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A User-Oriented and Computerized Model for Estimating Vehicle Ride Quality

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INTRODUCTION

The ride development engineer has long needed a reliable method for objectively predicting and assessing vehicle ride quality. Such a method is particularly important in order to avoid the necessity of implementing costly and time-consuming ad hoc fixes to achieve acceptable vehicle ride comfort. This problem may be further complicated by the fact that passenger ride discomfort results from a complex interaction of vibration in several axes combined with vehicle interior noise. Ride-quality estimators that do not account for the multi-dimensional nature of a vehicle ride environment may be prone to serious errors when applied to combined environments. A recent study (ref. 1) of helicopter ride quality showed that simple physical noise and vibration metrics inadequately predicted crew comfort. The ride quality design community specifically needs methods (1) for estimating total ride comfort in combined noise and vibration ride environments, particularly at early stages of the design process; (2) for determining trade-offs between total ride comfort and the individual noise and vibration components of a ride environment; (3) for accurately evaluating comparative ride comfort; and (4) for developing accurate and verifiable criteria of passenger acceptance.

In response to the above needs, NASA Langley Research Center conducted an extensive research program to develop a general and comprehensive empirical model for estimating passenger ride comfort as a function of vehicle vibration and interior noise. The NASA ride comfort model was developed in the research program, which obtained subjective comfort ratings from more than 3000 persons who were exposed to controlled combinations of noise and vibration in the passenger ride-quality apparatus at NASA Langley Research Center. The resultant model has the unique capability of transforming individual components of the noise and vibration environment into subjective discomfort units and then combining the subjective units to produce a single discomfort index typifying passenger acceptance of the environment. This capability is one of the major advantages of the NASA model approach. Results of individual studies in the NASA research program have been reported in references 2 through 11, and the resultant model is presented in reference 12. The reader is referred to these references for detailed information on the model studies, for definition of the discomfort index, and for discussion of the ride-quality literature.

To apply the model presented in reference 12 to assess or predict vehicle ride comfort requires specific knowledge of the spectral characteristics of the interior noise and vibration. For example, in several of the vibration axes, the level, center frequency, and bandwidths of dominant spectral peaks must be identified. This is not always straightforward. Experience in applying the model to actual vehicle ride spectra has indicated that model comfort estimates can be sensitive to variations in spectrum identification judgments by different observers. Certainly, it would be desirable to eliminate such judgments from the model application process and thus remove a major source of human error. Then model predictions obtained by various users could be directly compared.

This paper presents and describes a simplified version of the NASA ride comfort model that removes the necessity that the user identify vibration spectral peaks as a part of model input. The computational procedures required to obtain discomfort estimates are discussed, and a user-oriented ride comfort computer program is described. The simplified model is applied to sample helicopter and automobile ride environments.

DESCRIPTION OF SIMPLIFIED NASA RIDE COMFORT MODEL

Development of Simplified Model

Because of the complexity and judgment required in identifying spectral details for input to the original NASA ride comfort model, an alternative method was considered. This method involved the concept of applying frequency weightings to the vibration acceleration spectra within each axis of vibration. The frequency weighting for each axis reflected human comfort sensitivity to vibration frequency for that particular axis. The root-mean-square (rms) acceleration level of each weighted spectrum was then determined and input to the comfort model.

The frequency weighting factors for vertical and lateral vibration were based on human comfort sensitivity to narrow-band vibration (bandwidth of 2 Hz). The weighting factors for roll vibration were based on human comfort sensitivity to sinusoidal vibration. Longitudinal and pitch vibrations were weighted uniformly over the frequency range from approximately 1 to 5 Hz because human comfort sensitivity to vibration in these axes had been obtained only for random vibration centered at 3 Hz with a bandwidth of 5 Hz. The weighting factors for the five vibration axes are listed in table I. When applying these weightings to actual vibration acceleration spectra, interpolation may be necessary between frequency values. The weighting factors for each axis are plotted in figure 1.

The above frequency weighting of vibration can be justified by considering the vertical and lateral vibration conditions. The procedure involved computation of the discomfort produced by a wide range of random vertical and lateral vibrations having different center frequencies and bandwidths. These computations were performed using the single-axis discomfort equations for vertical and lateral random vibration given in reference 12. For ease of computation, the vibrations were assumed to have the spectral characteristics given in figure 2. For each center-frequency and bandwidth combination given in reference 12 the discomfort was computed for root-mean-square (rms) acceleration levels of 0.02g and 0.10g. (The acceleration due to gravity, g, is 32.2 ft/sec^2.) Next the square of the vertical or the lateral weighting function (figs. 1(a) and 1(b)) was applied to each spectrum (i.e., center-frequency and bandwidth combination), and the weighted rms acceleration level was computed for each axis. The resultant weighted rms vertical and lateral acceleration levels were plotted against the corresponding discomfort predictions, as shown in figures 3 and 4. The correlation coefficient between computed discomfort and the weighted vertical rms acceleration levels was 0.970 with a standard error of estimate of 0.28. For lateral vibration the correlation coefficient was 0.948 with a standard error of estimate of 0.19. These high correlations indicated that in the range of random vibration characteristics for which the model is valid, weighted rms acceleration is a good discomfort estimator. The final step was to relate the weighted rms acceleration to subjective discomfort units by computing the least squares linear regression fit to the data in figures 3 and 4. The resulting equations could then be used to compute subjective discomfort when weighted rms vertical and lateral accelerations were known.

A similar approach could not be applied to verify use of frequency weighting for roll vibrations. However, based on the results obtained for vertical and lateral vibrations, we assumed that the weighting function derived from the sinusoidal roll discomfort equations of reference 12 would produce similar results.

Model Inputs

Vibration.- The basic inputs to the model are the weighted rms vibration levels in one or more of the five axes of vibration. The user must apply the frequency weighting (table I) to determine the weighted rms acceleration levels of each contributing axis. For purposes of this model, the vibration can be measured at any floor location of the user's choice.

Noise.- The noise inputs required by the ride comfort model are the A-weighted noise levels measured at approximate head level above the point at which vibration measurements are made (or at a location that the user considers representative of the vehicle interior noise environment). The A-weighted levels used are those within each of six octave bands having center frequencies of 63, 125, 250, 500, 1000, and 2000 Hz.

Trip duration.- An optional model input is trip duration (in minutes) defined as the elapsed time from the start of a vehicle ride. Duration is included if the user wishes to correct discomfort estimates for adaptation effects.

DISCOMFORT COMPUTATION

Procedure

The procedure required to compute estimates of passenger discomfort in a given ride environment is as follows: (1) compute discomfort due to vibration in each applicable axis; (2) compute combined-axes discomfort; (3) correct for trip duration effect, if desired; (4) compute discomfort due to interior noise in each octave band; (5) compute total noise discomfort; and (6) compute total estimated discomfort. The step-by-step computation procedure is described below.

Step 1. Compute discomfort due to vibration in each applicable axis.- The equations relating discomfort to weighted rms acceleration for random vibration in each axis are

$$D_{vert} = \begin{cases} 0.241 + 44.672\ (g_w)_{vert} & \text{For } (g_w)_{vert} > 0.01g \\ 68.772\ (g_w)_{vert} & \text{For } (g_w)_{vert} < 0.01g \end{cases} \qquad (1)$$

$$D_{lat} = \begin{cases} 0.393 + 47.494\ (g_w)_{lat} & \text{For } (g_w)_{lat} > 0.01g \\ 86.794\ (g_w)_{lat} & \text{For } (g_w)_{lat} < 0.01g \end{cases} \qquad (2)$$

$$D_{long} = -0.02 + 42.24\ (g_w)_{long} \qquad (3)$$

$$D_{roll} = \begin{cases} -0.21 + 4.506\ \ddot{\theta}_w & \text{For } \ddot{\theta}_w > 0.10 \text{ rad/sec}^2 \\ 2.406\ \ddot{\theta}_w & \text{For } \ddot{\theta}_w < 0.10 \text{ rad/sec}^2 \end{cases} \tag{4}$$

$$D_{pitch} = \begin{cases} 0.41 + 5.07\ \ddot{\phi}_w & \text{For } \ddot{\phi}_w > 0.116 \text{ rad/sec}^2 \\ 8.62\ \ddot{\phi}_w & \text{For } \ddot{\phi}_w < 0.116 \text{ rad/sec}^2 \end{cases} \tag{5}$$

where D_{vert}, D_{lat}, D_{long}, D_{roll}, and D_{pitch} are estimated discomfort values in DISC[1] units for vertical, lateral, longitudinal, roll, and pitch axes, respectively; and $(g_w)_{vert}$, $(g_w)_{lat}$, $(g_w)_{long}$, $\ddot{\theta}_w$, and $\ddot{\phi}_w$ are the weighted rms acceleration levels in the vertical, lateral, longitudinal, roll, and pitch axes, respectively, in g units for linear accelerations and in rad/sec^2 for angular accelerations.

When the vibration is known to be sinusoidal in the vertical, lateral, and roll axes, then the estimated discomfort is predicted from

$$(D_{vert})_{sine} = \begin{cases} K_0 + K_1\ (g_s)_{vert} & \text{For } (g_s)_{vert} > 0.06g \\ K_2\ (g_s)_{vert} & \text{For } (g_s)_{vert} < 0.06g \end{cases} \tag{6}$$

$$(D_{lat})_{sine} = \begin{cases} K_3 + K_4\ (g_s)_{lat} & \text{For } (g_s)_{lat} > 0.06g \\ K_5\ (g_s)_{lat} & \text{For } (g_s)_{lat} < 0.06g \end{cases} \tag{7}$$

$$(D_{roll})_{sine} = \begin{cases} K_6 + K_7\ \ddot{\theta}_s & \text{For } \ddot{\theta}_s > K_9 \\ K_8\ \ddot{\theta}_s & \text{For } \ddot{\theta}_s < K_9 \end{cases} \tag{8}$$

where the subscript sine indicates that the estimated values of discomfort are due to sinusoidal vibrations; $(g_s)_{vert}$, $(g_s)_{lat}$, and $\ddot{\theta}_s$ are the peak (not rms) acceleration levels due to sinusoidal vibrations in the vertical, lateral, and roll axes, respectively, in g units for linear accelerations and rad/sec^2 for angular accelerations; and K_0, K_1, ..., K_9 are empirical constants given in table II for sinusoidal vertical vibrations, in table III for sinusoidal lateral vibrations, and in table IV for sinusoidal roll vibrations. Longitudinal and pitch vibrations are assumed to be random in nature and are always computed using equations (3) and (5).

Step 2. Compute combined-axes discomfort.- To compute combined-axes discomfort, the user must first compute the discomfort produced by combined vertical, lateral,

[1]The discomfort values are in subjective discomfort units called DISC. These units are measured along a ratio scale so that all estimated values bear a direct ratio relationship to one another. For example, if $D_{vert} = 2$ and $D_{lat} = 1$, then discomfort due to vertical vibration is twice the discomfort due to lateral vibration.

and roll vibrations and then the additional discomfort due to combined longitudinal and pitch vibrations. These computations are performed as follows:

1. Rank the discomfort values for vertical, lateral, and roll vibrations that were computed in step 1. Let D_1, D_2, and D_3 represent the highest, middle, and lowest discomfort values, respectively.

2. Compute

$$R_1 = D_1/D_2 \tag{9}$$

$$D_4 = \sqrt{D_2^2 + D_3^2} \tag{10}$$

$$D_{c1} = \sqrt{D_1^2 + D_2^2 + D_3^2} \tag{11}$$

$$D_{comb1} = \begin{cases} -0.44 + 1.65\, D_{c1} & \text{For } D_{c1} > 0.88 \\ 1.14\, D_{c1} & \text{For } D_{c1} < 0.88 \end{cases} \tag{12}$$

3. The discomfort, in DISC units, due to vibration in the vertical, lateral, and roll axes is

$$D_{VLR} = \begin{cases} D_1 + D_4(D_{comb1} - D_1)/0.40 & \text{For } D_4 < 0.40 \text{ and } R_1 > 3.0 \\ D_{comb1} & \text{Otherwise} \end{cases} \tag{13}$$

The value of D_{VLR} obtained from equation (13) should be retained for subsequent use.

4. Set D_5 equal to the larger and D_6 equal to the smaller of the discomfort values calculated from equations (3) and (5) for longitudinal and pitch vibrations.

5. Compute

$$R_2 = D_5/D_6 \tag{14}$$

$$D_{c2} = \sqrt{D_5^2 + D_6^2} \tag{15}$$

$$D_{comb2} = \begin{cases} -1.07 + 1.77\, D_{c2} & \text{For } D_{c2} > 1.0 \\ 0.70\, D_{c2} & \text{For } D_{c2} < 1.0 \end{cases} \tag{16}$$

6. The discomfort in DISC units, due to vibration in the longitudinal and pitch axes is

$$D_{LP} = \begin{cases} D_5 + D_6(D_{comb2} - D_5)/0.40 & \text{For } D_6 < 0.40 \text{ and } R_2 > 3.0 \\ D_{comb2} & \text{Otherwise} \end{cases} \tag{17}$$

The value of D_{LP} from equation (17) must be retained for subsequent use.

7. Compute the combined-axes discomfort in DISC units, from

$$D_{comb} = \sqrt{D_{VLR}^2 + D_{LP}^2} \tag{18}$$

Step 3. Correct for trip duration effect.- The NASA ride comfort studies indicated that passengers tended to adapt to vibration environments presented for durations up to 2 hours. If desired, a duration correction, in DISC units, can be computed as follows:

$$\Delta D_{dur} = \begin{cases} 0.0031 - 0.012\ t & \text{For } 1 \text{ min} \leq t \leq 60 \text{ min} \\ -0.72 & \text{For } 60 \text{ min} < t \leq 120 \text{ min} \\ 0 & \text{For } t < 1 \text{ min} \end{cases} \tag{19}$$

where t is the elapsed trip time in minutes. Duration corrections were not determined for trips longer than 120 minutes. We anticipate that fatigue may become a factor for very long trips and might tend to counteract the adaptation effect described above. No data are currently available, however, to define specific effects of longer durations.

The total duration-corrected vibration discomfort is given by

$$D_{VIB} = D_{comb} + \Delta D_{dur} \tag{20}$$

Step 4. Compute discomfort due to interior noise in each octave band.- Noise discomfort contributions are computed for noises within six octave bands having center frequencies of 63, 125, 250, 500, 1000, and 2000 Hz. The model does not apply to noise contained within octave bands outside this range. The A-weighted sound pressure levels L_A within each of the six octave bands are required. The model is applicable for L_A = 65 to 100 dB. If the noise level within an individual octave band is less than 65 dB(A), then that octave band is assumed to contribute zero discomfort. The actual level of discomfort produced by any of the octave bands depends on the level of vibration simultaneously present in the environment. The equation used to estimate the noise discomfort contributed by an octave band of noise is

$$D_{N(i,j)} = (A_j + B_j D_{VIB}) W_i \tag{21}$$

where $D_{N(i,j)}$ is noise discomfort contribution due to a noise level of j dB(A) within the octave band with center frequency at i Hz, in the presence of vibration that produces a discomfort level of D_{VIB}; A_j and B_j are empirically determined coefficients (see ref. 11) for each noise level in the range from 65 to 100 dB(A) (see table V); and W_i is a weighting factor (see ref. 11) that corrects for the effect of the octave band at i Hz (see table VI). Equation (21) is applied for each applicable octave band.

Step 5. Compute total noise discomfort.- If noise is present at a sufficient level in more than one octave band, then the total noise discomfort is computed from the following equation:

$$D_{Noise} = D_{N(i,j)max} + 0.3 \left[\sum_i D_{N(i,j)} - D_{N(i,j)max} \right] \tag{22}$$

where $D_{N(i,j)max}$ is the discomfort associated with the octave band that produces maximum discomfort and Σ_i implies summation over octave bands.

Step 6. Compute total estimated discomfort.- The total discomfort produced by the combined noise and vibration environment is given by

$$D_T = D_{Noise} + D_{VIB} \tag{23}$$

Discussion of Model Outputs

The various discomfort parameters computed in the preceding section provide the ride development specialist with a variety of useful information for use in assessing and diagnosing vehicle ride-quality problems. The total discomfort index, equation (23), corresponds to the overall average discomfort level that a given ride environment would produce. It incorporates the combined effects of the noise and vibration present in the environment and can be used for direct comparison of ride comfort in different ride environments. When used in the design stage, it provides estimates of vehicle ride comfort in the presence of anticipated noise and vibration levels.

One of the more powerful aspects of the NASA ride comfort model is the capability to separate and identify the relative contributions of noise and vibration to total discomfort. For example, equations (20) and (22) would indicate to the ride-quality engineer whether a ride-quality problem derives from noise, from vibration, or from both. Additional information can be obtained from equation (21) to determine the discomfort contributed by individual noise octave bands and from equations (1) through (8) to determine discomfort contributed by individual vibration axes. Ultimately, the engineer could examine individual vibration and noise spectra to identify the particular spectral components that are the source of ride-quality problems and, then, institute remedial measures. The potential of this approach in determining comfort trade-offs due to noise and vibration is apparent. Such a comprehensive ride-quality design and assessment tool has heretofore been unavailable.

DESCRIPTION OF COMPUTER PROGRAM

General Description

The ride comfort model described in the preceding sections has been implemented in a user-oriented computer program, named RIDEQUL, on the NASA Langley Research Center computer system. This program, which is available through COSMIC (ref. 13), can be exercised by either of two basic approaches. One approach requires the user to analyze noise and vibration data to obtain the weighted rms acceleration levels and A-weighted octave-band noise levels required as model input. The resultant data are then input to the model in either a batch processing or an interactive mode of operation. The second approach requires only analog tape recordings of the required data. These recordings are digitized, calibrated, and processed through programs available at Langley for time series analysis (see ref. 14) and noise analysis. Outputs of these programs are provided in a file format suitable for input to the computer program. These files are accessible for either batch or interactive processing. Thus, this approach requires no pre-analysis of the physical data by the user.

The computer program RIDEQUL is written in Control Data Corporation's FORTRAN Version 5, based on FORTRAN 77, for the CDC CYBER 170 series computers operating under the Network Operating System at the NASA Langley Research Center. It utilizes one specific library subroutine available at Langley and the NAMELIST method for input and, therefore, may not be directly compatible with other systems even with the subroutine present. However, only minor adjustments should be required to run the program anywhere that a compiler for FORTRAN 77 is available. The data structures are those in use at Langley and may need to be adapted to the user's computer system.

General Program Requirements

To run the RIDEQUL program requires only that vibration, duration, and noise data be available for each situation to be analyzed. However, there are options for how these data may be available. There must be vibration present in at least one axis for the program to analyze a situation. This vibration may be characterized as random or sinusoidal, but not both. Random vibration is relevant in all five axes (vertical, lateral, longitudinal, roll, and pitch). Sinusoidal vibration is relevant in only three axes: vertical, lateral, and roll. The duration of the situation may or may not be taken into account. Likewise, any noise present in the situation may or may not be taken into account. All input to the program should be nonnegative, as negative data are undefined.

The vibration and the noise data are either input as specific physical parameters known from prior analysis or input from TIFT-formatted (time history interface file tape) multifile files obtained from the time series analysis or the noise analysis programs. The TIFT format for multifile files is described in appendix A. Each component file of a multifile file contains data for one situation. (These component files are interchangeably referred to as files and as serials.) Data files in this format are obtained at the NASA Langley Research Center via the Central Dynamic Data Transcription Subsystem.

Program Inputs

Vibration.- The first input needed is a specification as to whether the vibration is random or sinusoidal. If vibration is random, a TIFT-formatted multifile file containing power spectral density (psd) levels for the axes of vibration is expected. All five axes (vertical, lateral, longitudinal, roll, and pitch) may be involved. The multifile file should be known locally as TAPE1. Input is then the serial numbers for the files for each of the axes. Serial number 0 indicates that there is no vibration in an axis. The frequency and the psd level must be channels 1 and 2, respectively, of the file, frequency taking the place of time in the format. The special case of a situation with essentially purely sinusoidal vibration is handled by indicating that the vibration is not random. Vibration in only the vertical, lateral, and roll axes may be specified to be sinusoidal and must then have been analyzed to determine the frequencies and root-mean-square (rms) acceleration levels associated with the dominant spectral components within each axis. Up to five components per "sinusoidal" axis may be used, although usually fewer will be required. The user chooses which spectral components to employ.

Duration.- Duration input must be given in minutes but may be given as 0.0 if duration effect is not to be taken into account.

Noise.- Whichever kind of vibration is present, noise is either input from a file or directly input as octave-band A-weighted sound pressure levels. If the user indicates that noise data are to come from a file, a TIFT-formatted multifile file known locally as TAPE8 is expected. The serial number of the appropriate file is then the noise input. This file must have the unweighted sound pressure levels for the one-third octaves beginning at 3.2 Hz as channels 2 through 31 of the data record. Extra one-third-octave sound pressure levels are ignored. Only one data record is expected in this file. If there is no noise to account for, a serial number of 0 may be given. If it is indicated that the noise data are not on a file, then A-weighted sound pressure levels for the six relevant octave bands may be input directly.

Program Execution

The program may be executed in batch mode or from an interactive terminal. When accessed from the Langley computer complex directly, the compiled program may be found on an indirect access file named RQM under user number 036623C. The subroutine GETJO from the library UTLIB5, an indirect access file under the user number UTIL, must be available for loading at execution. The following commands will then invoke the program:

```
FETCH,RQM/UN=036623C.
FETCH,UTLIB5/UN=UTIL.
LIBRARY,UTLIB5.
RQM.
```

If the program is obtained through COSMIC (ref. 13), refer to the information that comes with the program and to the compilation and linking requirements of the local computer installation.

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Multiple situations may be processed during the same program execution. At the beginning of execution the program assumes all the user-definable variables to be either zero or true, depending on their type.

Batch mode.- When the program is run in the batch mode, a card deck may be read in or a file of card images may be submitted to the input queue. The input file consists of a series of NAMELIST input groups, each followed, if the vibration is sinusoidal, by a card image of up to 80 characters used to identify the situation. If the vibration is random, the identification is taken from the header record on TAPE1 for the first axis with vibration. Each NAMELIST input group provides the information needed for a particular situation. The NAMELIST conventions apply and are explained in Chapter 5 of the CDC FORTRAN Version 5 Reference Manual (ref. 15) under "NAMELIST Input/Output." The NAMELIST group name is DSCPRMS. The variables in it are

RANDOMV — Logical variable set to
- TRUE If vibration is random
- FALSE If vibration is sinusoidal

Initialized to TRUE.

ISER(5) — Integer array of serial numbers of files on multifile file TAPE1 containing random vibration power spectral densities for 5 axes:
- ISER(1) For vertical axis
- ISER(2) For lateral axis
- ISER(3) For longitudinal axis
- ISER(4) For roll axis
- ISER(5) For pitch axis

Initialized to all 0.

NVIBPKS(3) — Integer array of the number of vibration spectral components which will be input directly for 3 axes relevant to sinusoidal vibration.
- NVIBPKS(1) For vertical axis
- NVIBPKS(2) For lateral axis
- NVIBPKS(3) For roll axis

Initialized to all 0.

FRQPKS(5,3) — Real array of frequencies, in hertz, of up to 5 vibration spectral components in each of 3 axes relevant to sinusoidal vibration.
Initialized to all 0.0.

RMSVBPK(5,3) — Real array of rms levels, in g units or rad/sec^2, of vibration spectral components corresponding to frequencies in FRQPKS.
Initialized to all 0.0.

DRATION — Real length of time, in minutes, of the situation.
Initialized to 0.0.

NOISAVD — Logical variable set to
- TRUE If unweighted one-third-octave sound pressure levels are on multifile file TAPE8
- FALSE If A-weighted octave sound pressure levels are to be directly entered at relevant center frequencies

Initialized to TRUE.

NOISER — Integer serial number of the file on multifile file TAPE8 containing one-third-octave sound pressure levels.
Initialized to 0.

DBNOISE(6) — Real array of the A-weighted octave sound pressure levels at the 6 center frequencies.
Initialized to all 0.0.

The NAMELIST variables are not reinitialized between analyses of situations, so all must be respecified except those that are not different for the new situation. However, if RANDOMV is true, NVIBPKS, FRQPKS, and RMSVBPK are ignored and need not be reset. If RANDOMV is false, ISER is ignored and need not be reset. If NOISAVD is true, DBNOISE need not be reset. If NOISAVD is false, NOISER need not be reset. See appendixes B and C for examples of batch execution setups.

Interactive mode.- If the program is being executed interactively, it asks for each piece of needed information before analyzing a situation. All numeric input is "list directed." This type of input is described in Chapter 5 of the CDC FORTRAN Version 5 Reference Manual, (ref. 15) under "List Directed Input." The A descriptor is used to input character data so that keying in apostrophes around the characters is unnecessary. This descriptor is explained in the same chapter under "Format Specification," "Edit Descriptors." Any question which contains "(Y/N)" requires the character Y to be entered for a yes response. Any other entry, including the character N or a carriage return without an entry, is taken to be a no response. Only initially does the program ask whether the vibration is random or sinusoidal and whether the noise sound pressure levels have been saved; these are assumed to be the same for all situations during an interactive execution of the program. If the vibration is random, there are prompts to supply the serial numbers on multifile file TAPE1 for the files containing the vibration data. If the vibration is sinusoidal, there are prompts for supplying the frequency and rms acceleration levels for each sinusoidal component for each axis and for supplying the identification for the situation. If sound pressure levels are on multifile file TAPE8, the corresponding serial number is requested. If not, the A-weighted octave sound pressure levels are requested. See appendixes B and C for examples of interactive program execution. (The user's input is seen as lower case.) After analyzing each situation, the program inquires, "Do you have more data to analyze?" to determine whether another situation is to be evaluated.

Program Outputs

Output from the program consists of a list of the frequency ranges over which the model is valid and, for each situation analyzed, the echoed input parameters with a summary of the discomfort analysis. If the program is being executed interactively, the list of ranges is optional. The summary of the discomfort analysis contains first the identification for the situation, derived from either the vibration data file or from input. Then the discomfort components for each axis of vibration are printed. If the vibration is random, the unweighted rms acceleration level of vibration at all relevant frequencies, the weighted rms acceleration level of vibration at these frequencies, and the discomfort level due to vibration in this axis are reported for each axis. If the vibration is sinusoidal, the discomfort levels due to each vibration spectral component and the discomfort level due to all vibration in each axis are reported. The combined-axes discomfort levels for the combination of the vertical, lateral, and roll axes and for the combination of the longitudinal and pitch axes are then output. If there is a duration factor to be considered, the contribution to the discomfort level due to trip duration and the duration-corrected vibration discomfort level are printed. If there is any noise input, the contribution to discomfort due to noise in each of the relevant octave bands is printed, followed by the contribution to the discomfort level due to noise in all relevant octaves and the noise-corrected, duration-corrected vibration discomfort. Finally, the overall discomfort level is output. All values referred to as discomfort levels are given in the subjective DISC units. See examples in the section "Application of Computer Program." All output is also on a local file named TAPE7 so that additional copies may be made either by rewinding it and copying it to OUTPUT or by sending it to a printer.

SAMPLE APPLICATIONS

This section illustrates the application of the simplified NASA ride comfort model to ride environments measured on helicopters and automobiles. For each vehicle the various discomfort estimates are first obtained by manual computation using the procedure described in this paper and then by use of the computer program RIDEQUL. For these examples the vibration input is random.

For purposes of illustration the reader should assume that time histories of vertical vibration and interior noise have been measured and recorded during cruise flight of a currently operational helicopter. These measurements are available in analog form on magnetic tape. These tapes also contain sufficient calibration data to permit conversion of tape voltage output to appropriate engineering units. Similar analog tapes are available to define the vibration environment measured at the floor of an automobile. Three axes of vibration (vertical, lateral, roll) were simultaneously recorded in the automobile, but no interior noise data were collected. The total discomfort level associated with each vehicle is to be estimated as well as individual components of discomfort due to noise and vibration.

Manual Computation

Helicopter.- Assume that the analog tapes measured during flight of the helicopter were analyzed by the user to determine the parameters required as model input. For this case only vertical vibration and interior noise were measured. The unweighted rms acceleration, weighted rms acceleration, and A-weighted sound pressure levels within the six required octave bands are

$$(g_{uw})_{vert} = 0.1142g$$

$$(g_w)_{vert} = 0.0751g$$

$$L_{A,63} = 69.8$$

$$L_{A,125} = 81.2$$

$$L_{A,250} = 89.8$$

$$L_{A,500} = 85.5$$

$$L_{A,1K} = 88.1$$

$$L_{A,2K} = 73.4$$

where $(a_{uw})_{vert}$ is the measured unweighted vertical rms acceleration level and $L_{A,i}$ are the A-weighted sound pressure levels in the octave bands with the indicated center frequencies. The computation procedure is as follows:

1. For vertical vibration equation (1) gives a single-axis discomfort of

$$D_{vert} = 0.241 + 44.672(0.0751)$$
$$= 3.60 \text{ DISC}$$

The discomfort due to vibration in the other four axes is assumed to be zero.

2. Since vibration in only one axis was measured, it is not necessary to apply equations (9) through (18). Instead, the total combined-axes discomfort is identical to the single-axis component that is present; i.e.,

$$D_{comb} = D_{vert} = 3.60 \text{ DISC}$$

3. Discomfort estimates are desired without corrections for duration; $\Delta D_{dur} = 0$ and the total vibration discomfort from equation (20) is

$$D_{VIB} = 3.60 \text{ DISC}$$

The above value of total vibration discomfort is used in the computation of noise discomfort in the steps that follow. It also represents the contribution of vibration to total estimated discomfort and is used again in equation (23).

4. Equation (21) is now applied to compute the noise discomfort produced by individual octave bands of noise. The computations for each octave band are shown below. The reader should note that the noise levels L_A are rounded to the nearest integer value prior to entering table V to obtain the coefficients of equation (21).

a. For the 63-Hz octave band, $L_A = 70$, so $A_j = 0.7452$ and $B_j = -0.2337$ (from table V) and $W_i = 1.470$ (from table VI). Thus,

$$D_{N(63,70)} = [0.7452 - 0.2337(3.60)](1.470)$$
$$= -0.14 \text{ DISC}$$

Since $D_{N(63,70)}$ is negative, set

$$D_{N(63,70)} = 0$$

b. For the 125-Hz octave band, $L_A = 81$, so $A_j = 1.9605$, $B_j = -0.4704$, and $W_i = 0.963$. Thus,

$$\begin{aligned} D_{N(125,81)} &= [1.9605 - 0.4704(3.60)](0.963) \\ &= 0.26 \text{ DISC} \end{aligned}$$

c. For the 250-Hz octave band, $L_A = 90$, so $A_j = 3.2968$, $B_j = -0.6547$, and $W_i = 0.786$. Thus,

$$\begin{aligned} D_{N(250,90)} &= [3.2968 - 0.6547(3.60)](0.786) \\ &= 0.74 \text{ DISC} \end{aligned}$$

d. For the 500-Hz octave band, $L_A = 86$, so $A_j = 2.6649$, $B_j = -0.5738$, and $W_i = 0.646$. Thus,

$$\begin{aligned} D_{N(500,86)} &= [2.6649 - 0.5738(3.60)](0.646) \\ &= 0.39 \text{ DISC} \end{aligned}$$

e. For the 1000-Hz octave band, $L_A = 88$, so $A_j = 2.9732$, $B_j = -0.6145$, and $W_i = 0.688$. Thus,

$$\begin{aligned} D_{N(1000,88)} &= [2.9732 - 0.6145(3.60)](0.688) \\ &= 0.52 \text{ DISC} \end{aligned}$$

f. For the 2000-Hz octave band, $L_A = 73$, so $A_j = 1.0312$, $B_j = -0.2995$, and $W_i = 1.448$. Thus,

$$\begin{aligned} D_{N(2000,73)} &= [1.0312 - 0.2995(3.60)](1.448) \\ &= -0.07 \text{ DISC} \end{aligned}$$

Since $D_{N(2000,73)}$ is negative, set

$$D_{N(2000,73)} = 0$$

5. Total discomfort due to noise is computed by application of equation (22) as follows:

$$D_{N(i,j)max} = 0.74 \text{ DISC}$$

$$\sum_i D_{N(i,j)} = 0 + 0.26 + 0.74 + 0.39 + 0.52 + 0$$

$$= 1.91 \text{ DISC}$$

Thus,

$$D_{Noise} = 0.74 + 0.3(1.91 - 0.74)$$
$$= 1.09 \text{ DISC}$$

6. Total estimated discomfort is computed by adding the vibration and noise components of discomfort using equation (23):

$$D_T = 1.09 + 3.60$$
$$= 4.69 \text{ DISC}$$

Automobile.- Analog tapes of automobile vibration in the vertical, lateral, and roll axes of vibration were analyzed by the user to obtain the weighted rms acceleration levels in each of these axes. Interior noise was not measured. Thus, this example illustrates the computational steps required to estimate passenger discomfort in the presence of multiple axes of vibration. The unweighted and weighted rms acceleration levels are given below:

Axis	Unweighted rms acceleration	Weighted rms acceleration
Vertical	0.0692g	0.0405g
Lateral	0.0230g	0.0153g
Roll	0.2454 rad/sec^2	0.1943 rad/sec^2

1. The applicable equations for computing vertical, lateral, and roll acceleration are equations (1), (2), and (4), respectively. Applying these equations gives

$$D_{vert} = 0.241 + 44.672(0.0405)$$
$$= 2.05 \text{ DISC}$$

$$D_{lat} = 0.393 + 47.494(0.0153)$$
$$= 1.12 \text{ DISC}$$

$$D_{roll} = -0.21 + 4.506(0.1943)$$
$$= 0.67 \text{ DISC}$$

2. Since only vertical, lateral, and roll vibrations were measured, it is necessary to apply only equations (9) through (13) to compute D_{VLR}. The procedure is as follows:

a. Rank the single-axis discomfort components such that $D_1 = 2.05$, $D_2 = 1.12$, and $D_3 = 0.67$.

b. Compute

$$R_1 = 2.05/1.12$$
$$= 1.83$$

$$D_4 = \sqrt{(1.12)^2 + (0.67)^2}$$
$$= 1.305$$

$$D_{c1} = \sqrt{(2.05)^2 + (1.12)^2 + (0.67)^2}$$
$$= 2.430$$

c. Since $D_{c1} > 0.88$, then

$$D_{comb1} = -0.44 + 1.65(2.43)$$
$$= 3.57$$

d. For this case, $D_4 > 0.40$, so

$$D_{VLR} = D_{comb1} = 3.57 \text{ DISC}$$

e. Since longitudinal and pitch vibration were not measured, equation (18) becomes

$$D_{comb} = D_{VLR} = 3.57 \text{ DISC}$$

and since vibration discomfort is not to be corrected for duration effect, equation (20) becomes

$$D_{VIB} = D_{comb} = 3.57 \text{ DISC}$$

3. For this case vehicle interior noise was not of interest. Thus, in equation (23), D_{Noise} is set to zero. Therefore, total estimated discomfort is given by

$$D_T = D_{VIB} = 3.57 \text{ DISC}$$

Application of Computer Program

When applying the computer program RIDEQUL at NASA Langley Research Center, the user must supply only magnetic tape recordings that contain sufficient calibration information for conversion of the data to engineering units. These magnetic tapes are digitized, calibrated, and processed through the time series analysis program to produce TIFT-formatted files containing power spectral densities for the vibrations of interest and through the noise analysis program to produce similar files containing unweighted noise levels in one-third octaves. Both sets of files are used in the execution of RIDEQUL. The A-weighting and summation of the one-third octaves into A-weighted octave sound pressure levels is performed by RIDEQUL.

Helicopter.- A sample run deck, the NAMELIST input, and sample output for batch processing of the helicopter example are presented in appendix B. The dialogue from an interactive session for the helicopter example is also presented. The unweighted (solid line) and weighted (dashed line) vertical vibration spectra for the helicopter are shown in figure 5, and the interior noise spectrum is given in figure 6. The two curves in figure 5 differ because of the effect of the human comfort sensitivity weighting function for vertical vibration.

Automobile.- A sample run deck, the NAMELIST input, and sample output for the automobile example, without one-third-octave noise data saved on a file, are presented in appendix C. The dialogue from an interactive session for the example is also presented. It can be seen from this case that the absence of noise may be indicated equivalently by serial number 0 or by typing an "n" to the question of whether there is noise present. The unweighted and weighted acceleration spectra for vertical, lateral, and roll vibration are shown in figure 7.

CONCLUDING REMARKS

This paper has presented and discussed a simplified ride comfort model derived from a more complex model developed by NASA Langley Research Center. The major simplification involved frequency weighting of the vibration spectra of each axis in accordance with the respective human comfort sensitivity characteristics. The root-mean-square acceleration level of each resulting spectrum provided the basic vibration input to the simplified model. Treatment of the noise in the model was unchanged. The computational equations and procedures required to obtain discomfort estimates to combined noise and vibration environments were presented and illustrated by examples taken from helicopter and automobile ride quality studies. Implementation of the simplified ride comfort model in a user-oriented computer program was discussed, and applications of the program to helicopter and automobile ride environ-
nts were also presented. This computer program, in conjunction with time series
sis and noise analysis program capability, permits routine processing and con-
n of physical ride environment data from analog magnetic tape recordings to
fort estimates that relate directly to passenger acceptance of the environ-
These discomfort estimates (model outputs) are in the form of single numbers

reflecting total estimated passenger discomfort, noise and vibration contributions to total estimated discomfort, discomfort attributed to individual axes of vibration, and discomfort attributed to individual noise octave bands.

The model presented herein has several important features that distinguish it from other methods of evaluating vehicle ride quality. First, the model has the unique capability of transforming individual elements of noise and vibration environments into subjective discomfort units and then combining the subjective units to produce estimates of total discomfort as well as the various individual indices of discomfort. Secondly, the model is sensitive to changes in physical stimulus parameters such as vibration frequency, vibration acceleration level, noise octave-band frequency, and noise level. This renders the model very useful for determining ride-quality design trade-offs and especially for assessing comparative vehicle ride comfort and diagnosing the source of ride comfort problems.

Langley Research Center
National Aeronautics and Space Administration
Hampton, VA 23665
March 12, 1984

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APPENDIX A

TIFT FILE FORMAT

The TIFT (time history interface file tape) file format is based on the natural structure of time series data. Other types of data may also lend themselves to this structure. Data are arranged into groups of each kind of data, one group for each occurrence. Therefore, each "sample" (occurrence) represents the state of each "channel" (kind of recorded data) at a particular point in time. The time of the occurrence is the first channel and is counted when considering how many channels are recorded or how many words written. Because of the nature of time series, it is assumed that the values of the data in the first channel are in increasing order as one reads the file.

This format structures each file with a header logical record followed by data logical records, each of the latter representing a sample (or an occurrence). The header record contains the integer serial number of the file, the integer number of channels of data in the file, the corresponding names of the channels of data in words of 10 characters each, the corresponding units of the channels of data in words of 10 characters each, and 8 words of 10 characters each that identify the data in the file. The data records contain one word for each channel of data. Each file is terminated with an end of file mark. A multifile file is terminated with an additional end of file mark, resulting in two in a row.

The TIFT format may be visualized as

Record 1 - Header record

Word 1 - Serial number (integer)

Word 2 - Number of channels N (integer)

Word 3 - Alphanumeric name of first channel, usually 'TIME   '

Word 4 - Alphanumeric name of second channel

⋮

Word N+2 - Alphanumeric name of Nth channel

Word N+3 - Alphanumeric unit for first channel, usually 'SECOND   '

Word N+4 - Alphanumeric unit for second channel

⋮

Words 2N+2 - Alphanumeric unit for Nth channel

Words 2N+3 to 2N+10 - Alphanumeric header identifying data

rds 2 to n - Data records

1 - Value for first channel, usually time value

2 to N - Data values

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APPENDIX B

INPUT AND OUTPUT FOR BATCH OR INTERACTIVE PROCESSING OF HELICOPTER EXAMPLE

The following run deck and NAMELIST input result in batch processing by program RIDEQUL of the helicopter example given in the text. The output of this batch run is then presented. Finally an interactive session is presented in which the helicopter example is analyzed.

Run Deck

```
RIDEQUL,T1000,CM70000.
USER,000000X,XXXXXXX.
CHARGE,000000,LRC.
DELIVER.XXX XXX   YOUR DELIVERY
FETCH,TAPE1.
FETCH,TAPE8.
FETCH,ROM.
FETCH,UTLIB5/UN=UTIL.
LIBRARY(UTLIB5)
MAP,OFF.
ROM.
REWIND,TAPE6,TAPE7.
COPYCF,TAPE6,OUTPUT.
COPYCF,TAPE7,OUTPUT.
EXIT.
```

NAMELIST Input

```
$DSCPRMS ISER=1,0,0,0,0, NOISER=0, DRATION=0.25 $
$DSCPRMS ISER=2,0,0,0,0 $
$DSCPRMS ISER=3,0,0,0,0 $
$DSCPRMS ISER=4,0,0,0,0 $
$DSCPRMS ISER=5,0,0,0,0 $
$DSCPRMS ISER=6,0,0,0,0 $
$DSCPRMS ISER=7,0,0,0,0 $
$DSCPRMS ISER=8,0,0,0,0 $
$DSCPRMS ISER=9,0,0,0,0 $
$DSCPRMS ISER=10,0,0,0,0 $
$DSCPRMS ISER=11,0,0,0,0, NOISER=2 $
$DSCPRMS ISER=12,0,0,0,0, NOISER=3 $
$DSCPRMS ISER=13,0,0,0,0, NOISER=4 $
$DSCPRMS ISER=14,0,0,0,0, NOISER=5 $
$DSCPRMS ISER=15,0,0,0,0, NOISER=6 $
```

APPENDIX B

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Output

The following is part of the output resulting from the above run deck and NAMELIST input:

```
                    **  DISCOMFORT PROGRAM  **        16.19.34.  01/24/84

     IF THE VIBRATION IS RANDOM, ALL FIVE AXES ARE USED:

          AXIS                  FREQUENCY RANGE

        VERTICAL                  1.00 - 30.00
        LATERAL                   1.00 - 10.00
        LONGITUDINAL               .50 - 10.00
        ROLL                       .50 -  5.50
        PITCH                      .50 - 10.00

     IF THE VIBRATION IS SINUSOIDAL, THE FOLLOWING THREE AXES ARE USED:

          AXIS                  FREQUENCY RANGE

        VERTICAL                  1.00 - 30.00
        LATERAL                   1.00 - 10.00
        ROLL                      1.00 -  4.00

     CORRECTION FOR THE DURATION OF THE SITUATION CAN ACCOUNT FOR
BETWEEN 1 AND 120 MINUTES.

     NOISE FOR OCTAVE BANDS WITH THE FOLLOWING CENTER FREQUENCIES WILL
BE ACCOUNTED FOR IF THE NOISE LEVEL IS ABOVE 65 DB(A).  NOISE ABOVE
100 DB(A) CAN ONLY BE TREATED AS 100 DB(A).

              63. HZ
             125. HZ
             250. HZ
             500. HZ
            1000. HZ
            2000. HZ


$DSCPRMS

RANDOMV  = T,

ISER     = 11, 0, 0, 0, 0,

NVIBPKS  = 0, 0, 0,

FRQPKS   = 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0,

RMSVBPK  = 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0,

DRATION  = .25E+00,

NOISAVD  = T,

NOISER   = 2,

DBNOISE  = 0.0, 0.0, 0.0, 0.0, 0.0, 0.0,

$END
```

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OF POOR [illegible]

APPENDIX B

```
HELI SIM/NAVY-1/VIB/LEATHERWOOD          TEST NO. P-1          RUN NO. 1

    FOR THE VERTICAL     AXIS
THE UNWEIGHTED RMS IS  .1142
THE WEIGHTED RMS IS    .0751
THE DISCOMFORT DUE TO VIBRATION IN THIS AXIS IS 3.60 DISC UNITS.

COMBINED-AXIS DISCOMFORT FOR VERTICAL, LATERAL, AND ROLL AXES IS 3.60.
COMBINED-AXIS DISCOMFORT FOR LONGITUDINAL AND PITCH AXES IS      0.00.
THE COMBINED DISCOMFORT DUE TO VIBRATION IN ALL AXES IS          3.60.

LENGTH OF TIME LESS THAN 1 MINUTE CANNOT BE ACCOUNTED FOR; THERE WILL
BE NO CORRECTION FOR TIME.

DISCOMFORT FROM EACH OCTAVE:
   CENTER FREQUENCY          DB(A)        DISC UNITS
         63.                 69.8           0.00
        125.                 81.2            .26
        250.                 89.8            .74
        500.                 85.5            .39
       1000.                 88.1            .52
       2000.                 73.4           0.00

NOISE IN THE VIBRATION ENVIRONMENT CONTRIBUTES 1.09 DISCOMFORT UNITS.
NOISE-CORRECTED, DURATION-CORRECTED VIBRATION DISCOMFORT IS 4.69.

THE OVERALL DISCOMFORT INDEX IS 4.69.
```

Interactive Session

The following is the dialogue resulting from interactive processing by program RIDEQUL. The user's responses to RIDEQUL's prompts are presented in lowercase letters.

```
/fetch,rqm,tape1,tape8
 FETCH COMPLETE.
/fetch,utlib5/un=util
 FETCH COMPLETE.
/library(utlib5)
LIBRARY(UTLIB5)
/map,off
MAP,OFF.
/rqm


                 **  DISCOMFORT PROGRAM  **       15.17.34.  01/25/84

     THE PROGRAM YOU ARE RUNNING WILL CALCULATE SUBJECTIVE DISCOMFORT
 INDICES FOR SITUATIONS FOR WHICH VIBRATION AND NOISE LEVEL DATA ARE
 PROVIDED.  WOULD YOU LIKE TO SEE THE LIMITS WITHIN WHICH THE
 CONTRIBUTIONS DUE TO VIBRATION AND NOISE LEVELS CAN BE ACCOUNTED FOR?
 (Y/N)
? y

     IF THE VIBRATION IS RANDOM, ALL FIVE AXES ARE USED:

          AXIS                  FREQUENCY RANGE

         VERTICAL                 1.00 - 30.00
         LATERAL                  1.00 - 10.00
         LONGITUDINAL              .50 - 10.00
         ROLL                      .50 -  5.50
         PITCH                     .50 - 10.00
```

APPENDIX B

```
     IF THE VIBRATION IS SINUSOIDAL, THE FOLLOWING THREE AXES ARE USED:

          AXIS                    FREQUENCY RANGE

        VERTICAL                    1.00 - 30.00
        LATERAL                     1.00 - 10.00
        ROLL                        1.00 -  4.00

     CORRECTION FOR THE DURATION OF THE SITUATION CAN ACCOUNT FOR
BETWEEN 1 AND 120 MINUTES.

     NOISE FOR OCTAVE BANDS WITH THE FOLLOWING CENTER FREQUENCIES WILL
BE ACCOUNTED FOR IF THE NOISE LEVEL IS ABOVE 65 DB(A).  NOISE ABOVE
100 DB(A) CAN ONLY BE TREATED AS 100 DB(A).

                 63. HZ
                125. HZ
                250. HZ
                500. HZ
               1000. HZ
               2000. HZ

IS THE VIBRATION IN THESE SITUATIONS RANDOM (AS OPPOSED TO SINUSOIDAL)?
(Y/N)
? y

IS THE NOISE DATA SAVED ON A FILE (AS OPPOSED TO HAVING TO BE KEYED IN
AT THE TERMINAL)?  (Y/N)
? y

GIVE THE SERIAL NUMBERS ON TAPE1 FOR THE FIVE AXES' ACCELERATIONS --
THE VERTICAL, LATERAL, LONGITUDINAL, ROLL, AND PITCH FORCES.  (SERIAL 0
WILL INDICATE NOT TO ACCOUNT FOR THAT PARTICULAR AXIS.  AT LEAST ONE
SERIAL MUST BE NONZERO.)
? 11,0,0,0,0

WHAT IS THE LENGTH IN MINUTES OF THIS SITUATION?
? 0.25

WHAT IS THE SERIAL NUMBER ON TAPE8 FOR THE NOISE DATA?  (0 WILL BE
TAKEN TO MEAN NO NOISE CORRECTION IS DESIRED.)
? 2


SERIALS OF AXES' ACCELERATIONS ARE
 VERTICAL        11
 LATERAL          0
 LONGITUDINAL     0
 ROLL             0
 PITCH            0
TIME IN MINUTES IS     .25
SERIAL FOR NOISE DATA IS    2



HELI SIM/NAVY-1/VIB/LEATHERWOOD          TEST NO. P-1         RUN NO. 1


    FOR THE VERTICAL     AXIS
THE UNWEIGHTED RMS IS   .1142
THE WEIGHTED RMS IS    .0751
THE DISCOMFORT DUE TO VIBRATION IN THIS AXIS IS 3.60 DISC UNITS.


COMBINED-AXIS DISCOMFORT FOR VERTICAL, LATERAL, AND ROLL AXES IS 3.60.
COMBINED-AXIS DISCOMFORT FOR LONGITUDINAL AND PITCH AXES IS       0.00.
THE COMBINED DISCOMFORT DUE TO VIBRATION IN ALL AXES IS           3.60.

LENGTH OF TIME LESS THAN 1 MINUTE CANNOT BE ACCOUNTED FOR; THERE WILL
BE NO CORRECTION FOR TIME.
```

APPENDIX B

```
DISCOMFORT FROM EACH OCTAVE:
   CENTER FREQUENCY          DB(A)        DISC UNITS
          63.                69.8           0.00
         125.                81.2            .26
         250.                89.8            .74
         500.                85.5            .39
        1000.                88.1            .5[illegible]
        2000.                73.4           0.00

NOISE IN THE VIBRATION ENVIRONMENT CONTRIBUTES 1.09 DISCOMFORT UNITS.
NOISE-CORRECTED, DURATION-CORRECTED VIBRATION DISCOMFORT IS 4.69.

THE OVERALL DISCOMFORT INDEX IS 4.69.


DO YOU HAVE MORE DATA TO ANALYZE?  (Y/N)
? n


END OF PROGRAM EXECUTION.
SUMMARY OF RESULTS IS ON TAPE7.
    0.805 CP SECONDS EXECUTION TIME.
/route,tape7,dc=lp
ROUTE COMPLETE.
```

APPENDIX C

INPUT AND OUTPUT FOR BATCH OR INTERACTIVE PROCESSING OF AUTOMOBILE EXAMPLE

The following run deck and NAMELIST input result in batch processing by program RIDEQUL of the automobile example given in the text. The output of this batch run is then presented. Finally an interactive session is presented in which the automobile example is analyzed.

Run Deck

```
RIDEQUL,T1000,CM70000.
USER,000000X,XXXXXXX.
CHARGE,000000,LRC.
DELIVER,XXX XXX    YOUR DELIVERY
FETCH,TAPE1.
FETCH,RQM.
FETCH,UTLIB5/UN=UTIL.
LIBRARY(UTLIB5)
MAP,OFF.
RQM.
REWIND,TAPE6,TAPE7.
COPYCF,TAPE6,OUTPUT.
COPYCF,TAPE7,OUTPUT.
EXIT.
```

NAMELIST Input

```
$DSCPRMS ISER=1,2,0,3,0, NOISER=0, DRATION=0.0 $
$DSCPRMS ISER=4,5,0,6,0 $
$DSCPRMS ISER=7,8,0,9,0 $
$DSCPRMS ISER=10,11,0,12,0 $
$DSCPRMS ISER=13,14,0,15,0 $
$DSCPRMS ISER=565,566,0,567,0 $
$DSCPRMS ISER=568,569,0,570,0 $
$DSCPRMS ISER=571,572,0,573,0 $
$DSCPRMS ISER=574,575,0,576,0 $
```

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APPENDIX C

Output

The following is part of the output resulting from the above run deck and NAMELIST input:

```
                    **  DISCOMFORT PROGRAM  **       09.35.40.  01/25/84

      IF THE VIBRATION IS RANDOM, ALL FIVE AXES ARE USED:

           AXIS                  FREQUENCY RANGE

         VERTICAL                  1.00 - 30.00
         LATERAL                   1.00 - 10.00
         LONGITUDINAL               .50 - 10.00
         ROLL                       .50 -  5.50
         PITCH                      .50 - 10.00

      IF THE VIBRATION IS SINUSOIDAL, THE FOLLOWING THREE AXES ARE USED:

           AXIS                  FREQUENCY RANGE

         VERTICAL                  1.00 - 30.00
         LATERAL                   1.00 - 10.00
         ROLL                      1.00 -  4.00

      CORRECTION FOR THE DURATION OF THE SITUATION CAN ACCOUNT FOR
   BETWEEN 1 AND 120 MINUTES.

      NOISE FOR OCTAVE BANDS WITH THE FOLLOWING CENTER FREQUENCIES WILL
   BE ACCOUNTED FOR IF THE NOISE LEVEL IS ABOVE 65 DB(A).  NOISE ABOVE
   100 DB(A) CAN ONLY BE TREATED AS 100 DB(A).

                63. HZ
               125. HZ
               250. HZ
               500. HZ
              1000. HZ
              2000. HZ


$DSCPRMS

RANDOMV = T,

ISER    = 568, 569, 0, 570, 0,

NVIBPKS = 0, 0, 0,

FROPKS  = 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0,

RMSVBPK = 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0,

DRATION = 0.0,

NOISAVD = T,

NOISER  = 0,

DBNOISE = 0.0, 0.0, 0.0, 0.0, 0.0, 0.0,

$END

NO CORRECTION WILL BE MADE FOR TIME.

NO CORRECTION WILL BE MADE FOR NOISE.
```

APPENDIX C

```
NASA/FORD TEST MV-1/LEATHERWOOD          TEST NO. 16          RUN NO. 10

     FOR THE VERTICAL      AXIS
THE UNWEIGHTED RMS IS  .0592
THE WEIGHTED RMS IS    .0405
THE DISCOMFORT DUE TO VIBRATION IN THIS AXIS IS 2.05 DISC UNITS.

     FOR THE LATERAL       AXIS
THE UNWEIGHTED RMS IS  .0230
THE WEIGHTED RMS IS    .0153
THE DISCOMFORT DUE TO VIBRATION IN THIS AXIS IS 1.12 DISC UNITS.

     FOR THE ROLL          AXIS
THE UNWEIGHTED RMS IS  .2454
THE WEIGHTED RMS IS    .1943
THE DISCOMFORT DUE TO VIBRATION IN THIS AXIS IS  .67 DISC UNITS.

COMBINED-AXIS DISCOMFORT FOR VERTICAL, LATERAL, AND ROLL AXES IS 3.57.
COMBINED-AXIS DISCOMFORT FOR LONGITUDINAL AND PITCH AXES IS      0.00.
THE COMBINED DISCOMFORT DUE TO VIBRATION IN ALL AXES IS          3.57.

THE OVERALL DISCOMFORT INDEX IS 3.57.
```

Interactive Session

The following is the dialogue resulting from interactive processing by program RIDEQUL. The user's responses to RIDEQUL's prompts are presented in lowercase letters.

```
/fetch,rqm,tape1
 FETCH COMPLETE.
/fetch,utlib5/un=util
 FETCH COMPLETE.
/library(utlib5)
LIBRARY(UTLIB5)
/map,off
MAP,OFF.
/rqm


                  **  DISCOMFORT PROGRAM  **       15.09.21.  01/25/84

     THE PROGRAM YOU ARE RUNNING WILL CALCULATE SUBJECTIVE DISCOMFORT
INDICES FOR SITUATIONS FOR WHICH VIBRATION AND NOISE LEVEL DATA ARE
PROVIDED.  WOULD YOU LIKE TO SEE THE LIMITS WITHIN WHICH THE
CONTRIBUTIONS DUE TO VIBRATION AND NOISE LEVELS CAN BE ACCOUNTED FOR?
(Y/N)
? y


     IF THE VIBRATION IS RANDOM, ALL FIVE AXES ARE USED:

          AXIS                    FREQUENCY RANGE

        VERTICAL                    1.00 - 30.00
        LATERAL                     1.00 - 10.00
        LONGITUDINAL                 .50 - 10.00
        ROLL                         .50 -  5.50
        PITCH                        .50 - 10.00
```

APPENDIX C

```
     IF THE VIBRATION IS SINUSOIDAL, THE FOLLOWING THREE AXES ARE USED:

            AXIS                    FREQUENCY RANGE

          VERTICAL                     1.00 - 30.00
          LATERAL                      1.00 - 10.00
          ROLL                         1.00 -  4.00

     CORRECTION FOR THE DURATION OF THE SITUATION CAN ACCOUNT FOR
BETWEEN 1 AND 120 MINUTES.

     NOISE FOR OCTAVE BANDS WITH THE FOLLOWING CENTER FREQUENCIES WILL
BE ACCOUNTED FOR IF THE NOISE LEVEL IS ABOVE 65 DB(A).  NOISE ABOVE
100 DB(A) CAN ONLY BE TREATED AS 100 DB(A).

                 63. HZ
                125. HZ
                250. HZ
                500. HZ
               1000. HZ
               2000. HZ

 IS THE VIBRATION IN THESE SITUATIONS RANDOM (AS OPPOSED TO SINUSOIDAL)?
 (Y/N)
? y

 IS THE NOISE DATA SAVED ON A FILE (AS OPPOSED TO HAVING TO BE KEYED IN
 AT THE TERMINAL)?  (Y/N)
? n

 GIVE THE SERIAL NUMBERS ON TAPE1 FOR THE FIVE AXES' ACCELERATIONS --
 THE VERTICAL, LATERAL, LONGITUDINAL, ROLL, AND PITCH FORCES.  (SERIAL 0
 WILL INDICATE NOT TO ACCOUNT FOR THAT PARTICULAR AXIS.  AT LEAST ONE
 SERIAL MUST BE NONZERO.)
? 568,569,0,570,0

 WHAT IS THE LENGTH IN MINUTES OF THIS SITUATION?
? 0.0
 NO CORRECTION WILL BE MADE FOR TIME.

 IS THERE NOISE PRESENT? (Y/N)
? n


 SERIALS OF AXES' ACCELERATIONS ARE
  VERTICAL        568
  LATERAL         569
  LONGITUDINAL      0
  ROLL            570
  PITCH             0
 TIME IN MINUTES IS   0.00
 NO CORRECTION WILL BE MADE FOR NOISE.


 NASA/FORD TEST MV-1/LEATHERWOOD          TEST NO. 16          RUN NO. 10


     FOR THE VERTICAL      AXIS
 THE UNWEIGHTED RMS IS  .0692
 THE WEIGHTED RMS IS    .0405
 THE DISCOMFORT DUE TO VIBRATION IN THIS AXIS IS 2.05 DISC UNITS.

     FOR THE LATERAL       AXIS
 THE UNWEIGHTED RMS IS  .0230
 THE WEIGHTED RMS IS    .0153
 THE DISCOMFORT DUE TO VIBRATION IN THIS AXIS IS 1.12 DISC UNITS.

     FOR THE ROLL          AXIS
 THE UNWEIGHTED RMS IS  .2454
 THE WEIGHTED RMS IS    .1943
 THE DISCOMFORT DUE TO VIBRATION IN THIS AXIS IS  .67 DISC UNITS.
```

APPENDIX C

```
 COMBINED-AXIS DISCOMFORT FOR VERTICAL, LATERAL, AND ROLL AXES IS 3.57.
 COMBINED-AXIS DISCOMFORT FOR LONGITUDINAL AND PITCH AXIS IS      0.00.
 THE COMBINED DISCOMFORT DUE TO VIBRATION IN ALL AXES IS          3.57.

 THE OVERALL DISCOMFORT INDEX IS 3.57.


 DO YOU HAVE MORE DATA TO ANALYZE?  (Y/N)
? n


 END OF PROGRAM EXECUTION.
 SUMMARY OF RESULTS IS ON TAPE7.
     4.354 CP SECONDS EXECUTION TIME.
/route,tape7,dc=lp
 ROUTE COMPLETE.
```

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TABLE I.- HUMAN COMFORT SENSITIVITY WEIGHTING FACTORS FOR EACH AXIS OF VIBRATION

FREQUENCY, HZ	WEIGHTING FACTORS			
	VERTICAL	LATERAL	ROLL	LONGITUDINAL, PITCH
.50	.000	.000	.500	.010
.60	.000	.000	.518	.030
.70	.000	.000	.536	.070
.80	.000	.000	.554	.170
.90	.000	.000	.572	.410
1.00	.410	.600	.590	.890
1.25	.418	.700	.693	1.000
2.00	.440	1.000	1.000	1.000
3.00	.640	.750	.670	1.000
4.00	.830	.600	.660	1.000
4.75	.890	.525	.653	1.000
5.00	.910	.500	.650	.890
5.50	.955	.465	.640	.450
6.00	1.000	.430	.000	.230
6.50	.925	.400	.000	.130
7.00	.850	.370	.000	.080
7.50	.795	.350	.000	.050
8.00	.740	.330	.000	.040
9.00	.710	.300	.000	.020
10.00	.660	.250	.000	.010
11.00	.640	.000	.000	.000
12.00	.620	.000	.000	.000
13.00	.580	.000	.000	.000
14.00	.540	.000	.000	.000
15.00	.500	.000	.000	.000
16.00	.470	.000	.000	.000
17.00	.440	.000	.000	.000
18.00	.400	.000	.000	.000
19.00	.380	.000	.000	.000
20.00	.370	.000	.000	.000
21.00	.350	.000	.000	.000
22.00	.340	.000	.000	.000
23.00	.330	.000	.000	.000
24.00	.330	.000	.000	.000
25.00	.300	.000	.000	.000
26.00	.300	.000	.000	.000
27.00	.300	.000	.000	.000
28.00	.300	.000	.000	.000
29.00	.300	.000	.000	.000
30.00	.300	.000	.000	.000

TABLE II.- COEFFICIENTS OF EQUATION (6) FOR VERTICAL SINUSOIDAL VIBRATION

Frequency, Hz	K_0, DISC	K_1, DISC/g	K_2, DISC/g	Frequency, Hz	K_0, DISC	K_1, DISC/g	K_2, DISC/g
1	0.3946	8.8296	15.41	16	-0.1406	8.3656	6.02
2	-.3713	15.2731	9.08	17	.1650	6.8997	9.65
3	-.7685	21.4441	8.64	18	-.2190	7.5948	3.94
4	-1.0028	27.1273	10.41	19	-.3326	7.5326	1.99
5	-1.2352	32.2146	11.63	20	.0986	6.1421	7.79
6	-.7592	28.8279	16.17	21	-.1989	6.7045	3.39
7	-.7188	27.4856	15.51	22	-.1769	6.5021	3.55
8	-.0576	19.8988	18.94	23	.0345	5.9102	6.49
9	-.8919	21.9987	7.31	24	-.0465	6.0773	5.30
10	-1.2718	22.9530	1.76	25	.0494	5.8456	6.67
11	-.6912	16.9931	5.47	26	.0010	6.0208	6.04
12	-.4937	14.0437	5.82	27	-.0684	6.2664	5.13
13	-.3695	12.0297	5.87	28	-.1695	6.6472	3.82
14	-.3470	10.7501	4.97	29	-.0324	6.4483	5.91
15	-.5220	10.4234	1.72	30	-.0766	6.7358	5.46

TABLE III.- COEFFICIENTS OF EQUATION (7) FOR LATERAL SINUSOIDAL VIBRATION

Frequency, Hz	K_3, DISC	K_4, DISC/g	K_5, DISC/g
1	-0.8322	26.7849	12.91
2	-1.1106	52.2679	33.76
3	-.3586	32.1940	26.22
4	.0217	19.9130	20.27
5	-.3163	19.0267	13.76
6	-.7048	19.8629	8.12
7	-.7024	16.3704	4.66
8	-.4184	14.8952	7.92
9	-.0636	11.6969	10.64
10	.3307	8.9291	14.44

TABLE IV.- COEFFICIENTS OF EQUATION (8) FOR ROLL SINUSOIDAL VIBRATION

Frequency, Hz	K_6, DISC	K_7, DISC/(rad/sec^2)	K_8, DISC/(rad/sec^2)	K_9, rad/sec^2
1	-2.31	5.85	1.24	0.50
2	-.18	4.70	3.98	.25
3	.28	2.50	3.62	.25
4	.35	2.35	3.75	.25

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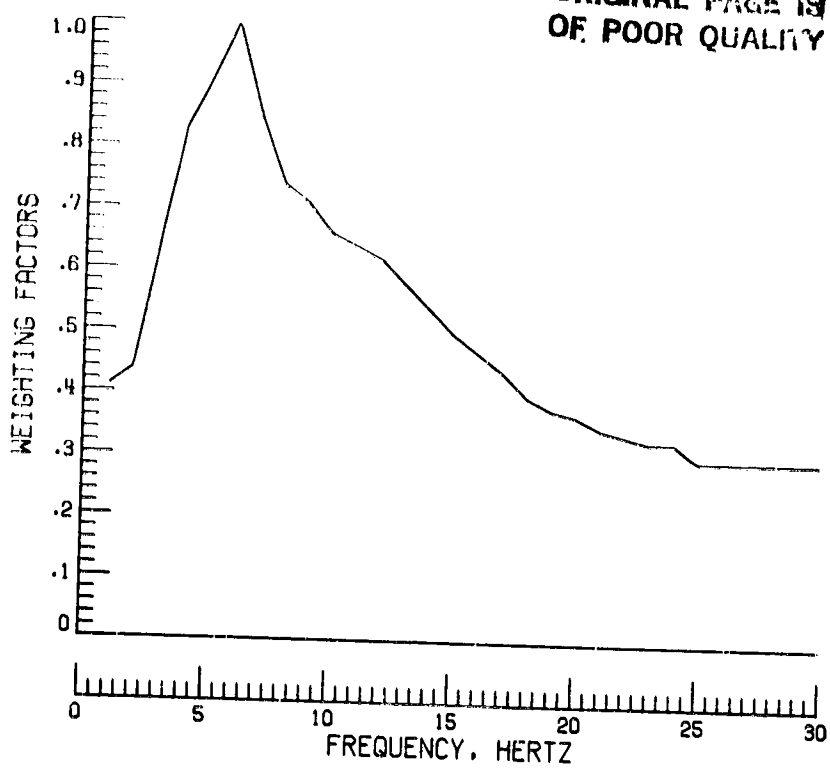
TABLE V.- SLOPE AND INTERCEPT COEFFICIENTS FOR EQUATION (21)

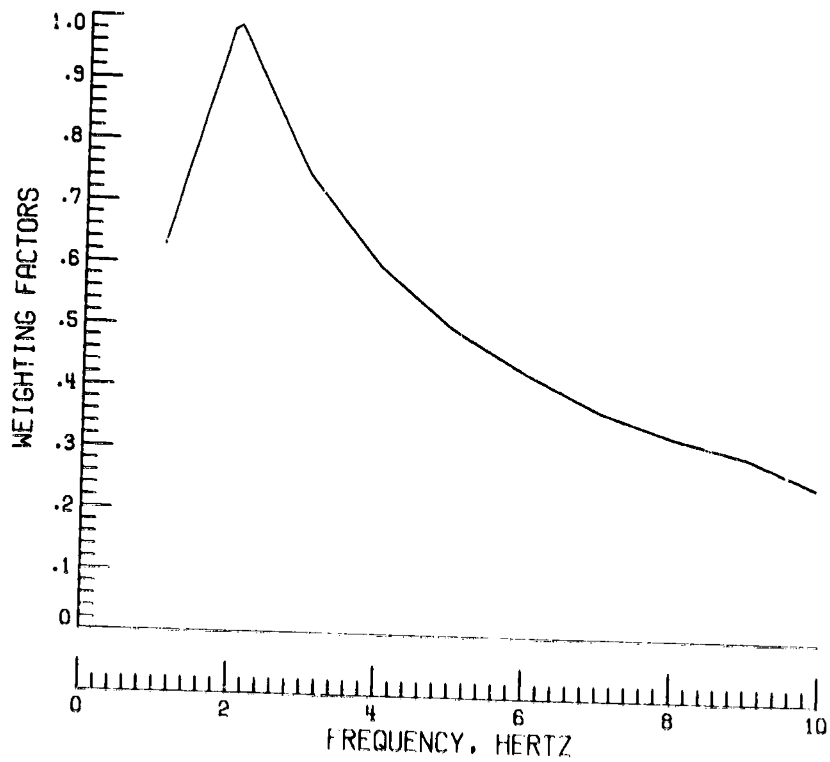
Noise level, L_A	Intercept, A_j, DISC	Slope, B_j	Noise level, L_A	Intercept, A_j, DISC	Slope, B_j
65	0.3447	-0.1219	83	2.2294	-0.5118
66	.4172	-.1445	84	2.3718	-.5329
67	.4935	-.1669	85	2.5164	-.5533
68	.5736	-.1893	86	2.6649	-.5738
69	.6575	-.2116	87	2.8172	-.5942
70	.7452	-.2337	88	2.9732	-.6145
71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

TABLE VI.- OCTAVE-BAND WEIGHTING FACTORS

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

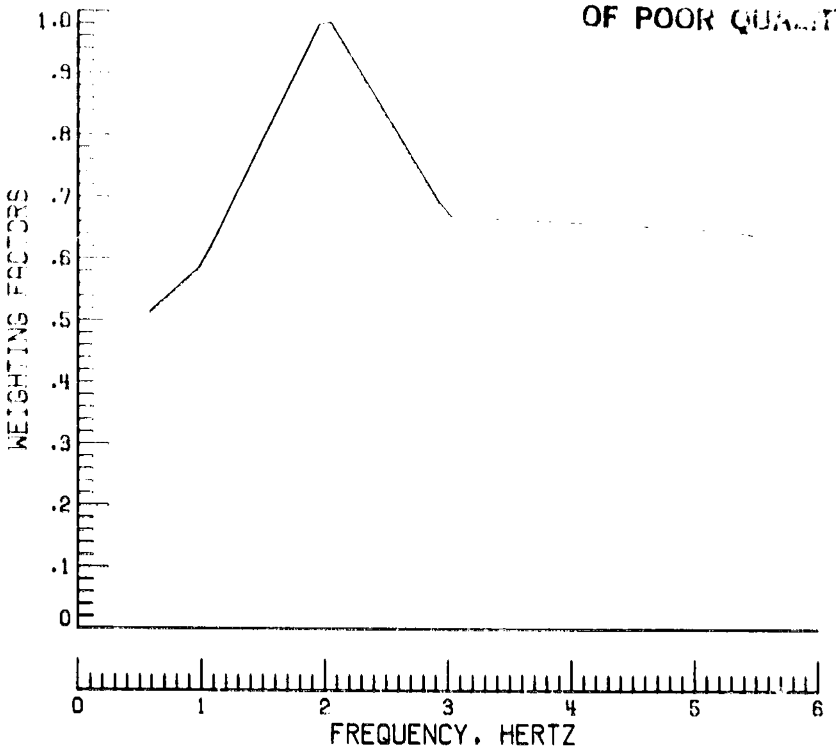


(a) Vertical axis.

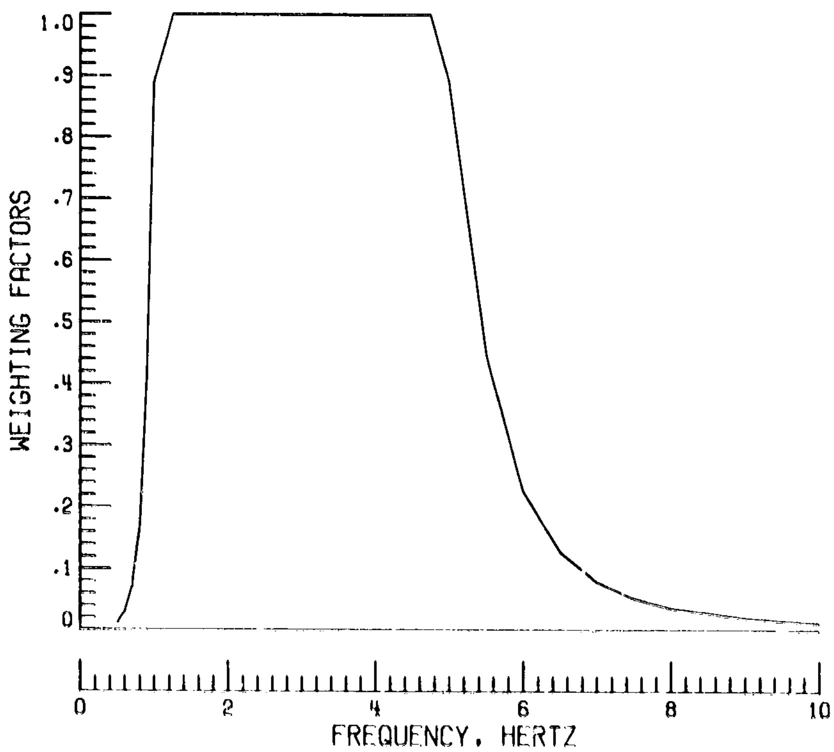


(b) Lateral axis.

Figure 1.- Human comfort sensitivity weighting functions for various axes of vibration.



(c) Roll axis.



(d) Longitudinal and pitch axes.

Figure 1.- Concluded.

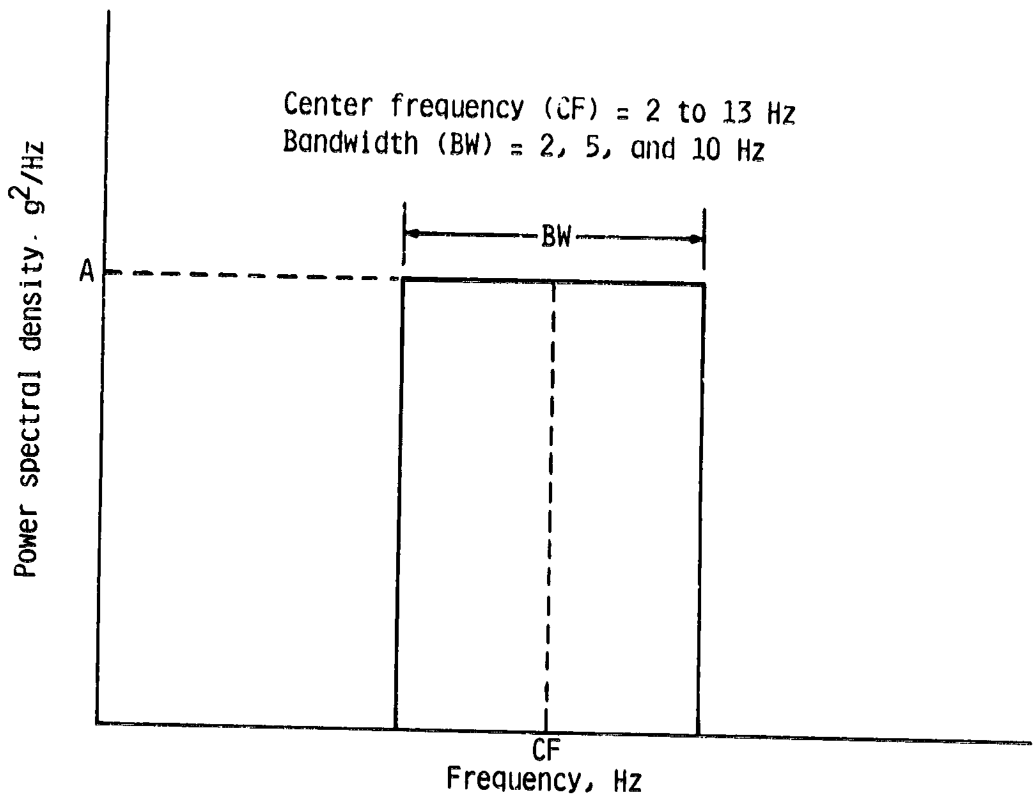


Figure 2.- Ideal spectral characteristics used in the development of the simplified NASA ride comfort model.

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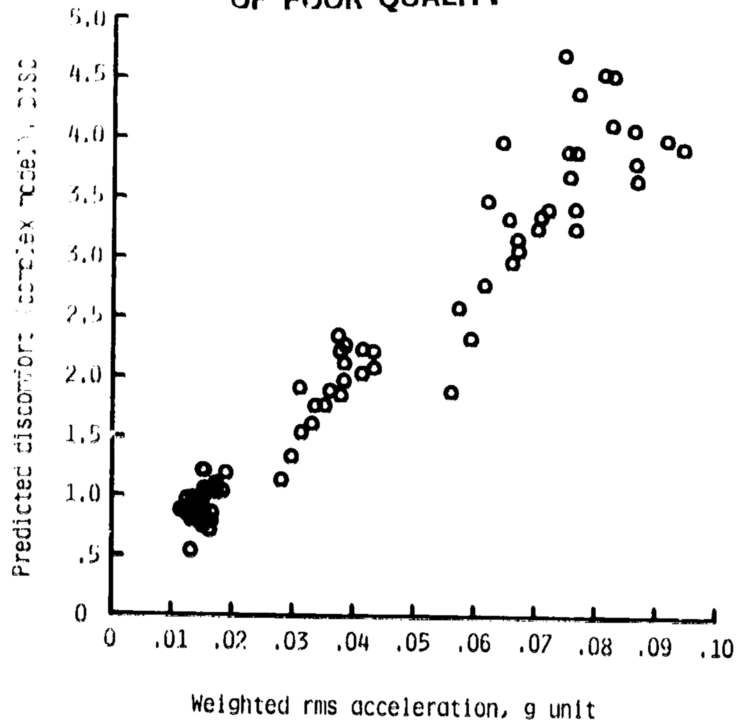

Figure 3.- Predicted discomfort (ref. 12) vs. weighted rms vertical acceleration.

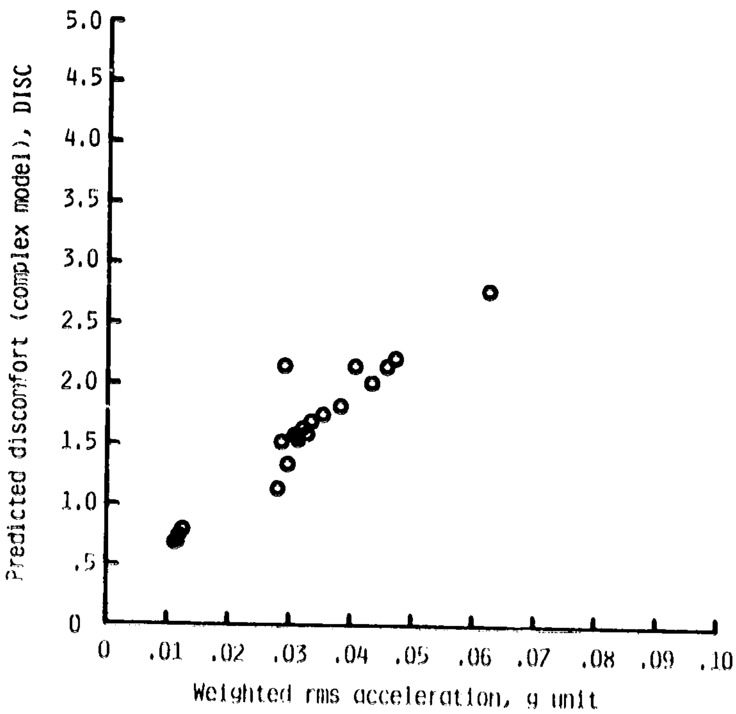

Figure 4.- Predicted discomfort (ref. 12) vs. weighted rms lateral acceleration.

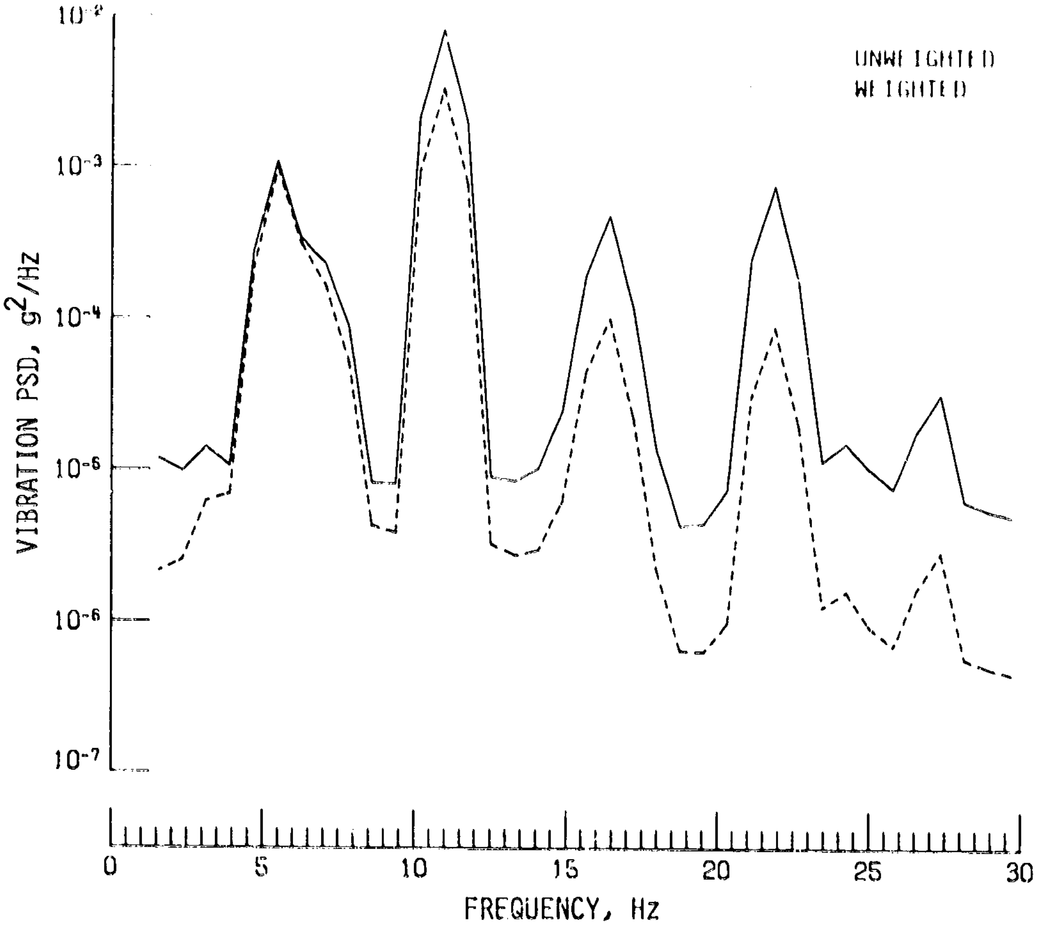

Figure 5.- Unweighted and weighted vertical vibration spectra for the helicopter example.

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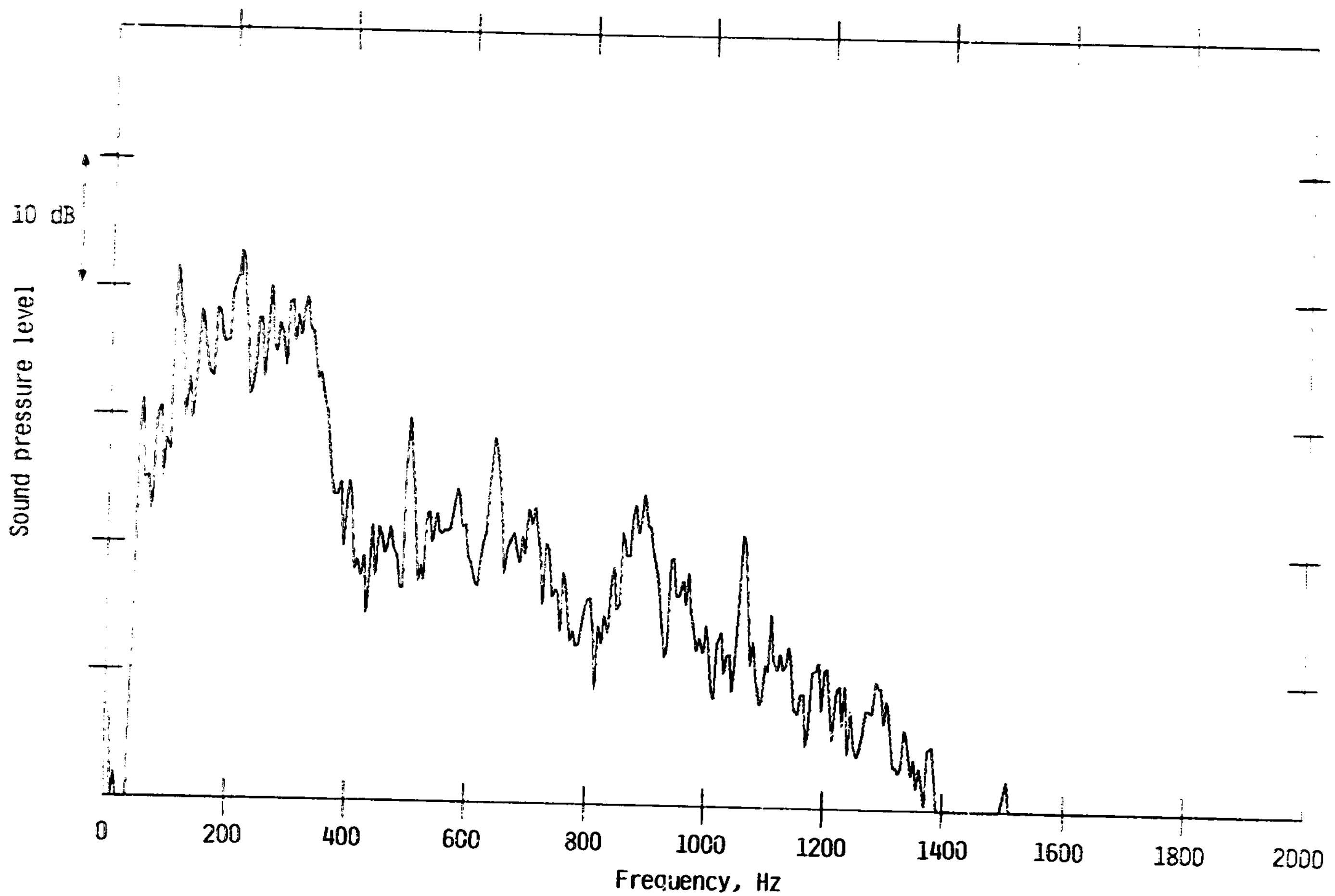

Figure 6.- Interior noise spectrum shape used in helicopter example.

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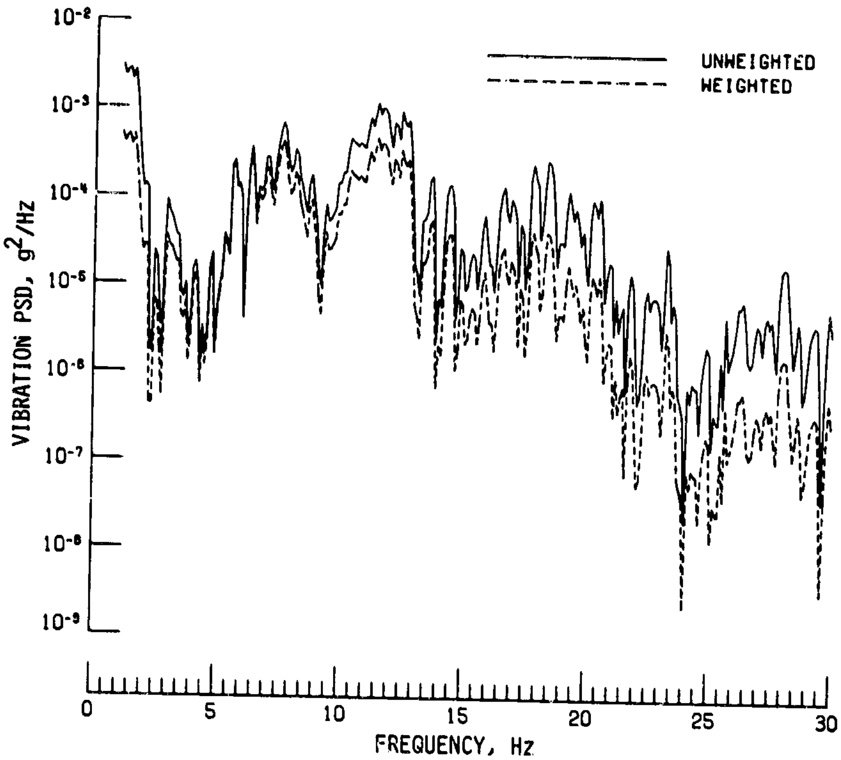

(a) Vertical axis.

Figure 7.- Weighted and unweighted vibration spectra for the automobile example.

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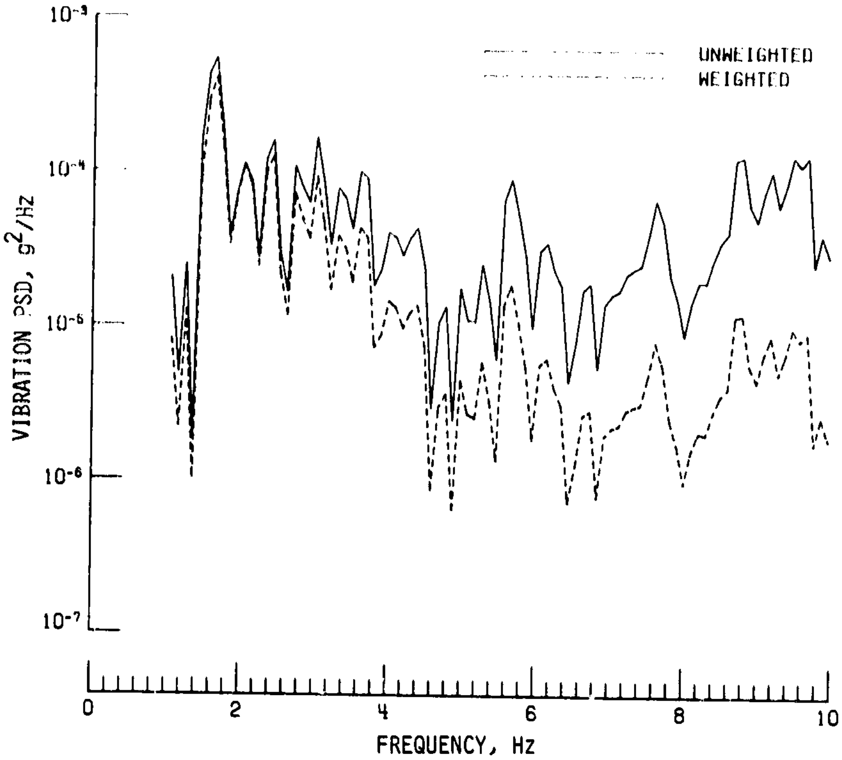
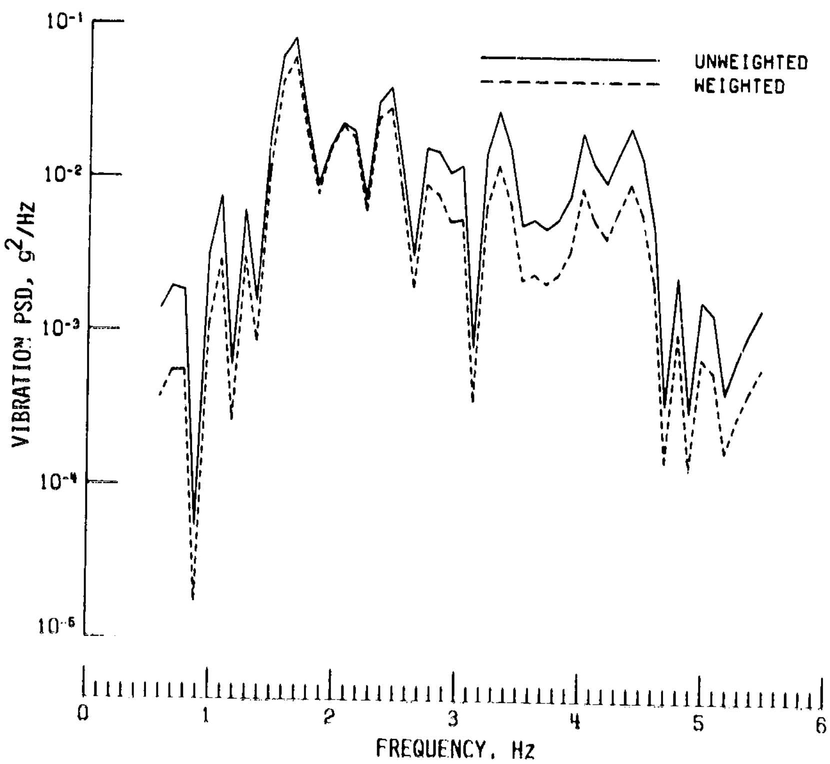


(b) Lateral axis.



(c) Roll axis.

Figure 7.- Concluded.