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REVIEW OF MEASURED VIBRATION AND NOISE ENVIRONMENTS EXPERIENCED BY  
PASSENGERS IN AIRCRAFT AND IN GROUND TRANSPORTATION SYSTEMS

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SUMMARY

Measured vibration and interior noise data are presented for a number of air and surface vehicles. Consideration is given to the importance of direction effects; of vehicle operations such as take-off, cruise, and landing; and of measurement location on the level and frequency of the measurements. Various physical measurement units or descriptors are used to quantify and compare the data. Results suggest the range of vibration and noise associated with a particular mode of transportation and illustrate the comparative levels in terms of each of the descriptors. Collectively, the results form a data base which may be useful in assessing the ride of existing or future systems relative to vehicles in current operation.

INTRODUCTION

The vibration and interior noise environments of current and future vehicles are important to the ride quality and passenger acceptance of the transportation system. To fully evaluate the influence of vibration and noise on ride quality and passenger acceptance, the dynamic characteristics of the vehicle environment as well as the response of passengers to these stimuli must be well understood. Furthermore, such an understanding of the environment and its effects is essential to the development of ride-quality and passenger-acceptance criteria and the development of ride-improvement technology.

Numerous studies have been conducted in which the environment and/or the passenger response have been examined (refs. 1 to 6). However, very few studies have been conducted in which both the environment and the passenger response have been simultaneously measured over a wide range of environmental conditions. As a consequence, a comprehensive understanding of the effects of vibration on comfort does not exist. In particular, methods for assessing the combined effects of vibration level, duration, frequency, noise, and seat dynamics of the type encountered in transportation systems are not well understood. This lack of understanding has hindered the development and acceptance of descriptors for characterizing the environment of vehicles and the subsequent development of a comprehensive data base for current vehicle systems.

Measured vibration and interior noise data are presented herein for a variety of operational vehicles. The purpose of this presentation is to illustrate some of the important considerations and factors in quantifying the environment and also to provide comparative data for a variety of air and surface vehicles in terms of several physical descriptors.

## VIBRATION AND NOISE MEASUREMENTS

### Research Programs

The data presented in the following sections were collected in conjunction with research programs being conducted at the Langley Research Center in the areas of ride quality and aircraft interior noise. Although these programs are closely related, the ride-quality program (ref. 7) has emphasized the vibration environment of air and surface transportation systems and the influence of vibrations on passenger acceptance. The interior noise program is a relatively new program at Langley and includes both objective and subjective studies of the noise levels within vehicles as well as interior noise prediction and noise control. As mentioned, these programs have many common aspects and future ride-quality studies at Langley Research Center will stress combined vibration and noise environments.

Measurements have been obtained on a wide variety of vehicles in the course of these programs. These measurements have been used for purposes such as: vehicle absolute and/or comparative ride assessment; identification of vibration and/or noise sources and paths; identification of external sources of vibration and noise (rail track inputs, for example); evaluation of vibration or noise control fixes; inputs for laboratory studies; and development of criteria. As a result of these studies, a relatively large data base exists which can be used in assessing the ride quality of existing or future transportation systems relative to vehicles in current operation.

### Measurement Methods

Vibration measurements are obtained by using the specially developed portable, battery-operated, instrumentation system shown in figure 1 and described in reference 8. The system consists of one or more acceleration packages, each containing three linear servoaccelerometers to measure vibration in the vertical, lateral, and fore-and-aft directions. The accelerometer data are recorded on a multichannel FM recorder and later digitized for frequency and amplitude analyses using a time series analysis program (ref. 9). The quasi-steady values of acceleration are removed from the recorded signals by passing the data through a high-pass filter which excludes values below 0.1 Hz.

In examining the vibration environment of a vehicle, the acceleration time history for a particular event, the amplitude of the vibration, and the frequency characteristics are of importance. In addition to providing important information for assessing comfort, the acceleration time history and the frequency analyses are often useful in diagnosing the source of the vibration input. For example, the acceleration time history may be used to identify a rough area in the runway whereas the frequency content may provide information on the wavelength of the input or the characteristic response frequencies of the vehicle.

Sound pressure measurements are usually obtained by recording the output of a microphone and a type 1 (precision scientific) sound level meter. The recorded data are subsequently digitized and a time series analysis program is used to obtain both numerical and graphical outputs in terms of octave-band, 1/3-octave-band, and narrow-band analyses.

## RESULTS AND DISCUSSION

Vibration data obtained in the Langley Research Center ride-quality programs are presented for both aircraft and surface vehicles. Selected data are used to illustrate the characteristics of recorded vibration data for a variety of conditions. This is followed by comparative data for several vehicles presented in terms of various physical descriptors to illustrate the character of the descriptors as well as to provide a data base for future use.

Interior noise data include the comparative levels and spectra for several vehicles along with selected data samples to illustrate the unique noise characteristics of certain aircraft being studied. In all cases, the vibration and noise data presented in this paper were obtained from rides described by the test engineer as a normal or average operating condition. Furthermore, the rides of the CTOL aircraft are believed to be quite comfortable.

### Vibration

Measurement considerations.- A great many variables must be considered in measuring the vibratory ride environment of a vehicle, and there are a comparable number of options available for describing the measured results. Certain of these considerations are listed in table I and graphically presented in figure 2 to illustrate the characteristic effects of direction of vibration, range of vibration level, operating condition, and mode of transportation. The level as a function of frequency of the vibration stimuli is presented by means of a power spectral density (PSD) plot. The data were recorded on the floor of the vehicle near the center of gravity and the PSD results were obtained from selected samples of the ride having a sample duration of approximately 2 minutes. The aircraft was a CTOL aircraft having three fuselage-mounted jet engines. Figure 2(a) presents typical vertical and lateral PSD functions during cruise operation. The levels of the selected

PSD's (2-minute sample) represent the maximum values observed during a normal flight of the aircraft. The general vibratory response of the aircraft is seen to be similar in both the vertical and lateral directions, with the highest levels of vibration occurring in the vertical direction. The vibratory energy is concentrated at frequencies less than 4 Hz. The range of vibration levels encountered during a typical flight of this aircraft is shown in figure 2(b) for the vertical direction. The frequency characteristics are similar except at the low end of the frequency range. In the smooth case, a relatively larger portion of the energy occurs at frequencies below 1 Hz. For the PSD's shown, the rms values of acceleration differ by a factor of about 4 and are discussed in more detail in subsequent sections. Figure 2(c) illustrates the difference in frequency response which results from differences in vehicle operation. As shown, the landing produces higher levels of vibration as well as frequency characteristics which are quite different from those for cruise. The high frequency response during landing is attributed to landing-gear-vehicle interactions. The response of the aircraft on the ground is not unlike that of many surface vehicles. As can be seen in figure 2(d), there is a significant difference between the response of the CTOL aircraft in cruise and that of an automobile; however, there are similarities between the aircraft during landing and the automobile. The automobile has considerable energy between 10 and 20 Hz due to wheel hop and response of the structure. The energy at approximately 1 Hz results from the fundamental suspension tuning and is typical of most surface vehicles. More detailed information for air and surface vehicle vibration level is presented in the next section.

Comparative vibration data.- In an effort to provide a comparative data base for future use as well as to provide insight into some of the vibration units, measured data are presented for a variety of vehicles and physical descriptors. Among the suggested units for describing the vibration associated with a particular vehicle, the following descriptors are of interest and were selected for this study:

- $g_p$  the maximum amplitude of vibratory acceleration associated with a selected time history
- $g_{rms}$  the overall root-mean-square value of acceleration for a selected frequency band (0.1 to 30 Hz or 1/3 octave for this study)
- $g_{\%10}$  the level of vibratory acceleration that is exceeded 10 percent of the time
- $g_w$  the root-mean-square value of the acceleration resulting from an acceleration signal that is weighted or filtered to better reflect human response to vibration

The values of these descriptors may in some cases vary depending upon the time duration of the measurement sample. As previously noted, all data were obtained from samples having a duration of approximately 2 minutes.

The levels presented represent the range of maximum values recorded during several normal operations. The weighted values  $g_w$  were obtained by filtering the data as recommended by the International Standards Organization (ISO) to reflect recommended equal comfort contours (ref. 10).

Comparative data obtained on a number of vehicles during cruise are presented in figures 3 and 4 in terms of the various descriptors. The vehicles are ranked according to the maximum level of vertical acceleration. The range of  $g_p$  observed in examining numerous 2-minute data samples for each of the vehicles is presented in figure 3(a). A comparison of the various vehicles suggests that the maximum values of  $g_p$  cover a range of about 3 to 1 ( $0.5g > g_p > 0.15g$ ) in the vertical direction. In general, the vertical levels are higher than the lateral levels and the ground vehicles have higher acceleration than the aircraft. A similar trend is noted in terms of  $g_{rms}$  (fig. 3(b)). Again, the maximum values of  $g_{rms}$  cover a range of about 3 to 1 in the vertical direction. In terms of  $g_{\ell 10}$  (fig. 3(c)), the vehicle ranking, with the exception of the helicopter, is identical to that obtained with  $g_{rms}$ . The relatively high values of  $g_{\ell 10}$  associated with the helicopter are due to discrete frequency vibration observed at the blade passage frequency.

The vehicle vibration data are presented in figure 3(d) and figure 4 in terms of descriptors which reflect both the amplitude and the frequency of the vibration. In figure 3(d), for example, the acceleration is weighted according to the ISO equal comfort contours (ref. 10). Data are presented for the vertical direction only. It is noted that the values of  $g_w$  are lower than the values of  $g_{rms}$  (unweighted) in figure 3(b) as would be expected; however, the vehicle ranking remains approximately the same. These findings are further amplified in figure 4 in which 1/3-octave-band data are presented for the surface vehicles and aircraft and are compared with the ISO 4-hour reduced comfort boundaries. The 1/3-octave amplitude-frequency distribution provides a clear picture of the vibratory frequency which is useful in determining the source of vibration.

In considering the various descriptors, the single units such as  $g_p$ ,  $g_{rms}$ ,  $g_{\ell 10}$ , and  $g_w$  all appear to provide a simple, relatively consistent or similar description of the ride and may be adequate for assessing ride quality in many applications. The selection of a preferred descriptor will depend upon the specific application as well as upon the development of more information on subjective response to vibration. For example,  $g_p$  may be preferred for examining aircraft landing vibration whereas  $g_w$  may be preferred for examining longer term cruise conditions. For examining the source of vibration, the narrow-band analyses such as PSD or the 1/3-octave analyses are useful. Although the data presented in figures 3 and 4 do not represent a large sample for certain vehicles, collectively the data are believed to be consistent and to represent a relatively large data base in comparison to previously published data on vehicle vibration. The data may be used for a comparative assessment of the ride quality of a particular vehicle of interest relative to the vehicles presented herein or in specifying design criteria for future systems in terms of currently acceptable vehicles.

In an effort to develop a statistically larger data base, measurements have been taken on two different CTOL aircraft during a total of 13 flights including taxi, climb to altitude, cruise, and landing. These data are presented in reference 11 and are summarized in figure 5. The vibration behavior of the two aircraft are very similar. As would be expected, the best ride occurs during cruise. Furthermore, the vibration levels in the vertical direction are seen to exceed the lateral levels by a factor of about 5 during cruise and of somewhat less than 5 during ground operations. As previously indicated, figure 5 represents a relatively large data base obtained from vehicles which are believed to be good riding, acceptable transportation systems.

Seat/passenger response.- The physical data presented in the previous sections have been obtained on the floor of the vehicle. In order to have a better understanding of how the measurements taken at the floor of the vehicle compare with the levels actually experienced by the passenger, simulator studies have been conducted (ref. 12) to determine the transmissibility of various seats. Tourist-class and first-class aircraft seats and bus seats were examined with seated passengers for single-axis sinusoidal inputs in the vertical and lateral directions. The acceleration measured at the seat/passenger interface is shown in figure 6 in terms of the amplitude response ratio (ratio of seat acceleration to floor acceleration) for a range of sinusoidal input frequencies. As noted, the resonant frequency in the vertical direction is in the range of 4 to 7 Hz with a maximum amplification of about 1.4. For lateral inputs, an amplification of about 1.5 is observed in the frequency range of 2 to 3 Hz. By coincidence, the area of greatest human sensitivity, according to the ISO standards, also occurs in these regions, as shown in the figure. The importance of considering seat transmissibility in the development of ride-quality criteria is currently under study in a simulator program wherein subjective ride-quality measurements are being compared with both seat and floor measurements.

In concluding this section on vibration, it is again noted that a data base does exist for a variety of vehicles in terms of several descriptors. However, the "best" descriptor (if such exists) as well as ways to compare the vibrations occurring in different directions will require extensive subjective testing in the laboratory and in the field.

#### Interior Noise

Interior noise spectra are presented in figure 7 for several aircraft and an automobile. As in the case of vibration, the vehicle noise spectra are dependent upon many factors such as vehicle type and operating condition; however, the selected spectra are believed to be representative in terms of relative amplitude and frequency for the particular class of vehicle. As shown, the interior noises of the aircraft are higher than those of the automobile and the noise levels of the STOL, helicopter, and general aviation vehicles are generally considered to be uncomfortable by most observers. These three vehicles have, in addition to the high levels, relatively low frequency characteristics which make noise control difficult.

The sources and detailed characteristics of the interior noise for the CTOL, general aviation, STOL, and helicopter are quite different. The boundary layer is an important noise source in the case of CTOL, whereas, it is relatively small in the other vehicles. The main sources in general aviation vehicles are the propeller and reciprocating engine, whereas the helicopter has, in addition to the rotor, a number of discrete inputs associated with gear clash in the transmissions. The STOL (powered-lift) levels are estimated to be high because of the impingement of the engine exhaust on the listing surfaces and the inboard location of the engines. These and other details are shown in figures 8 to 11.

The CTOL spectra are shown in figure 8 for three locations in a jet transport having fuselage-mounted engines. The highest levels are recorded at the aft cabin location in the proximity of the engines. At the pilot location, the noise is higher in frequency and is attributed to the boundary layer. Measured levels for a single-engine, light aircraft (ref. 13) are shown in figure 9 for several values of rpm and indicated airspeed (IAS). Note that an increase in rpm results in an increase in the dB(A) level but a decrease in the overall sound pressure level (OASPL). This results from the shift in frequency (crossover) and the frequency weighting in the dB(A) unit. As shown in figure 10, the STOL levels (ref. 14) are highly dependent on the operating condition. The externally-blown-flap (EBF) configuration has high levels during powered lift but lower levels during cruise, where powered lift is not required. If powered lift is utilized during cruise of the upper-surface-blowing (USB) configuration, the levels would be relatively higher than those of the EBF configuration as shown. The helicopter data of figure 11 were obtained on the Langley Research Center Civil Helicopter Research Aircraft (ref. 15) during hover and with an untreated cabin. These data show that the main noise source occurs at approximately 1370 Hz which corresponds to first-stage planetary gear clash in the main gear box. The peak amplitude at 1370 Hz is at least 10 dB above all other peaks in the spectrum, which indicates that for this flight condition the other sources of interior noise do not significantly contribute to the overall noise level.

Two other frequencies are emphasized in the figure. The tail rotor-blade passage frequency occurs at approximately 53 Hz; main bevel and tail take-off gear clash occurs at approximately 2700 Hz. The acceleration PSD also has peak amplitudes in the spectrum at 1370 Hz and 2700 Hz, which suggests that some relationship exists between noise and structural vibration at these frequencies.

For comparative purposes, the A-weighted interior noise levels for the aircraft are presented in figure 12 along with levels for bus, rail, and auto vehicles and the OSHA 8-hour limit of 90 dB(A). The data shown were obtained from references 6 and 13 to 21. Again, these data emphasize the fact that aircraft levels are considerably higher than those of the surface vehicles. Furthermore, the fact that several of the aircraft exceed the OSHA 8-hour limit suggests that better noise control is needed. The interior noise program currently underway at Langley will emphasize the noise reduction of STOL, helicopter, and general aviation vehicles as well as the establishment of acceptable levels (criteria) of interior noise for the safety and comfort of crew and passengers. Safety considerations will include speech intelligibility

and auditory effects, whereas the comfort studies will emphasize passenger acceptability and speech interference.

#### CONCLUDING REMARKS

Measured vibration and interior noise data are presented for a number of air and surface vehicles. In comparing air and surface vehicle environments, the vibration levels are relatively high in the ground vehicles and the noise levels are relatively high in the aircraft. For a particular vehicle, large variations in level are observed throughout the operating envelope of the system due to external effects (turbulence, for example) as well as the effects of vehicle operation and measurement location. The aircraft vibration and noise data base appears to be larger than that of the surface vehicles. However, when taken collectively the measurements form a data base which may be used in assessing the ride of existing or future systems relative to vehicles in current operation.



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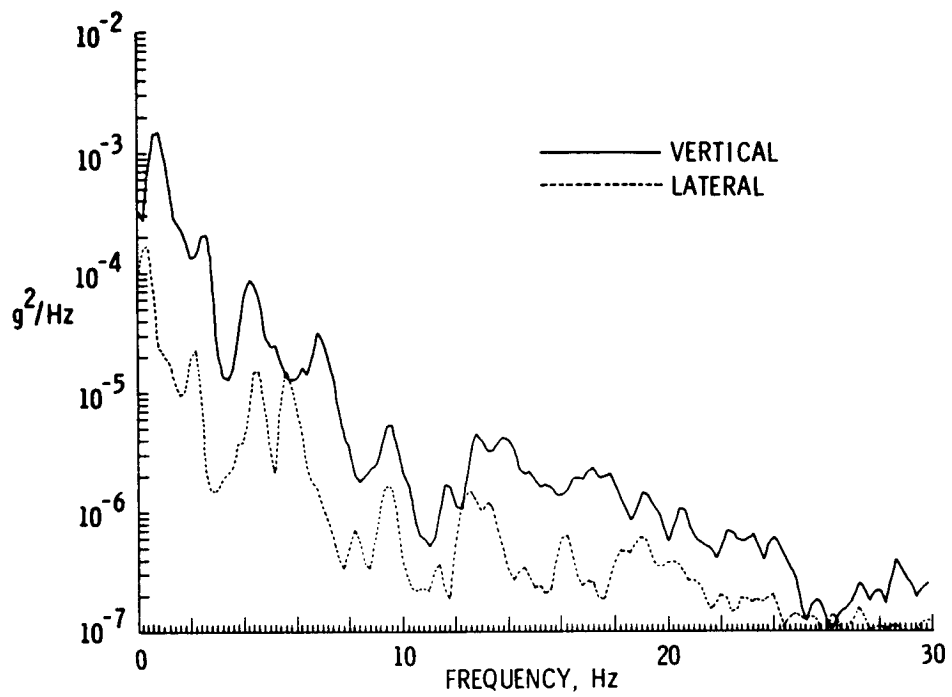
TABLE I.- DESCRIPTION OF RIDE ENVIRONMENT

MEASUREMENT CONSIDERATION	EXAMPLE
STIMULI	LEVEL, FREQUENCY, TIME
DIRECTION	VERTICAL, LATERAL, COMBINED
RANGE	SMOOTH, ROUGH
OPERATION	TAKE-OFF, CRUISE, LANDING
MODE	AIR, GROUND
DESCRIPTOR	PSD, 1/3-OCTAVE, g, dB
LOCATION	FLOOR, SEAT, FORE/AFT

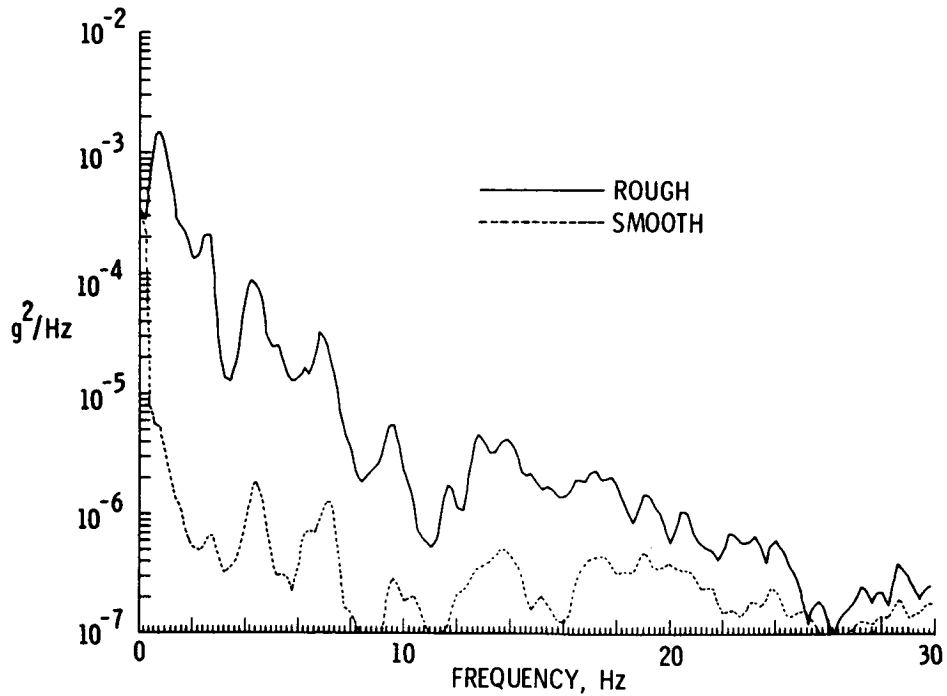


Figure 1.- Vibration measuring and recording system.

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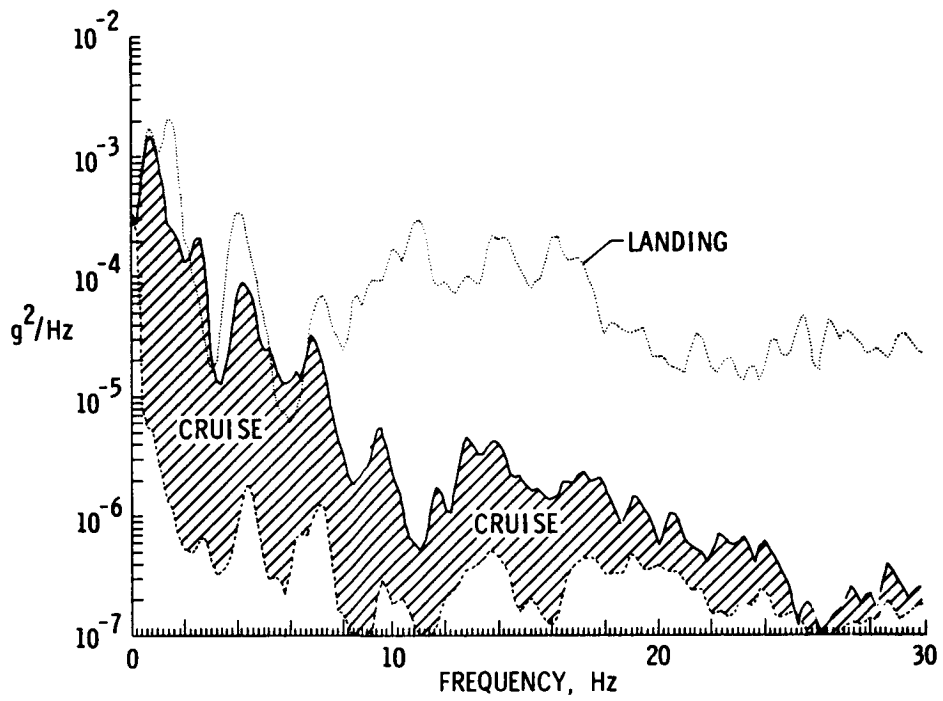


(a) Direction effects for CTOL aircraft in cruise.

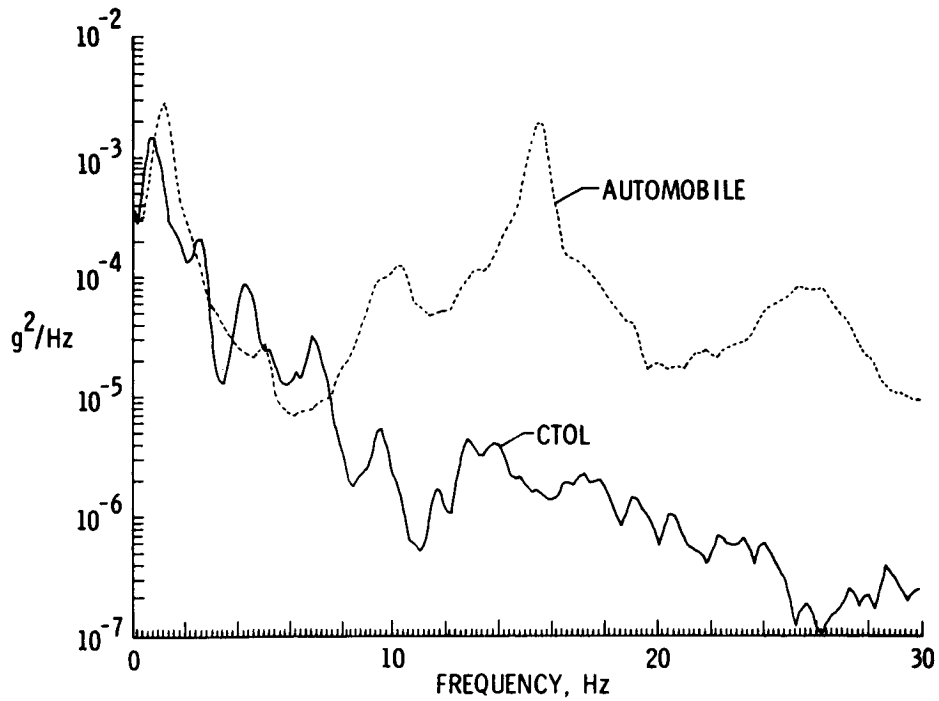


(b) Range of vibration in vertical direction for CTOL aircraft in cruise.

Figure 2.- Considerations for measuring and describing vibratory ride environments.

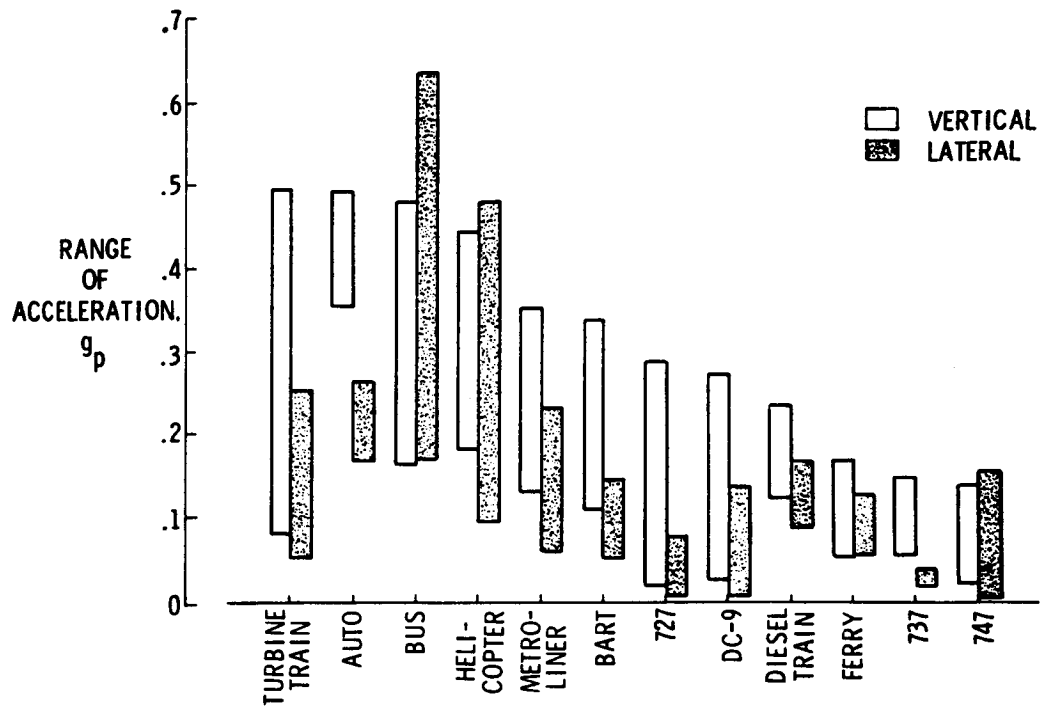


(c) Effects of vehicle operating condition on vertical vibration for CTOL aircraft.

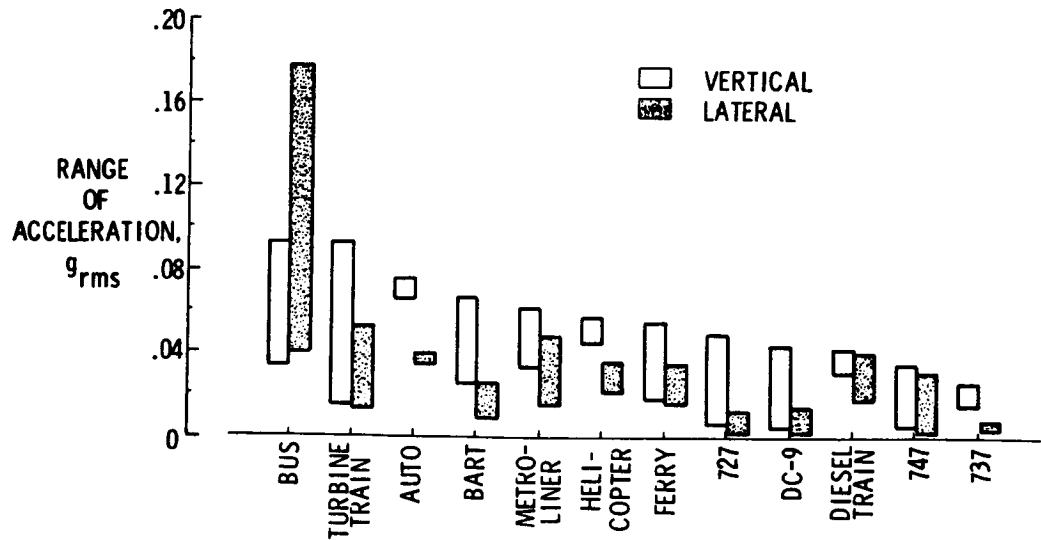


(d) Effects of mode of transportation on vertical vibration in cruise.

Figure 2.- Concluded.

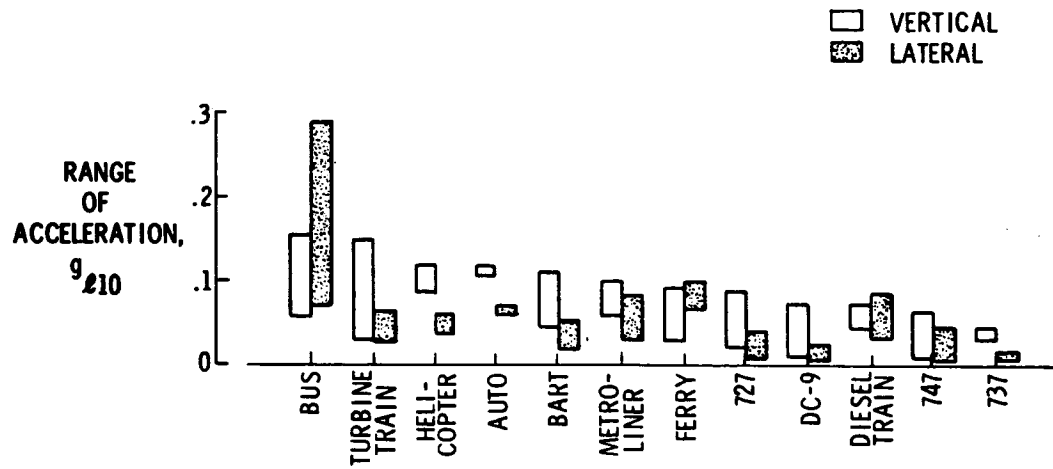


(a) Peak acceleration range.

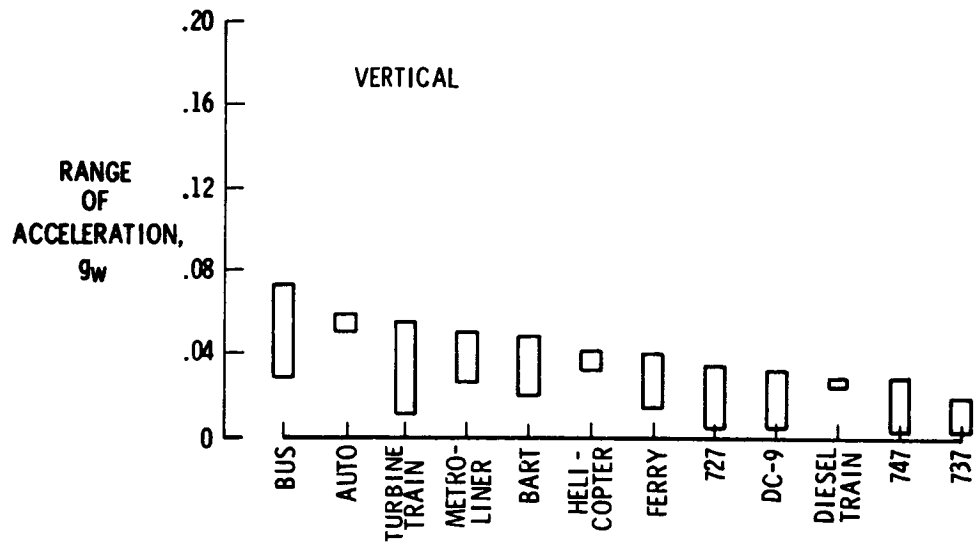


(b) RMS acceleration range.

Figure 3.- Vibration levels recorded during cruise.

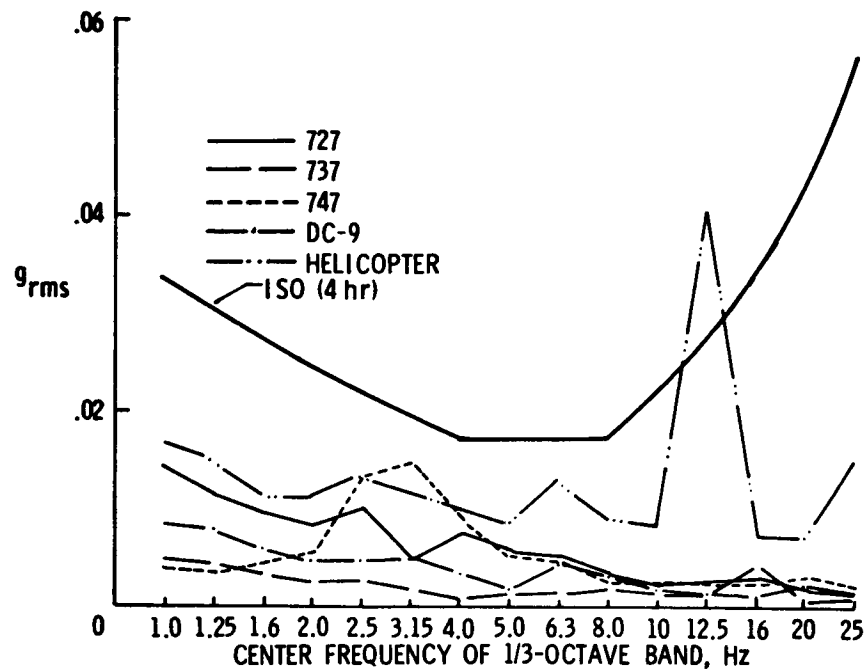


(c) Level exceeded 10 percent of time.

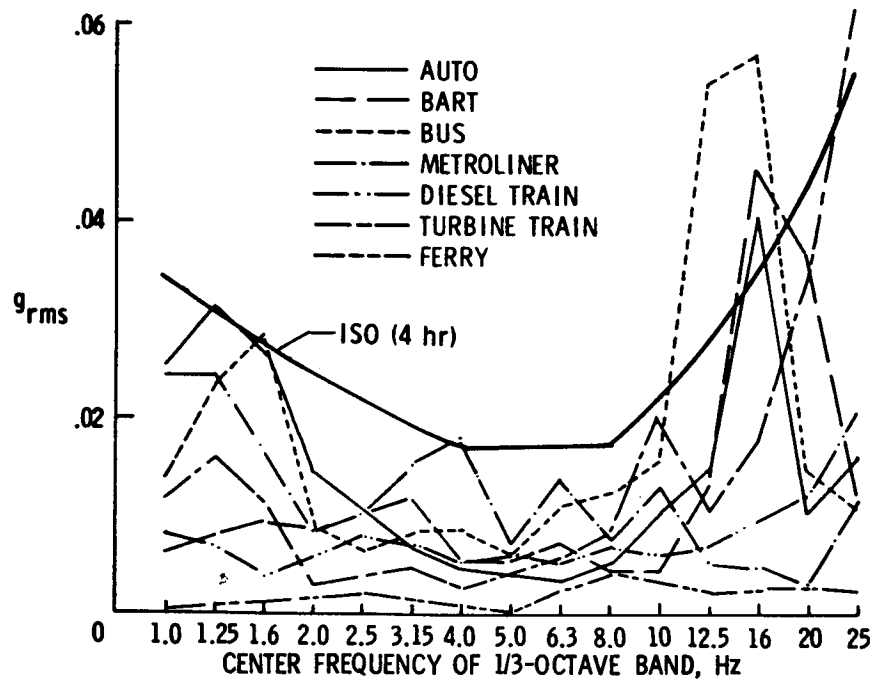


(d) ISO weighted RMS acceleration.

Figure 3.- Concluded.



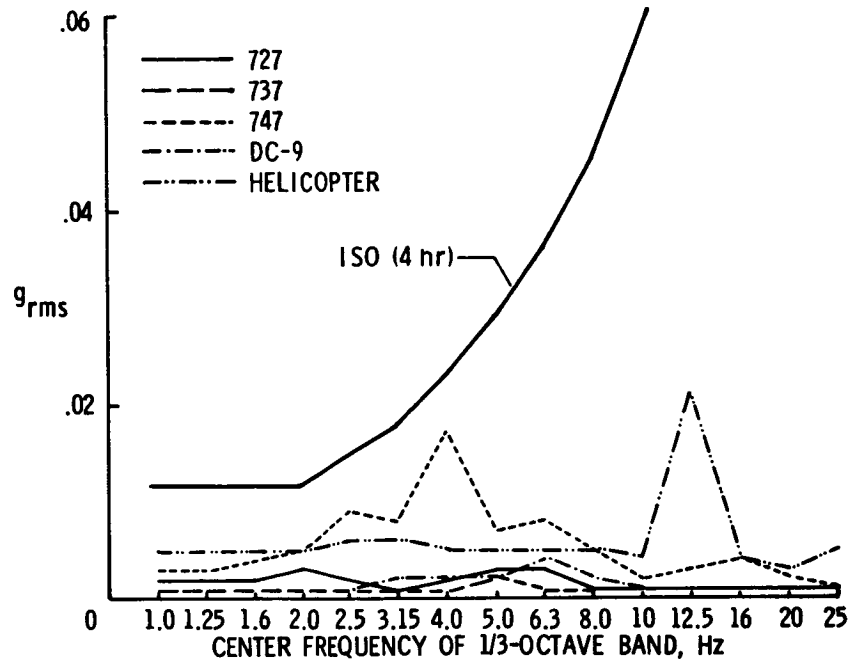
(a) Vertical response for aircraft.



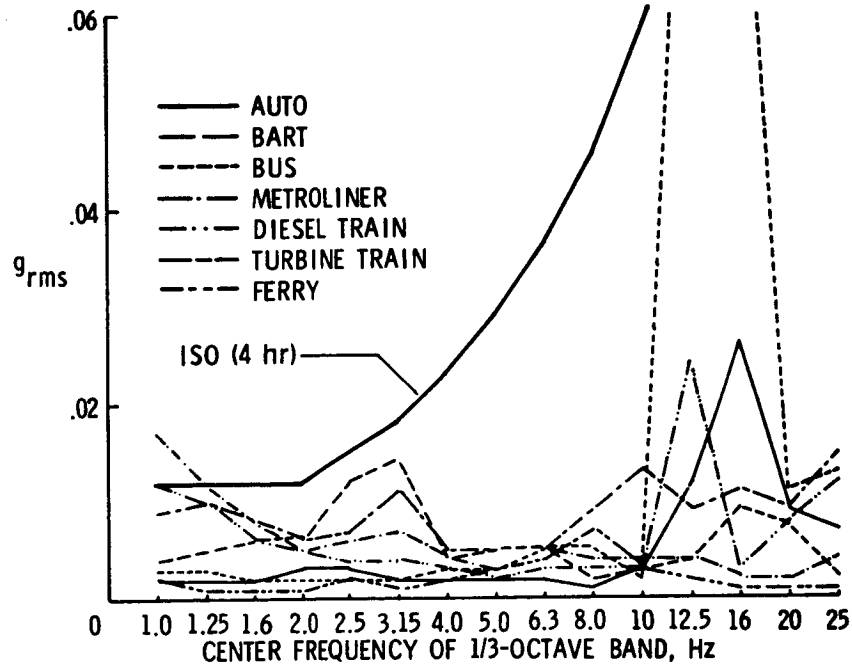
(b) Vertical response for surface vehicles.

Figure 4.- One-third-octave-band spectra recorded during cruise.





(c) Lateral response for aircraft.



(d) Lateral response for surface vehicles.

Figure 4.- Concluded.

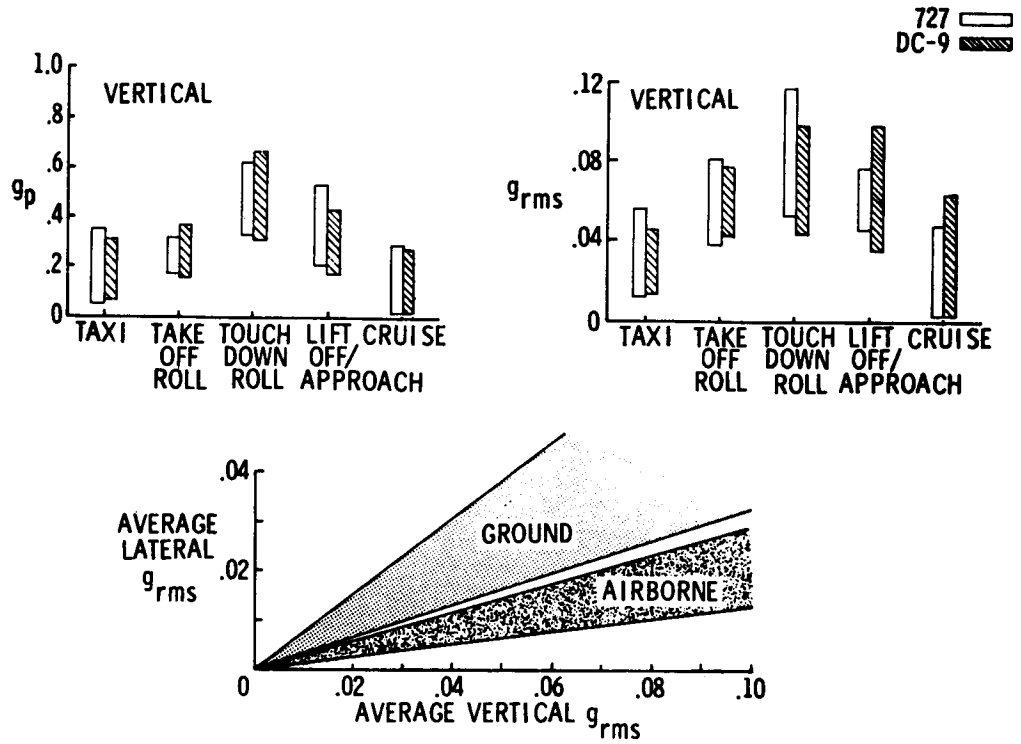


Figure 5.- CTOL vibration data base.

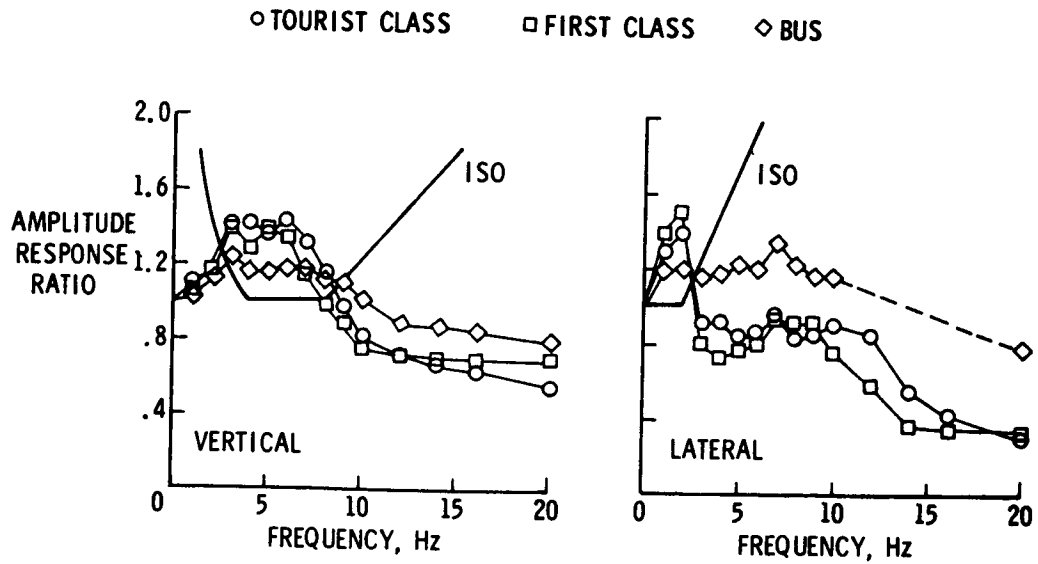


Figure 6.- Seat transmissibility.

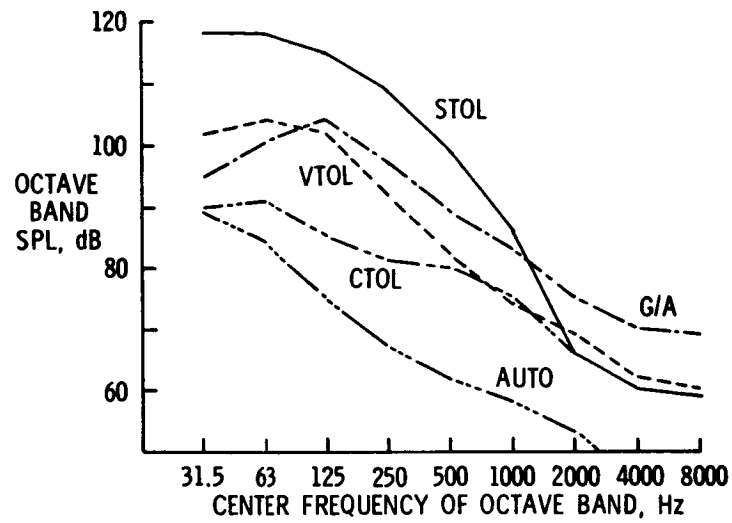


Figure 7.- Interior noise spectra for selected vehicles during cruise.

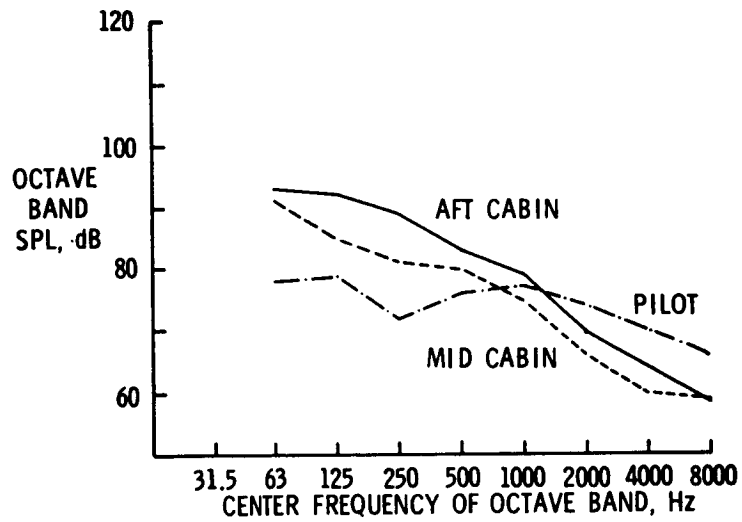


Figure 8.- Effects of measurement location on recorded CTOL noise during cruise.

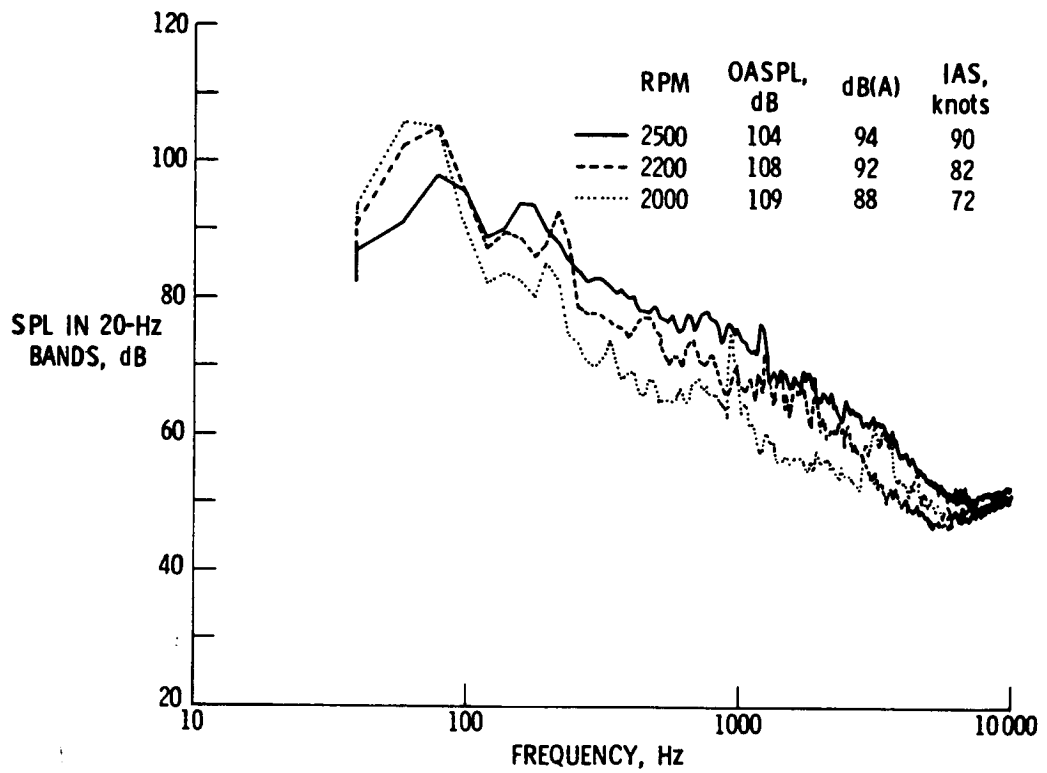


Figure 9.- General-aviation interior noise characteristics for single-engine aircraft cruising at 305 meters.

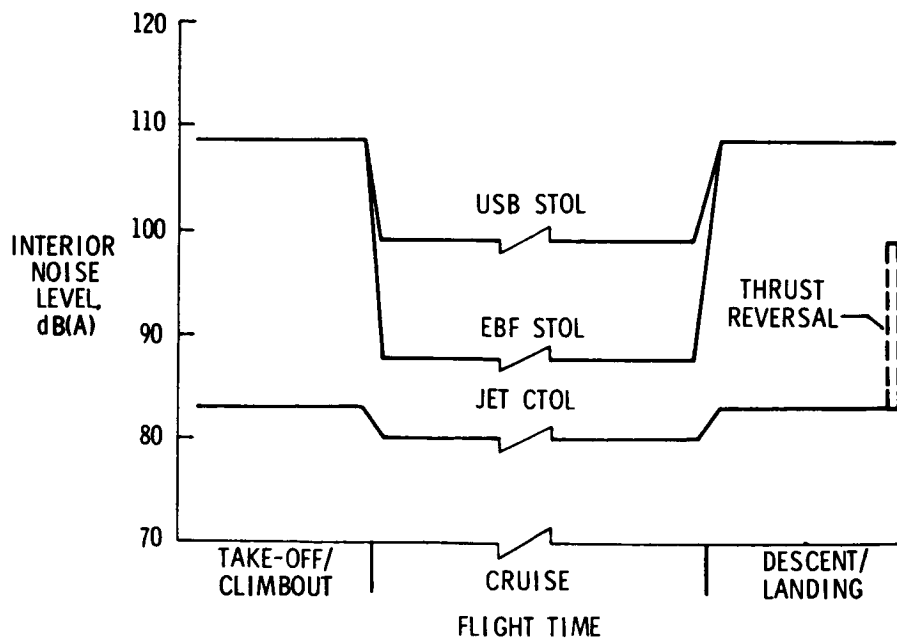


Figure 10.- STOL interior noise characteristics.

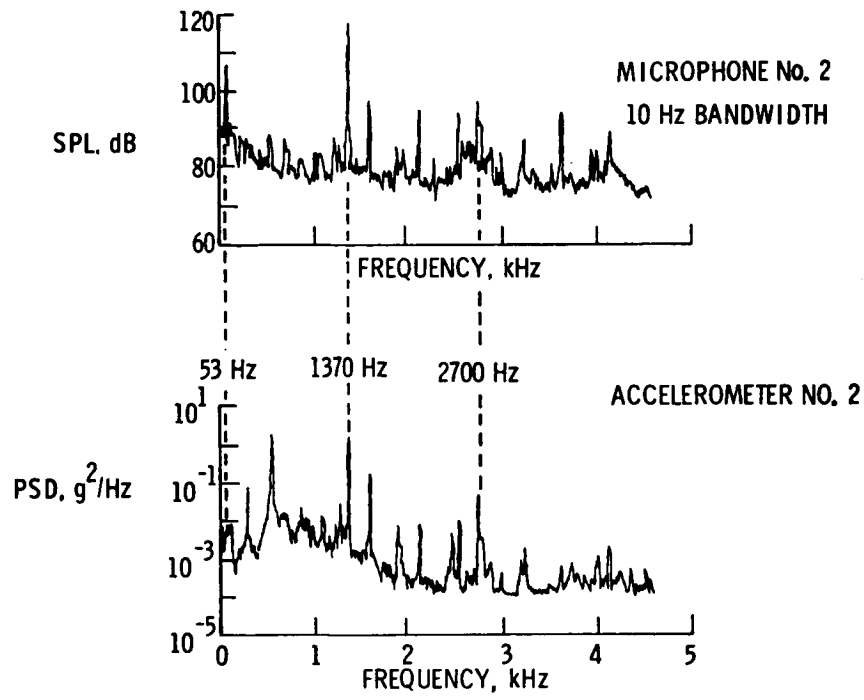


Figure 11.- Interior noise and acceleration for untreated helicopter during hover out of ground effect.

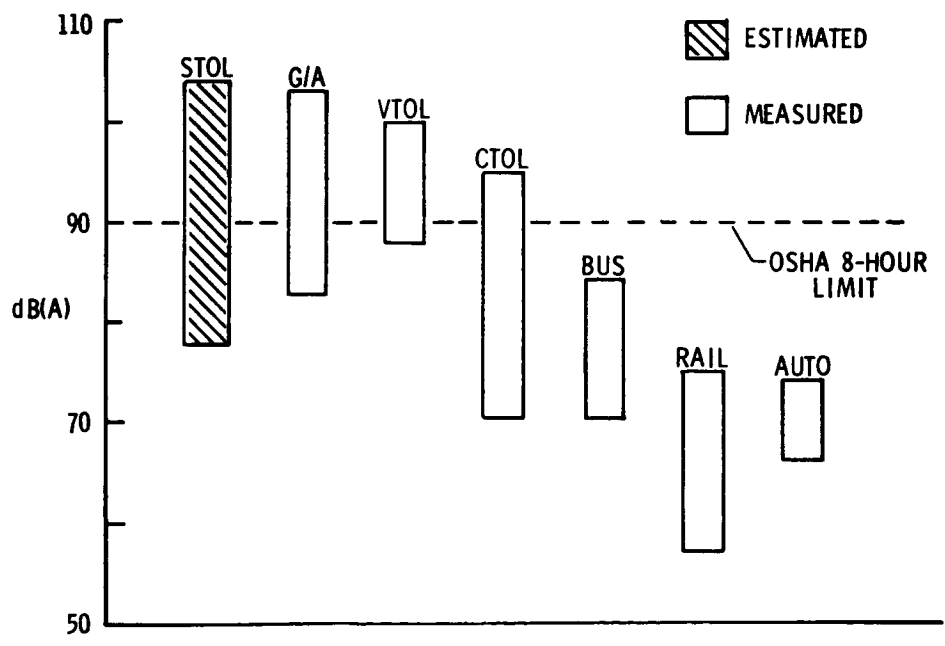


Figure 12.- Comparative interior noise levels during cruise.