.063	1.157	1.255	1.357	1.462	1.572	1.686	1.804
1.6	.768	.848	.932	1.020	1.112	1.208	1.308	1.410	1.519	1.631	1.747
1.7	.732	.810	.891	.977	1.067	1.161	1.258	1.359	1.466	1.576	1.689
1.8	.695	.771	.851	.934	1.022	1.114	1.209	1.308	1.412	1.520	1.632
1.9	.659	.732	.810	.892	.977	1.067	1.160	1.257	1.359	1.465	1.575
2.0	.622	.694	.769	.849	.932	1.020	1.111	1.206	1.306	1.410	1.517
2.1	.586	.655	.728	.806	.887	.973	1.062	1.155	1.253	1.354	1.460
2.2	.550	.617	.688	.763	.842	.926	1.013	1.103	1.199	1.299	1.402
2.3	.513	.578	.647	.720	.797	.878	.964	1.052	1.146	1.244	1.345
2.4	.477	.539	.606	.677	.752	.832	.915	1.001	1.093	1.188	1.288
2.5	.440	.501	.566	.634	.708	.784	.866	.950	1.040	1.133	1.230
2.6	.404	.462	.525	.592	.663	.737	.816	.899	.986	1.078	1.173
2.7	.367	.424	.484	.549	.618	.690	.767	.848	.933	1.022	1.116
2.8	.331	.385	.444	.506	.573	.643	.718	.796	.880	.967	1.058
2.9	.294	.346	.403	.463	.528	.596	.669	.745	.826	.912	1.001
3.0	.258	.308	.362	.420	.483	.549	.620	.694	.773	.856	.944
3.1	.222	.269	.321	.377	.438	.502	.571	.643	.720	.801	.886
3.2	.185	.231	.281	.335	.393	.455	.522	.592	.666	.746	.829
3.3	.149	.192	.240	.292	.348	.408	.472	.540	.613	.690	.771
3.4	.112	.154	.199	.249	.303	.361	.423	.489	.560	.635	.714
3.5	.076	.115	.159	.206	.258	.314	.374	.438	.507	.580	.657
3.6	.039	.076	.118	.163	.213	.267	.325	.387	.453	.524	.599
3.7	.003	.038	.077	.120	.168	.220	.276	.336	.400	.469	.542
3.8		.001	.036	.078	.123	.173	.227	.284	.347	.414	.484
3.9				.035	.078	.126	.178	.233	.293	.358	.427
4.0					.034	.079	.129	.182	.240	.303	.370

TABLE VII.- Continued

(c) 87 to 97 dB(A)

Vibration discomfort, DISC	Incremental discomfort for noise level, dB(A), of -										
	87	88	89	90	91	92	93	94	95	96	97
0.5	2.520	2.666	2.816	2.969	3.127	3.288	3.453	3.622	3.795	3.971	4.152
.6	2.461	2.604	2.752	2.904	3.059	3.219	3.382	3.549	3.720	3.894	4.073
.7	2.401	2.543	2.689	2.838	2.992	3.149	3.310	3.476	3.645	3.817	3.994
.8	2.342	2.482	2.625	2.773	2.924	3.080	3.293	3.402	3.569	3.739	3.915
.9	2.282	2.420	2.562	2.708	2.857	3.010	3.168	3.329	3.494	3.662	3.836
1.0	2.223	2.359	2.498	2.642	2.790	2.941	3.096	3.256	3.419	3.585	3.756
1.1	2.164	2.297	2.435	2.577	2.722	2.872	3.025	3.182	3.343	3.508	3.677
1.2	2.104	2.236	2.371	2.511	2.655	2.802	2.953	3.109	3.268	3.430	3.598
1.3	2.045	2.174	2.308	2.446	2.587	2.733	2.882	3.035	3.193	3.353	3.519
1.4	1.985	2.113	2.244	2.380	2.520	2.663	2.810	2.962	3.117	3.276	3.440
1.5	1.926	2.051	2.181	2.315	2.452	2.594	2.739	2.889	3.042	3.199	3.360
1.6	1.866	1.990	2.118	2.249	2.385	2.524	2.668	2.815	2.967	3.122	3.281
1.7	1.807	1.928	2.054	2.184	2.317	2.455	2.596	2.742	2.891	3.044	3.202
1.8	1.748	1.867	1.991	2.118	2.250	2.385	2.525	2.668	2.816	2.967	3.123
1.9	1.688	1.806	1.927	2.053	2.182	2.316	2.453	2.595	2.741	2.890	3.044
2.0	1.629	1.744	1.864	1.987	2.115	2.247	2.382	2.522	2.665	2.813	2.964
2.1	1.569	1.683	1.800	1.922	2.048	2.177	2.310	2.448	2.590	2.735	2.885
2.2	1.510	1.621	1.737	1.856	1.980	2.108	2.239	2.375	2.515	2.658	2.806
2.3	1.450	1.560	1.673	1.791	1.913	2.038	2.168	2.302	2.439	2.581	2.727
2.4	1.391	1.498	1.610	1.726	1.845	1.969	2.096	2.228	2.364	2.504	2.648
2.5	1.332	1.437	1.546	1.660	1.778	1.899	2.025	2.155	2.289	2.426	2.568
2.6	1.272	1.376	1.483	1.594	1.710	1.830	1.953	2.081	2.213	2.349	2.489
2.7	1.213	1.314	1.420	1.529	1.643	1.760	1.882	2.008	2.138	2.272	2.410
2.8	1.153	1.253	1.356	1.464	1.575	1.691	1.811	1.935	2.063	2.195	2.331
2.9	1.094	1.191	1.293	1.398	1.508	1.622	1.739	1.861	1.987	2.117	2.252
3.0	1.035	1.130	1.229	1.333	1.440	1.552	1.668	1.788	1.912	2.040	2.172
3.1	.975	1.068	1.166	1.267	1.373	1.483	1.596	1.714	1.837	1.963	2.093
3.2	.916	1.007	1.102	1.202	1.305	1.413	1.525	1.641	1.761	1.886	2.014
3.3	.856	.945	1.039	1.136	1.238	1.344	1.453	1.568	1.686	1.808	1.935
3.4	.797	.884	.975	1.071	1.170	1.274	1.382	1.494	1.611	1.731	1.855
3.5	.738	.822	.912	1.005	1.103	1.205	1.311	1.421	1.535	1.654	1.776
3.6	.678	.761	.848	.940	1.036	1.136	1.239	1.348	1.460	1.577	1.697
3.7	.619	.700	.785	.874	.968	1.066	1.168	1.274	1.385	1.500	1.617
3.8	.559	.638	.722	.809	.901	.997	1.096	1.201	1.309	1.422	1.539
3.9	.500	.577	.658	.743	.833	.927	1.025	1.127	1.234	1.345	1.459
4.0	.440	.515	.595	.678	.766	.858	.954	1.054	1.159	1.268	1.380

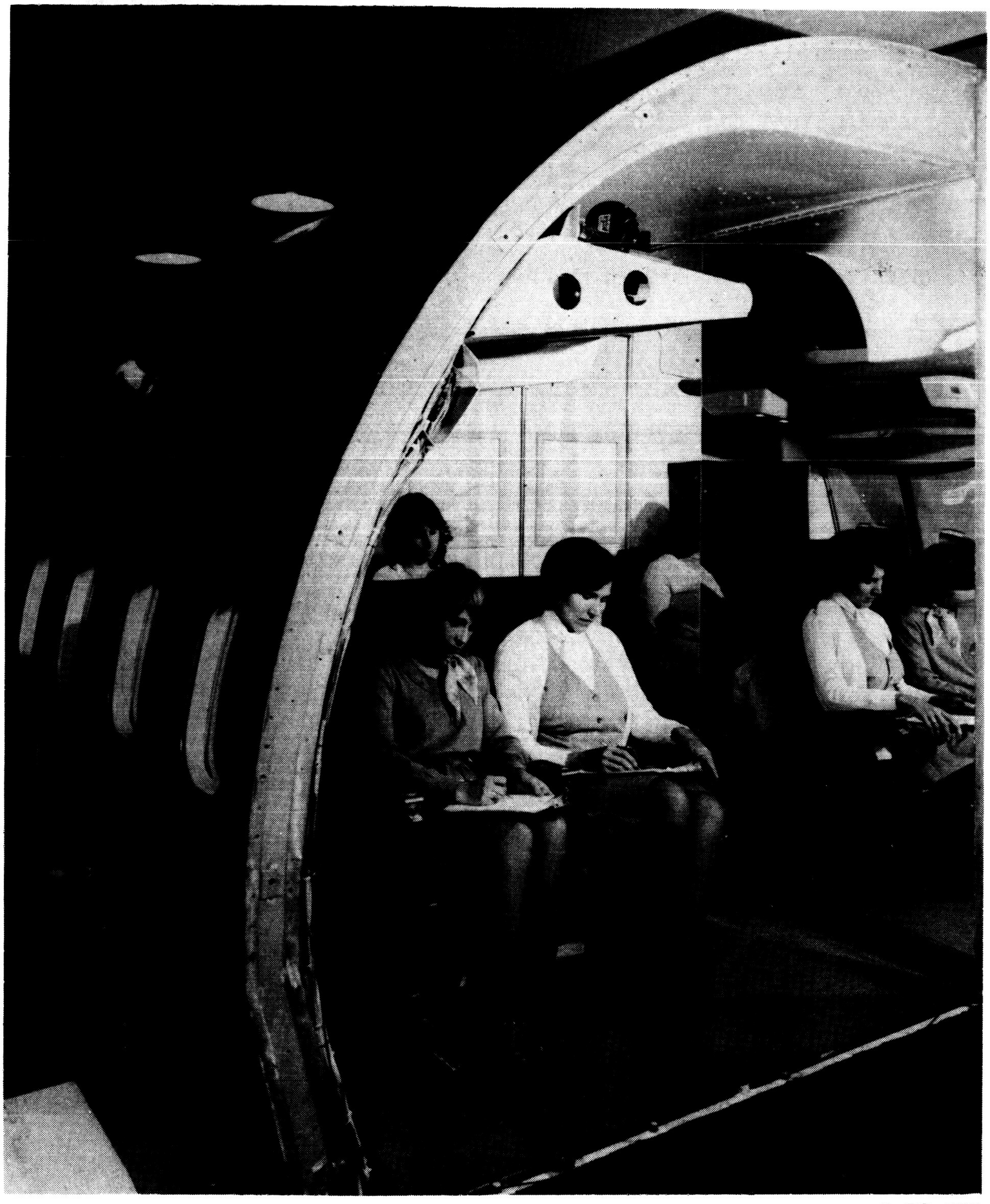
TABLE VII.- Concluded

(d) 98 to 100 dB(A)

Vibration discomfort, DISC	Incremental discomfort for noise level, dB(A), of -										
	98	99	100								
0.5	4.337	4.525	4.717								
.6	4.256	4.442	4.632								
.7	4.175	4.359	4.548								
.8	4.094	4.276	4.462								
.9	4.012	4.193	4.378								
1.0	3.931	4.110	4.293								
1.1	3.850	4.027	4.208								
1.2	3.769	3.944	4.123								
1.3	3.688	3.861	4.038								
1.4	3.607	3.778	3.953								
1.5	3.526	3.695	3.868								
1.6	3.444	3.612	3.783								
1.7	3.363	3.529	3.698								
1.8	3.282	3.446	3.613								
1.9	3.201	3.363	3.528								
2.0	3.120	3.280	3.443								
2.1	3.039	3.196	3.358								
2.2	2.958	3.113	3.273								
2.3	2.877	3.030	3.188								
2.4	2.795	2.947	3.103								
2.5	2.714	2.864	3.019								
2.6	2.633	2.781	2.934								
2.7	2.552	2.698	2.849								
2.8	2.471	2.615	2.764								
2.9	2.390	2.532	2.679								
3.0	2.309	2.449	2.594								
3.1	2.228	2.366	2.509								
3.2	2.146	2.283	2.424								
3.3	2.065	2.200	2.339								
3.4	1.984	2.117	2.254								
3.5	1.903	2.034	2.169								
3.6	1.822	1.951	2.084								
3.7	1.741	1.868	1.999								
3.8	1.660	1.785	1.914								
3.9	1.578	1.702	1.829								
4.0	1.497	1.619	1.744								

TABLE VIII.- SUMMARY OF INTERCEPTS AND SLOPES OF LEAST-SQUARE FUNCTIONS RELATING DISCOMFORT RESPONSES TO ACCELERATION LEVEL FOR SINUSOIDAL VIBRATIONS AT FREQUENCIES OF 1 TO 30 Hz

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



L-78-600

Figure 1.- View of passenger ride quality apparatus with front bulkhead removed.

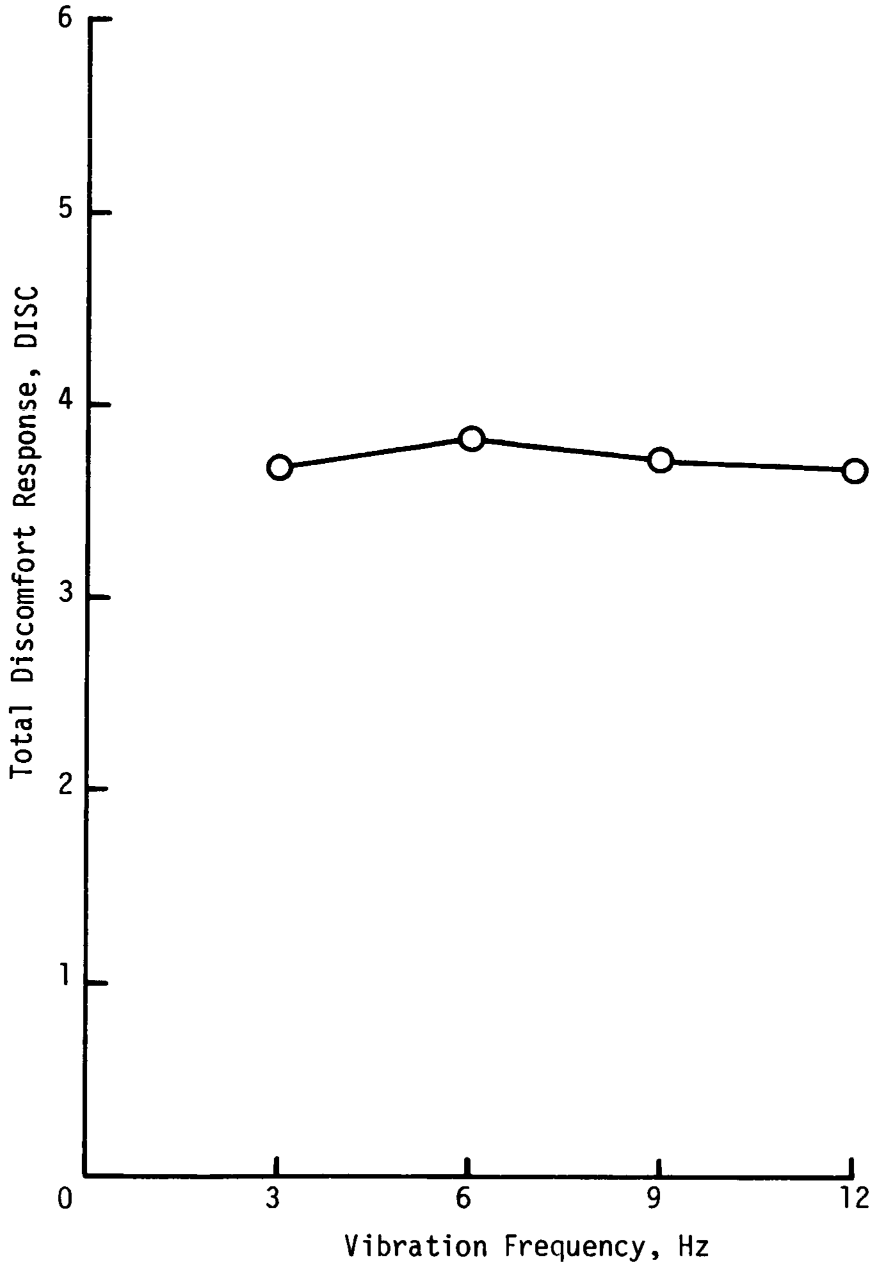


Figure 2.- Total discomfort response as function of vibration frequency.

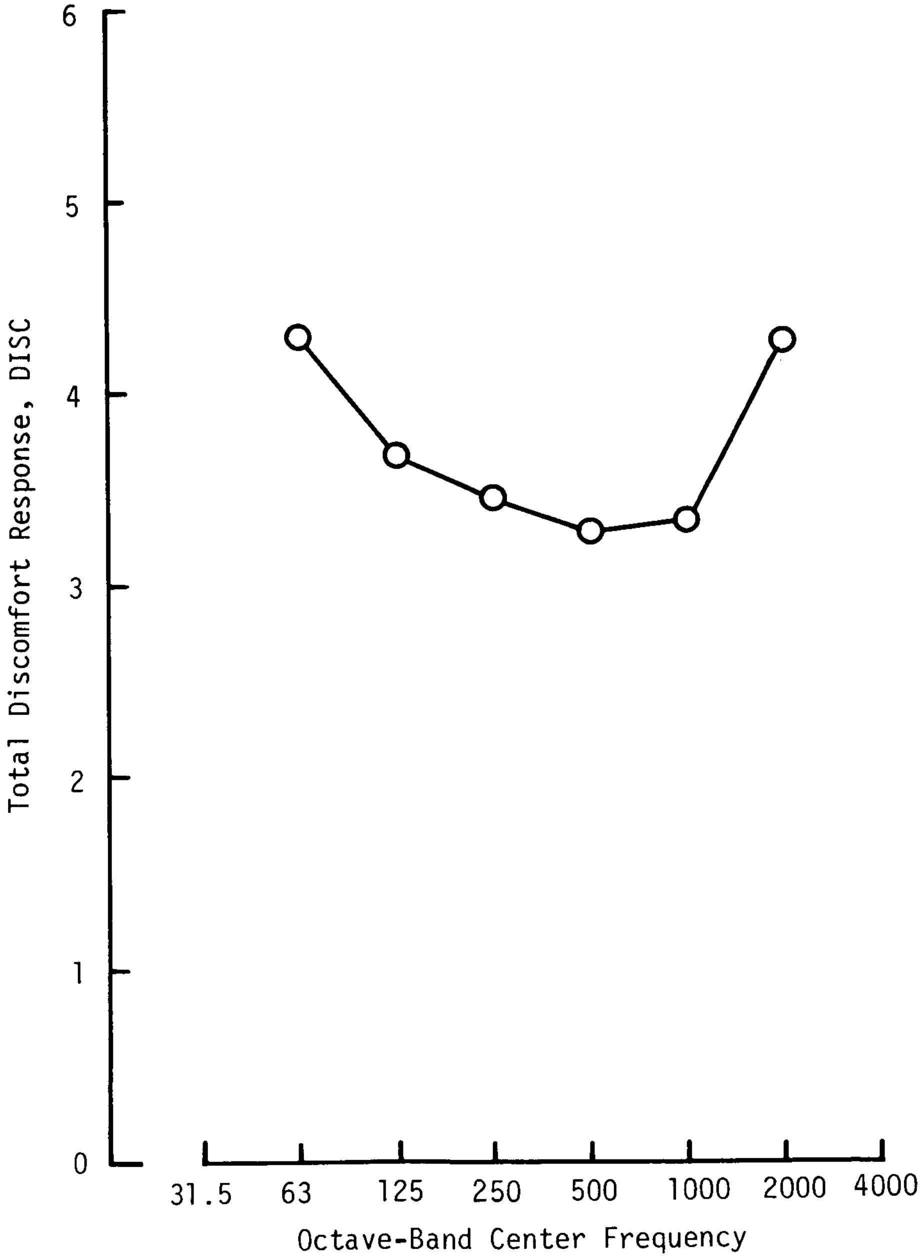


Figure 3.- Total discomfort response as function of octave-band center frequency.

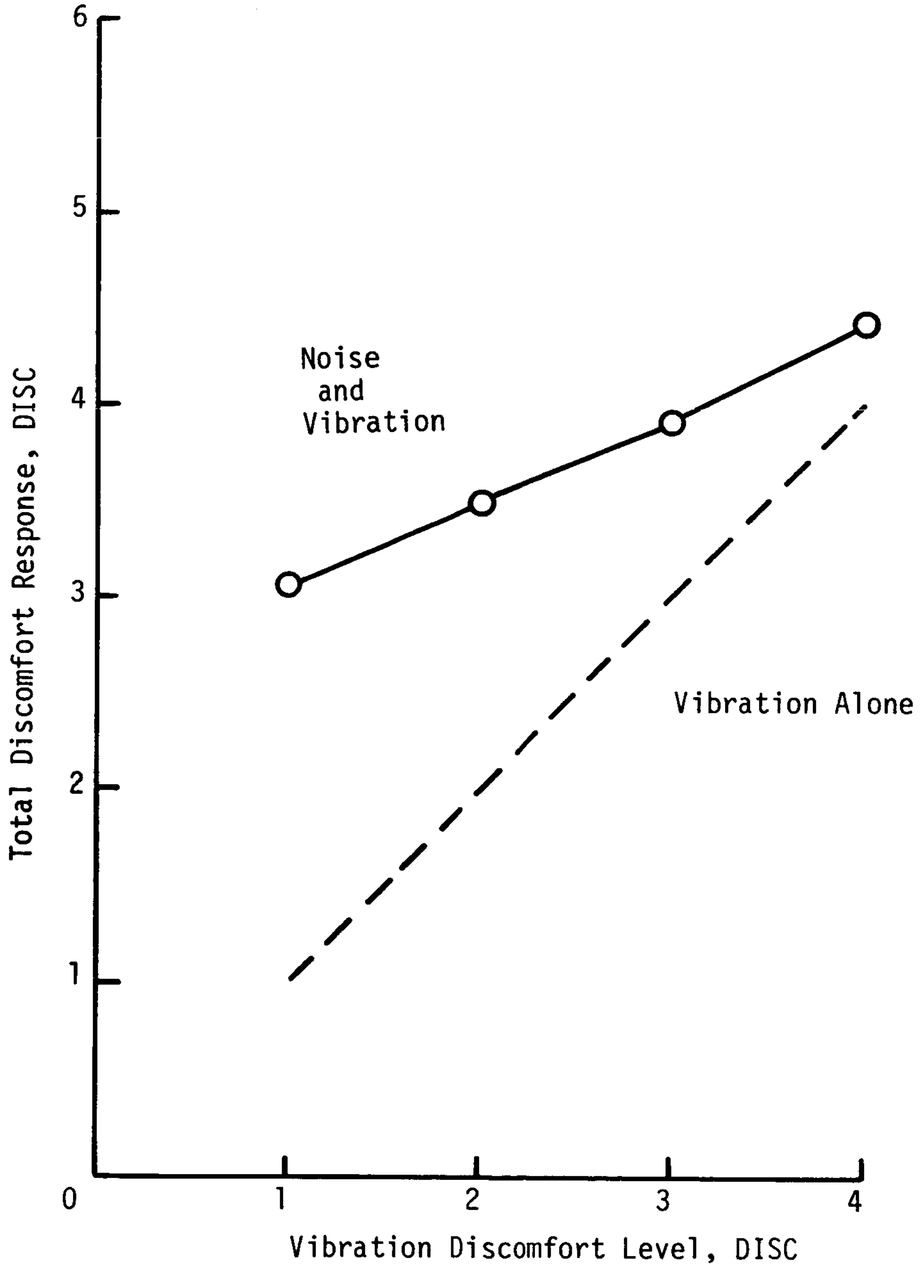


Figure 4.- Total discomfort response for combined noise and vibration condition compared to vibration only condition.

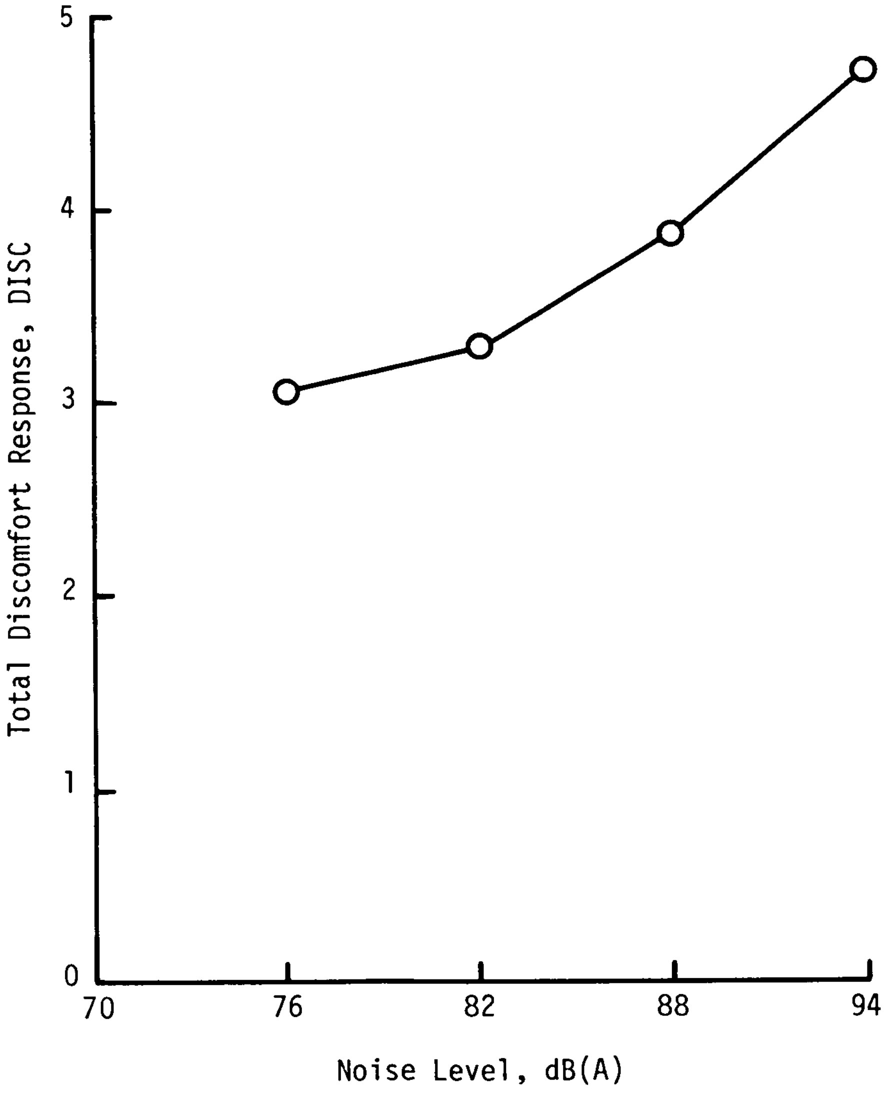


Figure 5.- Total discomfort response as function of noise level.

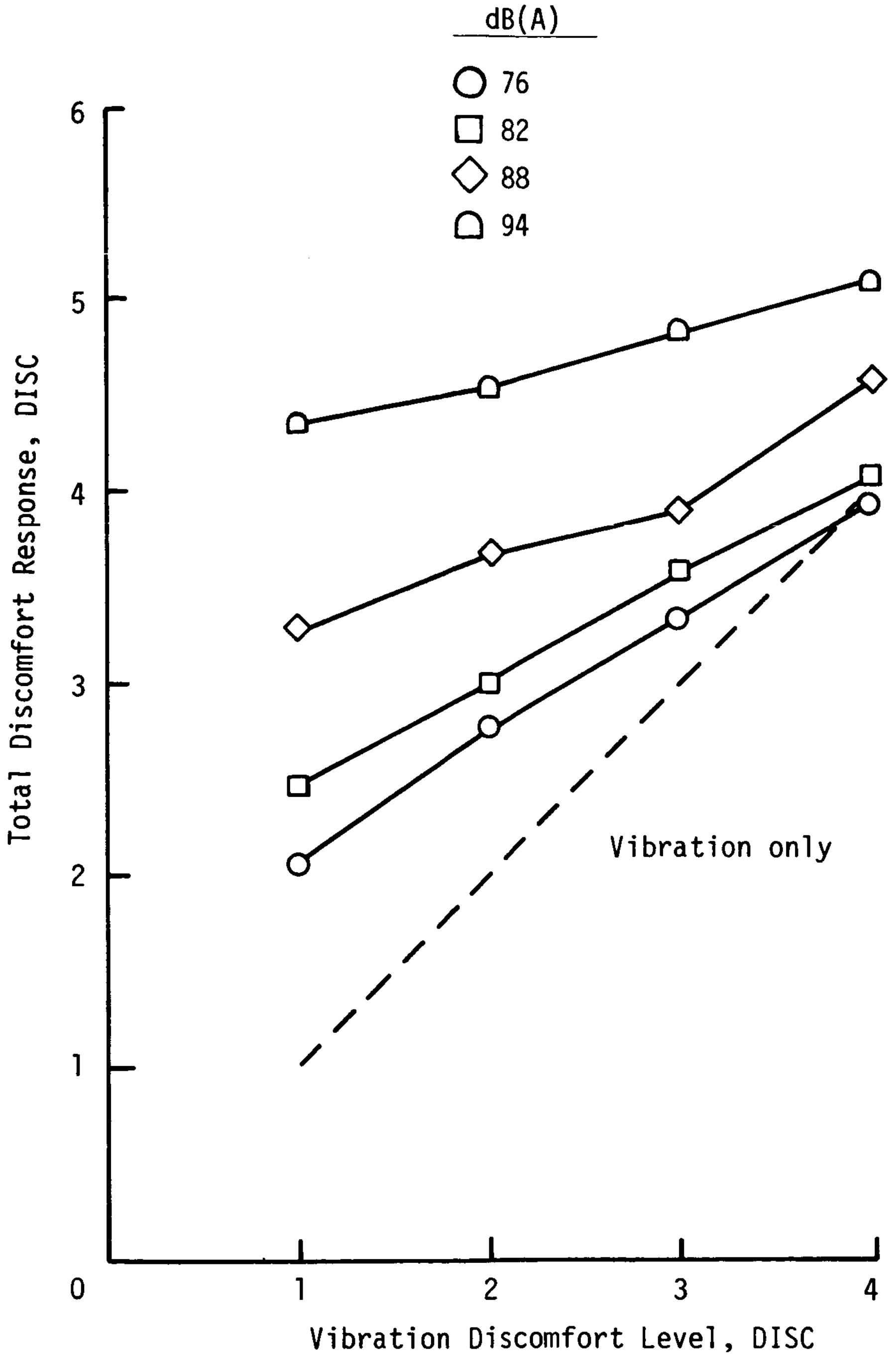


Figure 6.- Interaction of noise level and vibration discomfort level.

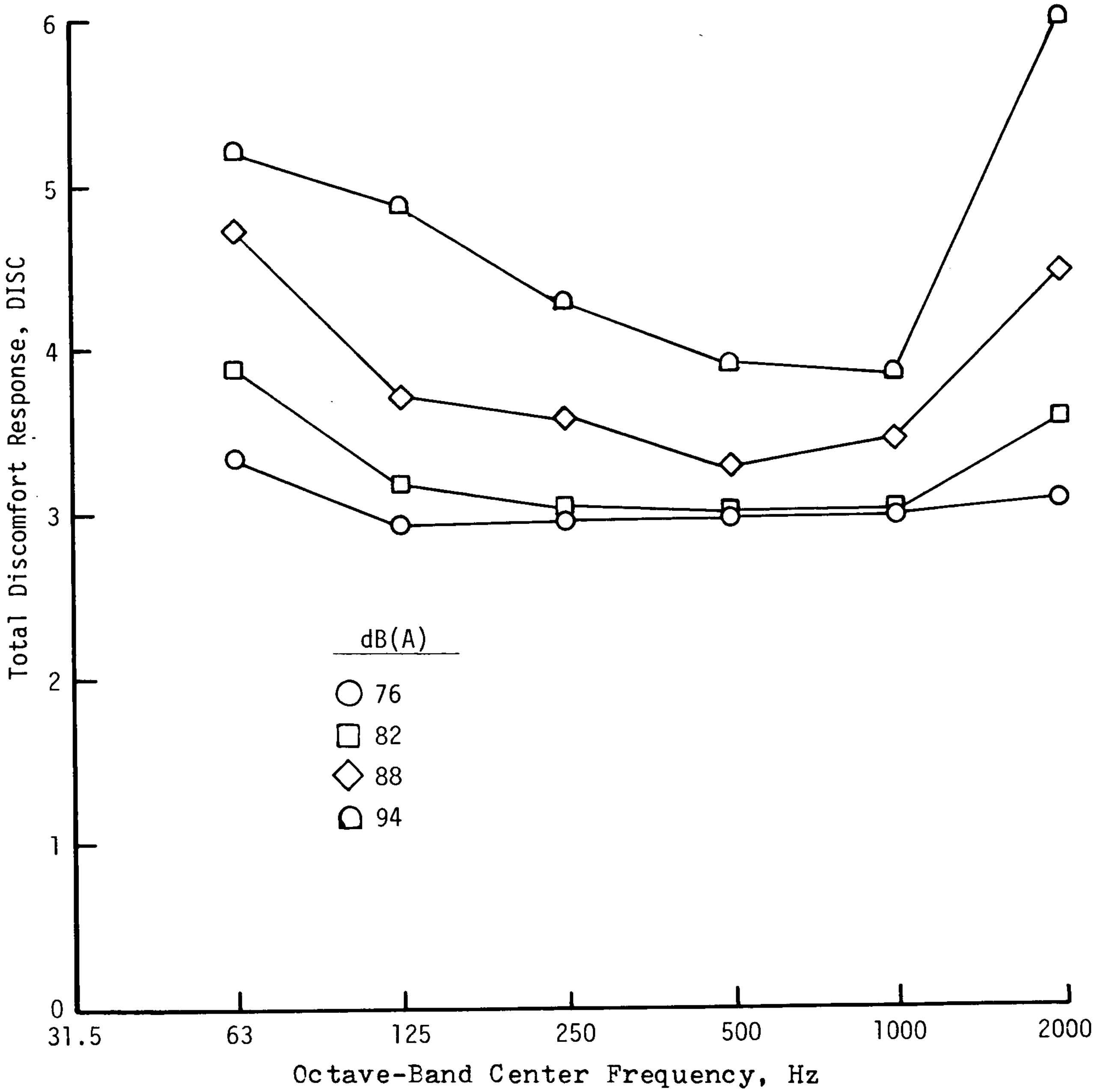


Figure 7.- Interaction of noise level and octave-band center frequency.

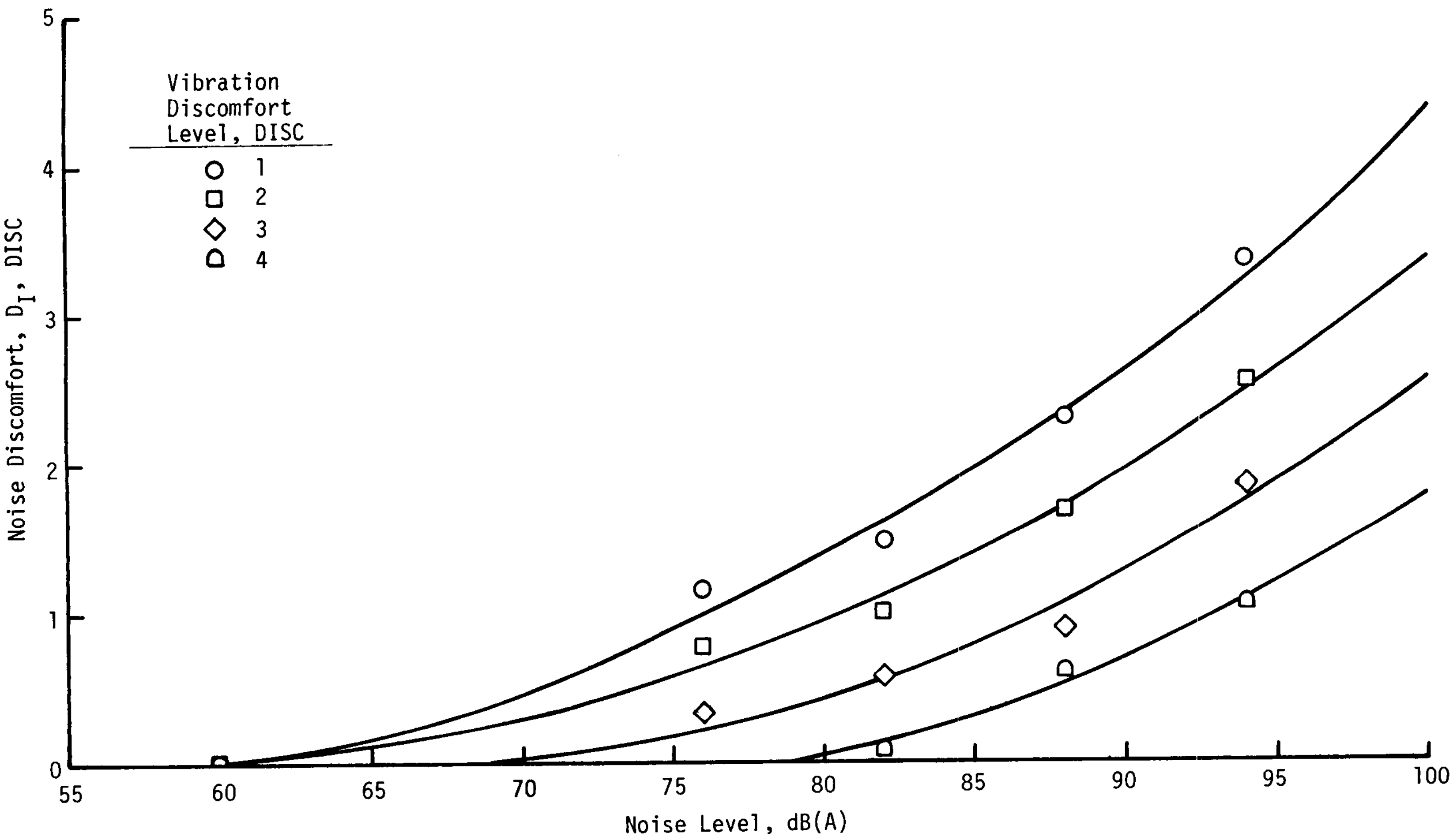


Figure 8.- Incremental discomfort due to presence of noise as function of noise level and vibration discomfort level (data fitted by least-square parabolic regression curves).

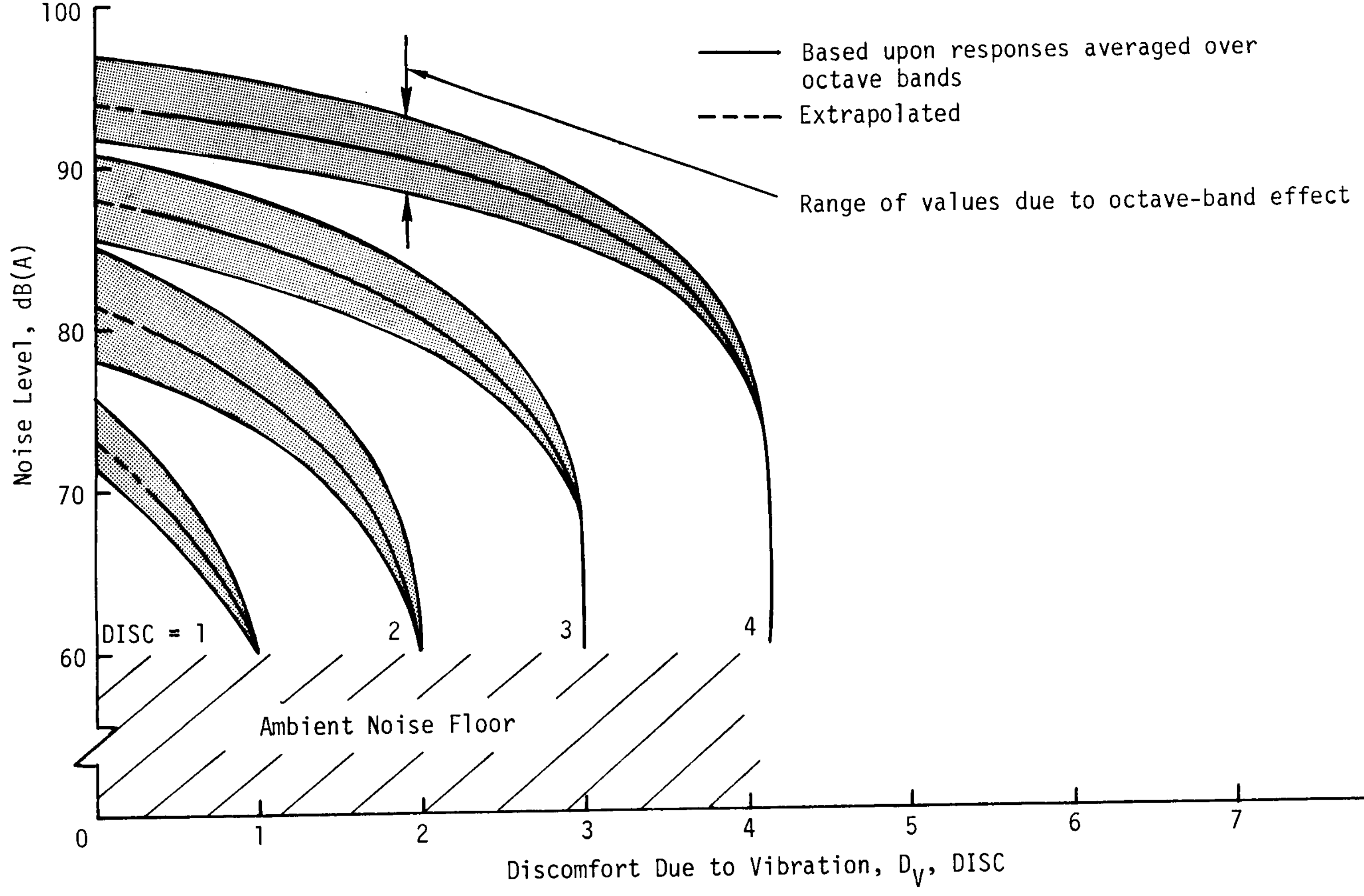


Figure 9.- Noise-vibration criteria boundaries (values of noise level and vibration discomfort level required to produce constant total discomfort (DISC = 1, 2, 3, and 4) for single octave bands).

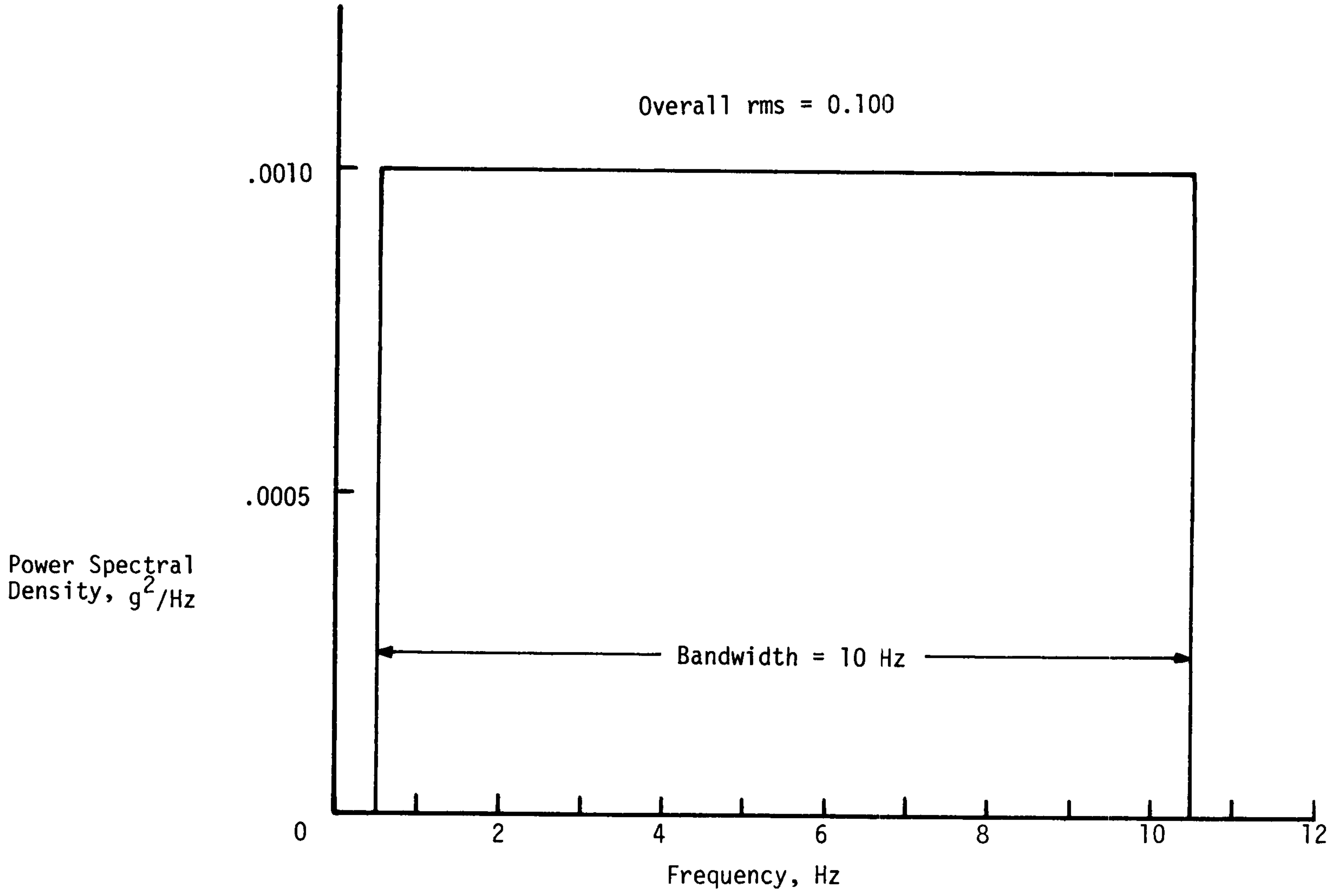
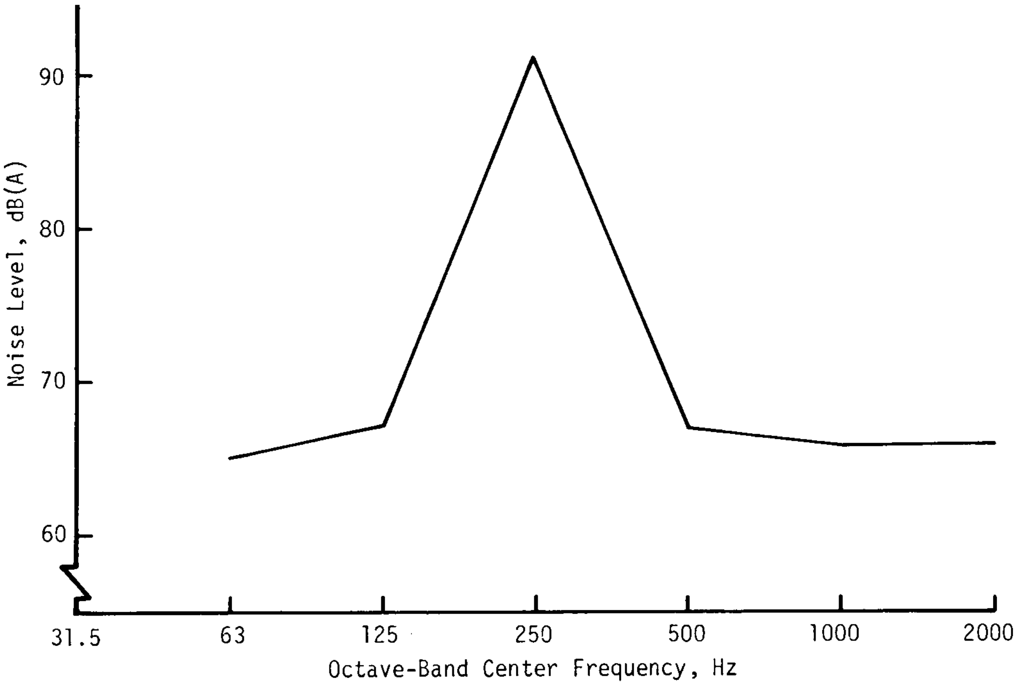
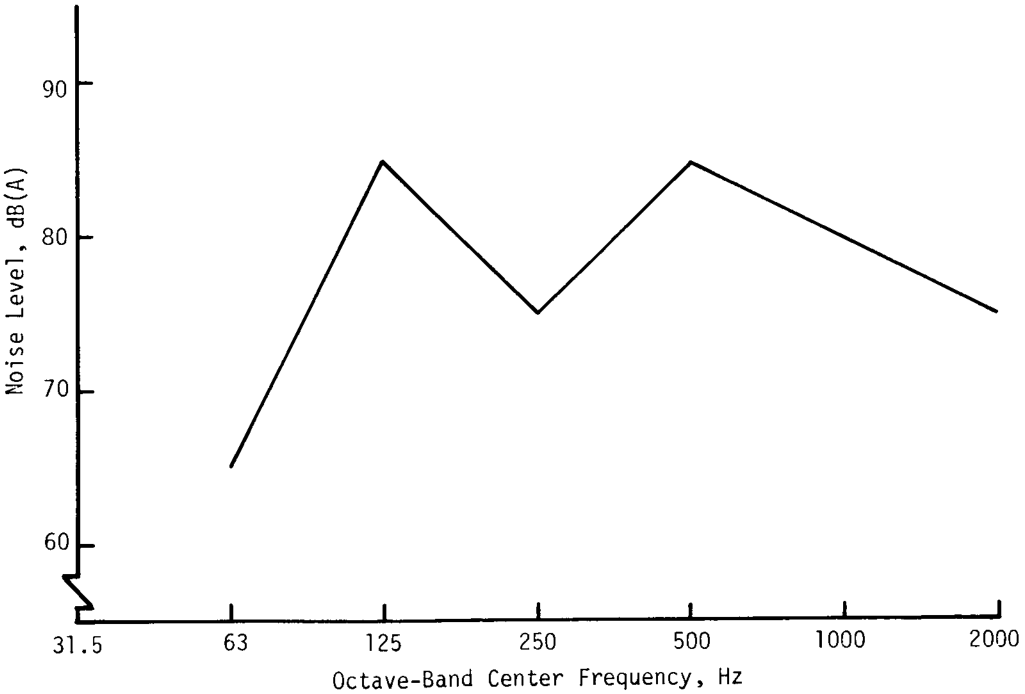


Figure 10.- Hypothetical vibration spectrum used to illustrate computational procedure.



(a) Case 1.



(b) Case 2.

Figure 11.- Hypothetical noise spectrum used to illustrate computational procedure.

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15. Supplementary Notes

16. Abstract

An experimental investigation was conducted (1) to determine the effects of combined environmental noise and vertical vibration upon human subjective discomfort response, (2) to develop a model for the prediction of passenger discomfort response to the combined environment, and (3) to develop a set of noise-vibration curves for use as criteria in ride quality design. Judgments of subjective discomfort were obtained from a total of 60 subjects who were exposed to parametric combinations of noise and vibrations through the use of a realistic laboratory simulator. Results of this investigation indicated that accurate prediction of passenger ride comfort requires knowledge of both the level and frequency content of the noise and vibration components of a ride environment as well as knowledge of the interactive effects of combined noise and vibration. A design tool in the form of an empirical model of passenger discomfort response to combined noise and vertical vibration was developed and illustrated by several computational examples. Finally, a set of noise-vibration criteria (constant discomfort) curves were generated to illustrate the fundamental design trade-off possible between passenger discomfort and the noise-vibration levels that produce the discomfort.

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