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PHYSICAL AND SUBJECTIVE STUDIES OF AIRCRAFT INTERIOR NOISE AND VIBRATION

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ACCEPTANCE AND CONTROL OF AIRCRAFT INTERIOR NOISE AND VIBRATION

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1. INTRODUCTION

Assuming that the interior environment of current and future helicopters will be important to the passenger acceptance of these vehicles, the noise control engineer will be faced with a challenge in reducing the helicopter noise and vibration levels to values comparable with other forms of transportation. As can be seen on figure 1 which represents a compilation of levels recorded on a number of air and surface vehicles, helicopter levels are relatively high in terms of both noise and vibration (reference 1). Technology advancements in the area of acceptance criteria and noise/vibration control will undoubtedly be required to effectively solve the unique passenger environmental problems of helicopters and, in particular, the interactive effects of noise and vibration.

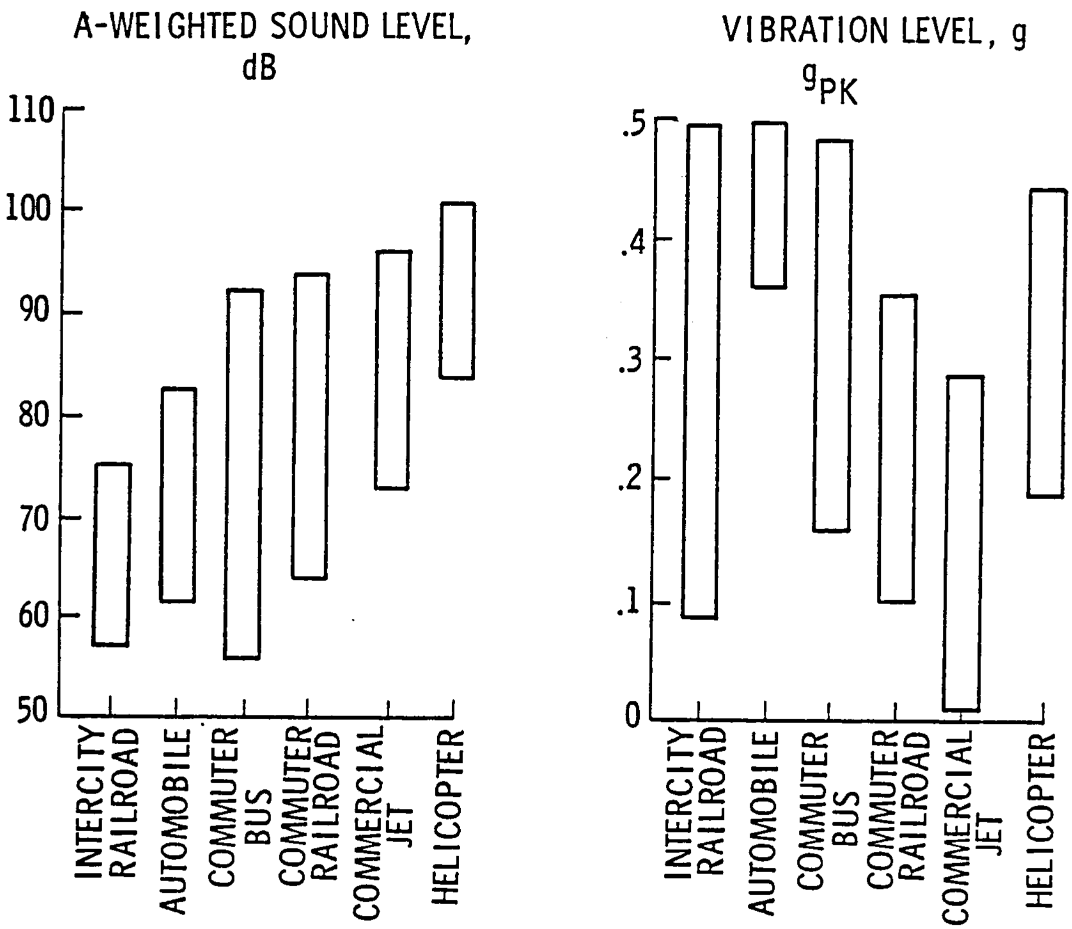

FIG 1 NOISE AND VIBRATION LEVELS FOR VARIOUS VEHICLES

The passenger acceptance of aircraft interior noise and vibration as well as the control of the interior levels are being studied at the Langley Research Center (LRC) as part of the NASA program in aircraft acoustics and noise reduction. Measurements to define and quantify the interior noise and vibration stimuli of

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aircraft (reference 1), field and simulator studies to determine the subjective response to such stimuli (reference 2), and theoretical and experimental studies to predict and control the interior environment (references 3 and 4) are being conducted. The purpose of this paper is to discuss ride quality criteria for noise, vibration, and combinations of these stimuli in relation to the helicopter cabin environment. Data from the LRC ride quality simulator on passenger response are presented to illustrate the effects of interior noise and vibration on comfort for conditions of reverie and communication. Furthermore, the interactive effects of noise with multifrequency and multiaxis vibration are illustrated by data from the ride quality program. With respect to aircraft interior noise and vibration control, ongoing studies to define the near-field noise, the transmission of noise through structures, and the effectiveness of control treatments are described.

2. PASSENGER ACCEPTANCE

Subjective response to noise and/or vibration is being studied both in the laboratory and in the field. In general, the laboratory studies examine the details of the environmental stimuli which cause adverse response whereas the field studies concentrate on understanding the integrated effects of noise and other environmental factors on passenger acceptability. Approximately 2,500 test subjects have participated in the NASA-LRC program to date. The principal laboratory tool used in this research is the three-degree-of-freedom motion simulator shown in figure 2. This simulator is configured to resemble the interior of a modern jet transport and can be fitted with six tourist-class aircraft seats (as illustrated) or four first-class seats (reference 5). Noise is simulated by an array of 12 speakers; 2 of which are located in the fore and aft bulkheads, 6 above the luggage racks and 4 under the seats. Four additional overhead speakers are available for voice communication and listening tasks. Vibratory motions in either single or multiple axes (vertical/lateral/roll; vertical/longitudinal/pitch) are provided by servocontrolled hydraulic actuators which are programed with either field-recorded tapes or signal-generating equipment (oscillators, noise generators). The vibratory response of the simulator covers the frequency range of 0 to 30 Hz with acceleration amplitudes up to $0.50g_{peak}$ (limited by man-rating considerations).

FIG 2 NASA RIDE QUALITY SIMULATOR

The following subsections contain selected research results which are the basis for a ride comfort model that accounts for the effects of multifrequency and multiaxis vibration inputs as well as the effects of vehicle interior noise.

2.1 Interior noise.
Several studies (references 6 through 8) have examined the effects of aircraft interior noise on passenger annoyance for conditions under which the subjects were engaged in reverie and/or a speech listening task. The most recent study (reference 9) investigated the effects of helicopter interior noise on annoyance for both reverie and listening situations as well as the relative effectiveness of several metrics (OASPL, dBA, SIL) for predicting annoyance responses for these situations. For the listening task, the subjects were asked to write down phonetically balanced (PB) words that were presented by means of the cabin communication system. Annoyance responses were obtained by use of a nine-point unipolar category scale with the anchor points labeled as "zero annoyance" and "maximum annoyance." The individual noise stimuli were obtained from actual measurements of interior noise levels within a Sikorsky CH-53A helicopter (fig 3). These noises were presented at levels ranging from approximately 70 to 86 dBA with various tonal components (gear clash, for example) selectively amplified or attenuated to give a range of stimuli. Duration of each noise stimulus was approximately 1 minute with an interstimulus interval of about 15 seconds. A total of 24 different noise stimuli were presented under both the reverie and the listening task conditions.

FIG 3 CIVIL HELICOPTER RESEARCH AIRCRAFT

Typical results of the above study are shown by the solid lines in figure 4. These lines represent linear least square fits to the mean annoyance responses as a function of overall sound pressure level (OASPL), A-weighted sound pressure level (dBA), and speech interference level (SIL) for both the listening task and the reverie condition. The annoyance responses obtained under the listening task condition were generally more severe than those obtained under the reverie condition for corresponding interior noise environments and for all three physical descriptors. The "penalty" due to the listening task varied from a maximum of approximately 4.4 dB at the lower noise levels to a maximum of 2.6 dB at the higher noise levels. These values are summarized in Table I which gives the approximate increment (penalty) for each descriptor at low, medium, and high noise levels as well as an average increment across all noise levels.

NOISE DESCRIPTOR	NOISE LEVEL LOW	MEDIUM	HIGH	AVERAGE INCREMENT
OASPL	4.4	3.7	2.6	3.6
dBA	3.1	2.5	1.8	2.5
SIL	4.2	3.0	0.8	2.7

Table I ANNOYANCE INCREMENT IN dB FOR LISTENING TASK

The dashed lines in figure 4 represent the results of an earlier study (reference 7) in which annoyance judgments were obtained from subjects engaged in both a conversational task and under reverie conditions. The agreement between the results of reference 7 and those of the present study is good with respect to both trend and increment due to the task condition. An implication arising from the results of these two studies is that annoyance correction factors which account for the effects of communication interference may be appropriate when predicting passenger annoyance response within an aircraft interior noise environment.

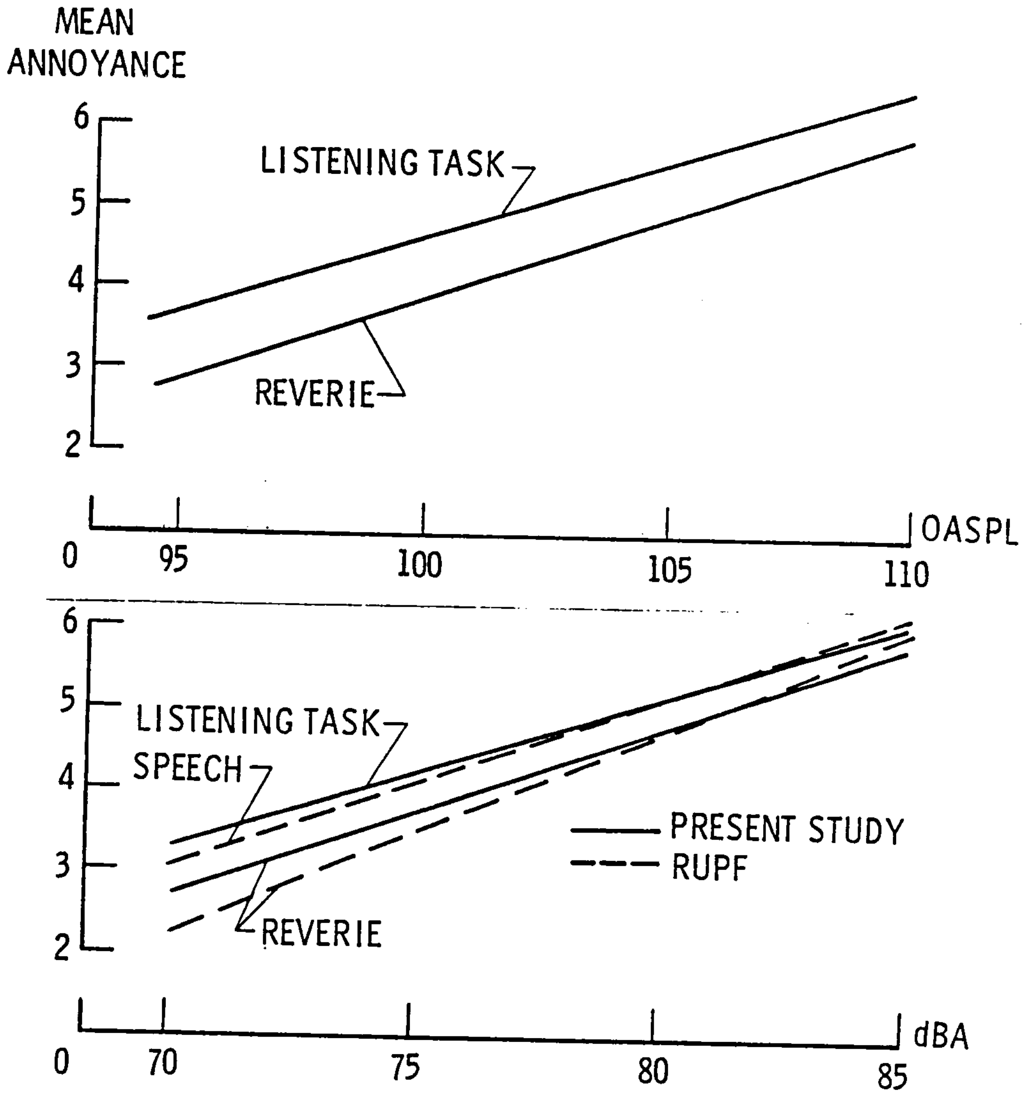

FIG 4 MEAN ANNOYANCE RESPONSE FOR REVERIE AND LISTENING TASK CONDITIONS IN TERMS OF OASPL, dBA, AND SIL

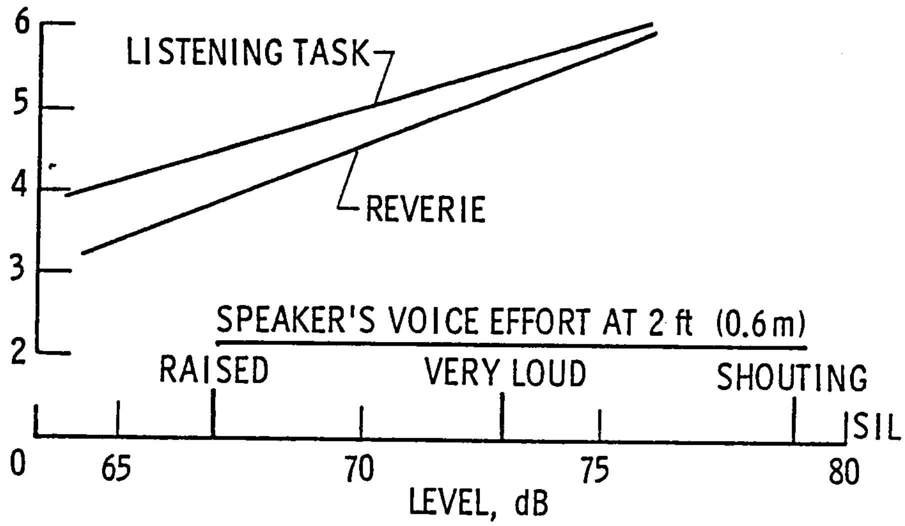

FIG 4 CONCLUDED

Correlation coefficients between mean annoyance response and the level of each physical descriptor for both the listening task and reverie conditions are given in Table II. It is seen that the correlations were highest for the dBA descriptor and generally slightly larger for the reverie condition. Subsequent statistical tests indicated that none of the correlation coefficients for the listening task differed significantly ($p<0.05$) from those for the reverie condition. However, dBA did correlate better ($p<0.05$) with mean annoyance response than OASPL for both the task and reverie conditions and better than SIL for the reverie condition. This implies that, within the context of the present study, dBA was the most appropriate measure for estimating annoyance response in an interior noise environment conducive to producing interruption of communication activities.

NOISE DESCRIPTOR	CONDITION	
	LISTENING TASK	REVERIE
OASPL	0.8514	0.8888
dBA	0.9521	0.9711
SIL	0.9173	0.9333

Table II CORRELATION COEFFICIENTS BETWEEN MEAN ANNOYANCE RESPONSE AND NOISE DESCRIPTOR

2.2 Vibration.

To date, the major emphasis of the research in passenger acceptance has dealt with passenger subjective response to vibration and the development of an appropriate model for use as a design tool. A fundamental step in the development of such a model was the determination of the psychophysical relationships governing human discomfort response to vibratory acceleration. These relationships, which were found to be linear (reference 10), were used to develop sets of constant discomfort curves for each axis of motion (reference 11). These are shown in figure 5 for sinusoidal vertical, lateral, and roll vibrations. The individual curves on each figure represent the acceleration level of sinusoidal vibration required at each frequency to produce a constant level of discomfort. The curves range from a value of one (DISC = 1), corresponding to the threshold of discomfort, to values as high as DISC = 12 which represents a very high level of discomfort. Of particular importance to ride quality design are the psychophysical relationships which define discomfort to vibration as a continuous function of the applied level of vibration and not in a dichotomous manner such as the proposed ISO reduced comfort boundary. Quantification of discomfort due to each axis (vertical, lateral, longitudinal, roll, pitch) as a continuous function of acceleration level has the additional advantage of enabling detailed design trade-off analyses to be made between discomfort and vehicle vibration characteristics. Empirical relationships that can be used in such trade-off analyses have been modeled in detail in reference 11.

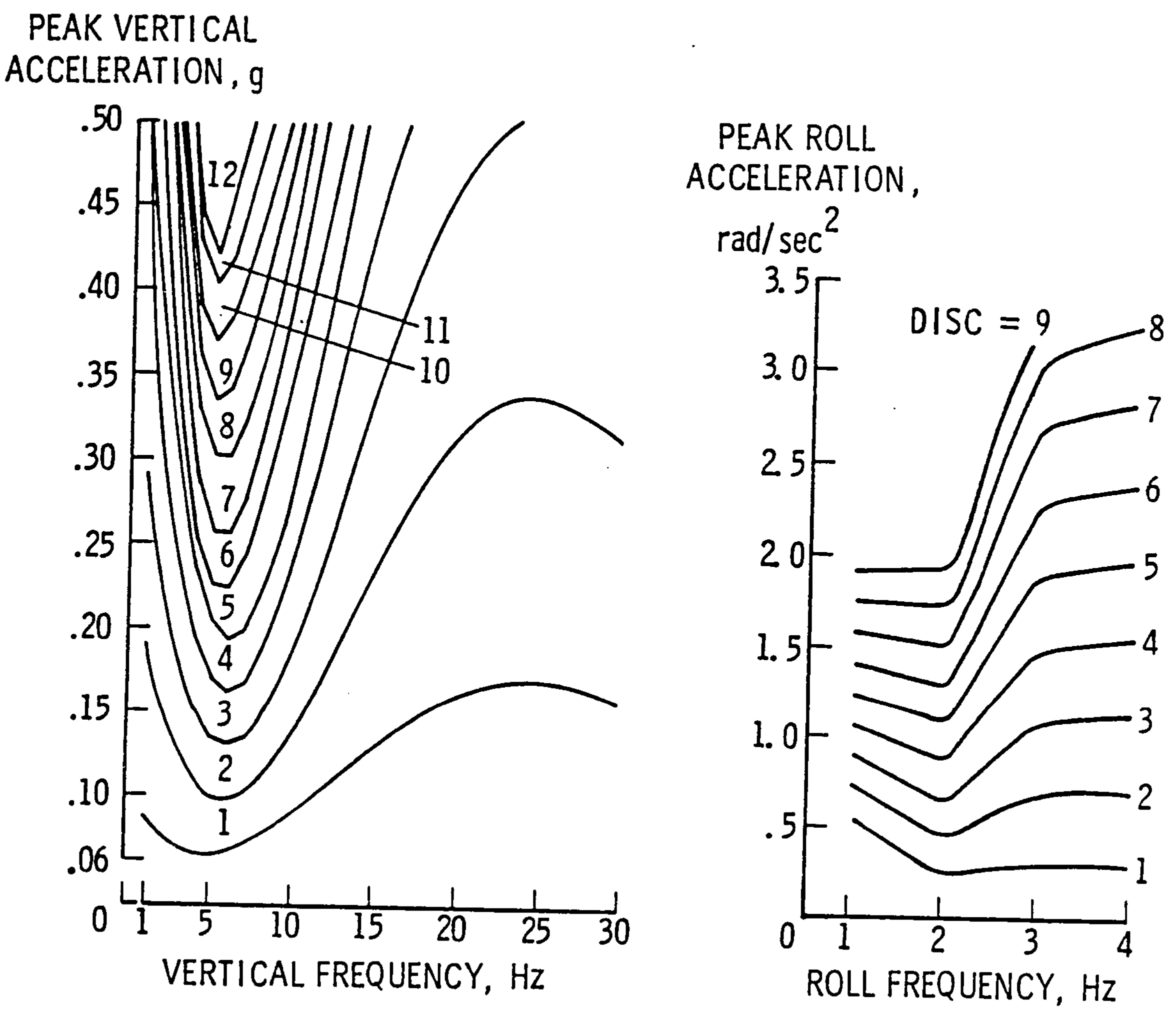

FIG 5 EQUAL DISCOMFORT CONTOURS FOR SINUSOIDAL VERTICAL, LATERAL, AND ROLL VIBRATION

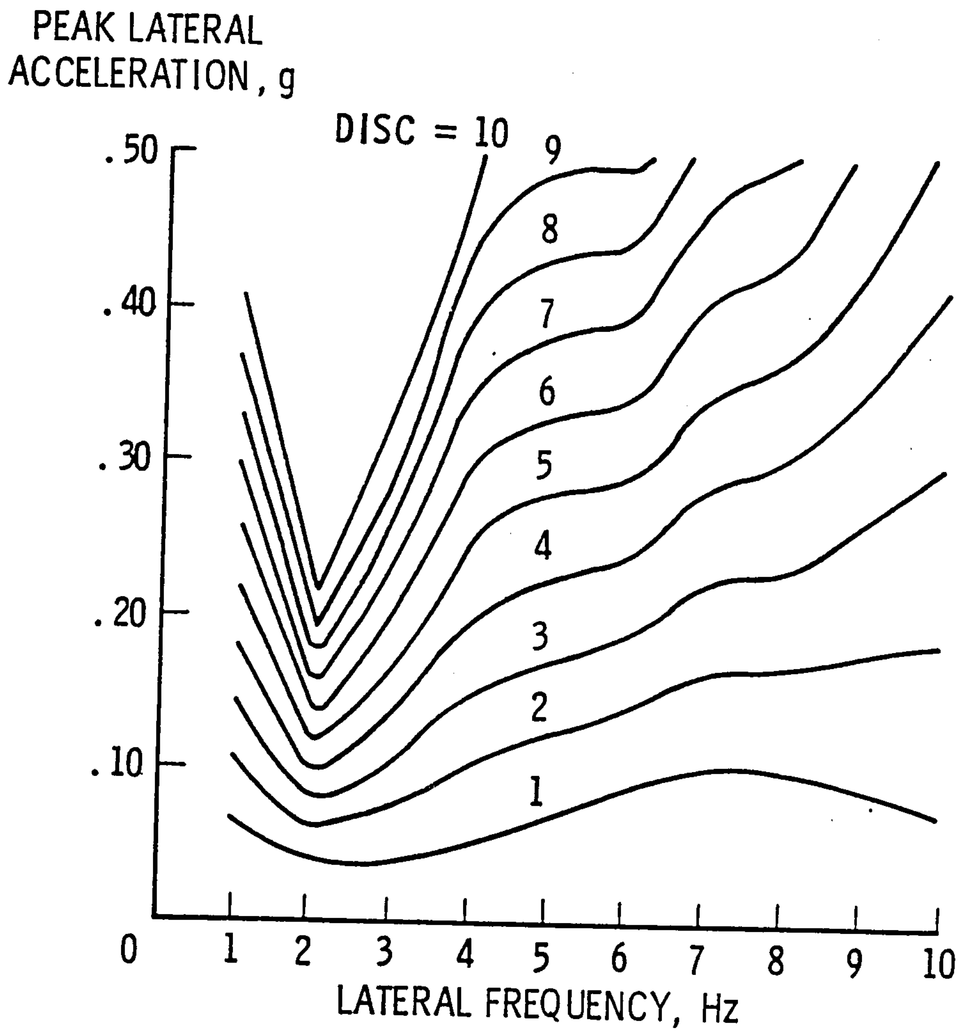

FIG 5 CONCLUDED

A comparison of the discomfort threshold curves for sinusoidal and random vertical vibration with the ISO 1-hour reduced comfort boundary is shown in figure 6. It is seen that the ISO 1-hour RCB corresponds closely to the discomfort threshold curve for sinusoidal vibrations of 15-second duration. Furthermore, the rms vertical acceleration levels corresponding to discomfort threshold for random vibrations were found to be considerably less than the levels obtained for sinusoidal vibration. Similar differences between discomfort threshold acceleration levels for sinusoidal and random vibrations were found for the other axes of motion. These results provide useful information for interpreting and anchoring the ISO curves and for the specification of ride comfort criteria. They also imply that sinusoidal criteria may not be appropriate when the ride vibrations are random in nature.

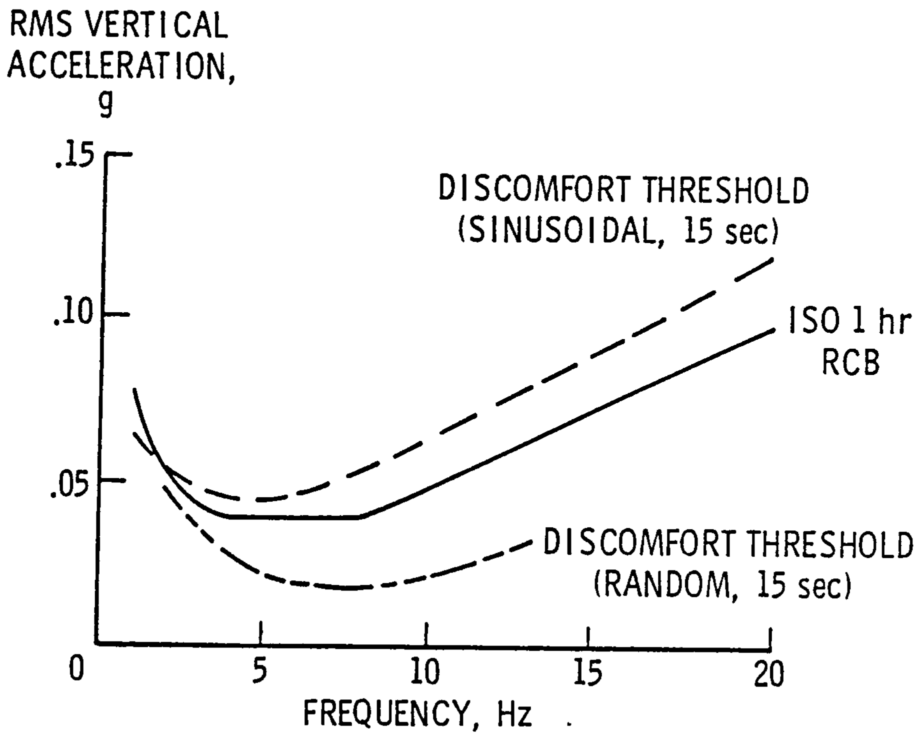

FIG 6 COMPARISON OF VERTICAL DISCOMFORT THRESHOLD WITH THE ISO REDUCED COMFORT BOUNDARY

2.3 Vibration duration.

The effect of the duration of vertical random vibration upon passenger discomfort response was investigated in a study (reference 12) utilizing 210 passenger subjects. The vibrations had a white noise spectrum with a bandwidth of 10 Hz and center frequency of 5 Hz. The results of that study are summarized in figure 7 which shows the normalized acceleration level corresponding to discomfort threshold as a function of the duration of vibration for durations of up to 1 hour. The discomfort threshold acceleration levels were normalized by the value of acceleration obtained for a duration of 1 minute. For comparison purposes, the recommended ISO duration correction (normalized in a similar manner) is also shown on the figure. The NASA results indicate that increases in duration (up to 1 hour) produced increases in the discomfort threshold acceleration level. This implies that the passenger subjects tended to adapt to the continuously applied ride environment. The ISO recommendation, however, indicates that subjective tolerance decreases (no adaptation) with increasing duration of vibration. A possible explanation for the difference between the two results is that the ISO trend was derived from performance-oriented investigations and, hence, may be valid for relatively high levels of acceleration, whereas the duration effect observed in the present study applies only to lower level vibrations typical of passenger transportation vehicles.

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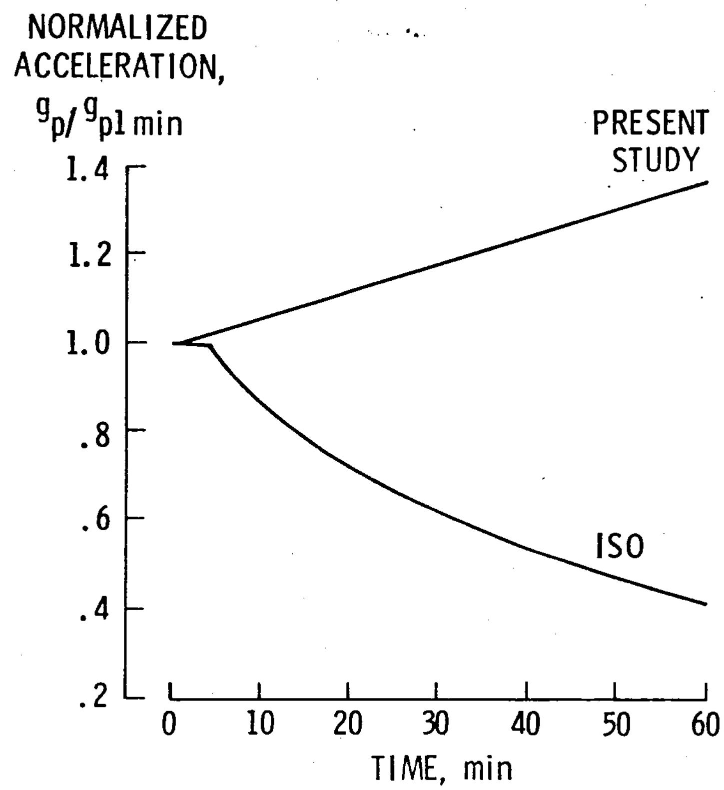

FIG 7 EFFECTS OF DURATION OF VIBRATION EXPOSURE

2.4 Combined noise and vibration.

A set of criteria (or constant discomfort) curves for human discomfort response to combined noise and vibration is presented in figure 8. The individual curves show the D-weighted noise levels and root-mean-square vertical vibration accelerations (5 Hz bandwidth and 5 Hz center frequency) required to produce constant amounts of overall discomfort. The dashed portions of each curve represent extrapolations of the physical data. These curves provide an important source of information for determining the trade-offs available between noise and vibration in terms of passenger discomfort. For example, at high levels of constant discomfort, for example DISC of 5 or 6, the noise level is the dominant factor in the determination of overall discomfort. For a low DISC level, however, the noise levels must be reduced substantially as acceleration increases in order to maintain a constant comfort level. These results indicate that human discomfort response is, in general, highly dependent upon both noise and vibration and that the degree of dependence is a function of the levels of each stimulus present in the ride environment. Consequently, accurate estimation and modeling of ride comfort within a combined noise and vibration environment requires knowledge of the levels and interactive effects of the two stimuli. Predictive models which incorporate these interactive effects have been developed in references 13 and 14.

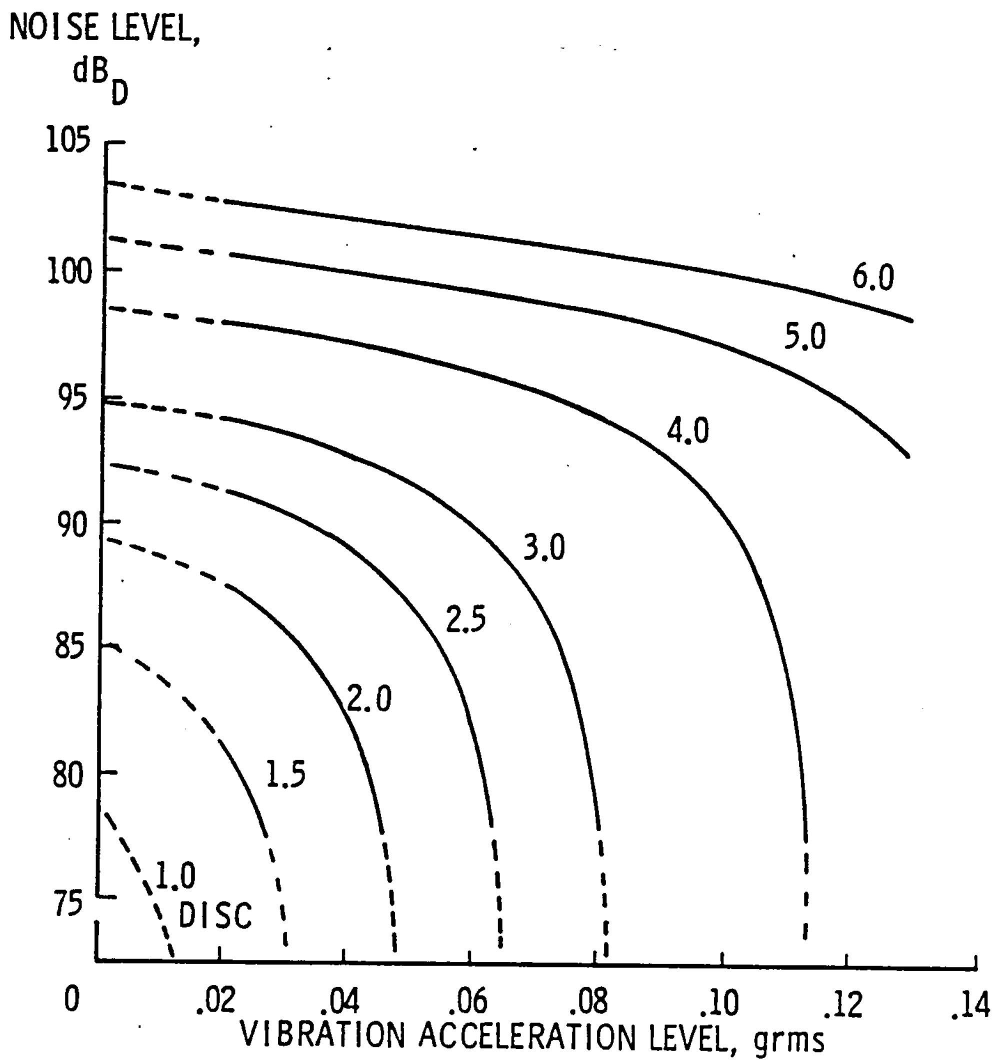

FIG 8 NOISE/VIBRATION TRADE-OFF

3. NOISE CONTROL

Aircraft interior noise reduction studies are being conducted to achieve increased comfort of crew and passengers with minimum weight and cost penalties. The approach consists of analytical, experimental, and flight studies to define the near-field noise source characteristics (acoustic inputs) of aircraft, the transmission of noise through aircraft structures, and the attenuation of noise by various noise control treatments. The source characteristics are being determined primarily by wind tunnel studies and flight tests and the results include the spectral content, the spatial distribution of the noise, and the point-to-point correlation of the noise. Vehicles include propeller-driven general aviation aircraft, reference 4; STOL vehicles, reference 15; and turbo-prop aircraft utilizing supersonic tip speed "propfans." The major thrust of the program consists of the development of improved analytical methods for predicting interior noise, and the application of these methods to the design of low-weight, low-transmission sidewalls. The analytical approach is to develop detailed models of the structural response to acoustic inputs including the influence and coupling of the acoustic (cabin) space. The models range in complexity from cavity-backed simple panels, reference 16, to stiffened panels, reference 17, and finally to stiffened cylinders, reference 18. In all cases, the validity of the analytical models are being examined through comparison with experimental tests. In addition to predicting the noise transmission through the structure, the effectiveness of various add-on noise reduction procedures is being examined. Treatment being studied analytically and experimentally include absorptive materials, double walls, damping tapes, constrained layer damping, composites for stiffness control, and so forth. The emphasis is on the development of maximum noise attenuation per unit weight/cost.

3.1 Helicopter noise reduction

A general description of the LRC program of helicopter noise research is given in reference 19. With respect to interior noise reduction, the only helicopter specific research program involved an evaluation of the effectiveness of noise reduction treatments to attain acceptable levels in a relatively large (20,000 kg) passenger-carrying helicopter (reference 20). The research vehicle (fig. 3) was a modified CH-53A military helicopter which was used by NASA to investigate several aspects of civil helicopter operations (reference 21). Tests were conducted before and after acoustic treatment to evaluate the effectiveness of a state-of-the-art treatment.

A sketch of the passenger cabin showing the acoustic treatment is presented in figure 9. The fuselage skin was covered with 0.5 mm thick damping tape to reduce vibrations and, hence, noise radiating from the vibrating surface. Damping tape was also applied, where practical, to structural members such as main frames of the aircraft. The 8 cm deep volume between the frames was filled with fiberglass. In the ceiling, two layers of lead separated with absorbent foam were installed with a total density of the ceiling treatment of approximately 7.3 kg/m^2. One layer of lead and foam was installed in the cabin

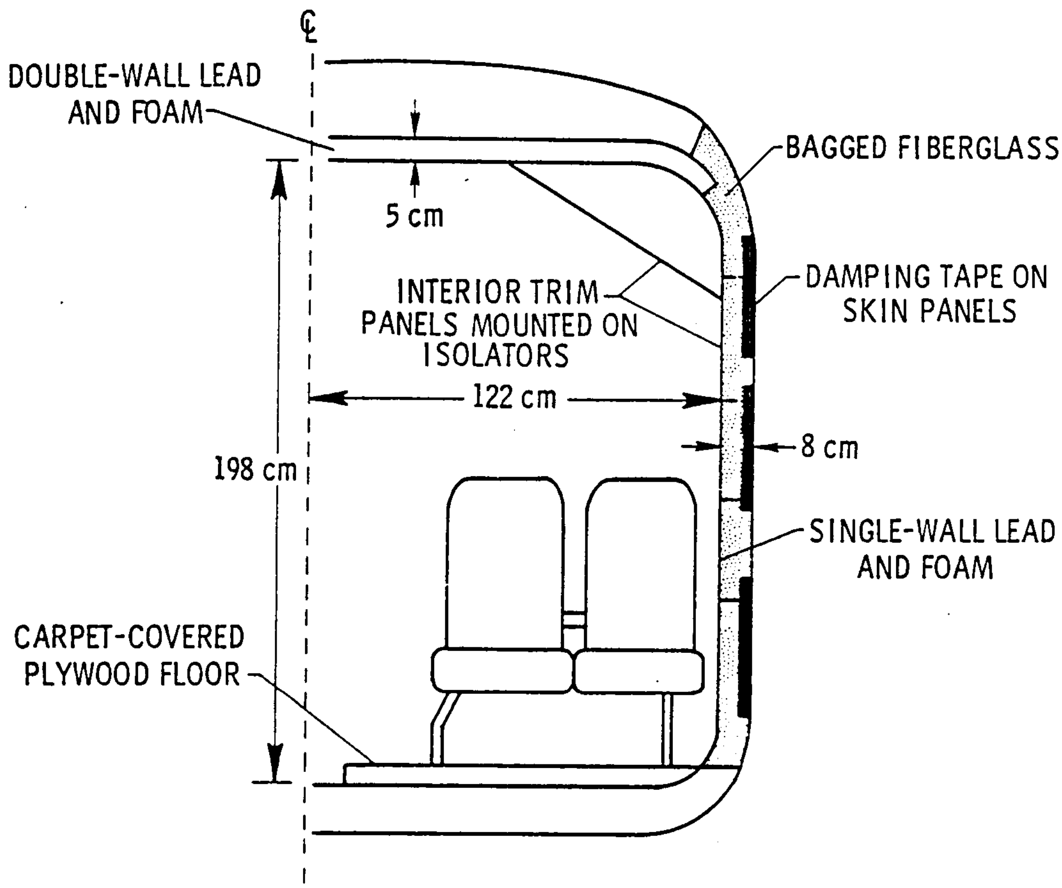

FIG 9 CABIN ACOUSTIC TREATMENT

sidewalls. Interior trim panels on the cabin sidewalls and ceiling were mounted on vibration isolators. A raised plywood floor covered with carpet was installed over the metal cargo floor. The forward and aft ends of the passenger cabin were separated from the rest of the vehicle by 2 cm thick plywood bulkheads which were mounted to the airframe with vibration isolators. The rear face of the aft bulkhead was covered with a 1.3 mm thick damping material, foam, and the installation was covered with fabric for the sake of appearance. The bulkheads had a cork covering on the passenger side and acoustically sealed doors.

The noise sources which were the primary contributors to the interior noise in the helicopter were determined from narrow-band spectra of the interior noise. There were three peaks above 100 dB in the spectrum of the untreated helicopter: tail rotor blade passage (nominally at 53 Hz), first-stage planetary gear clash (nominally at 1370 Hz) in the main gear box, and main bevel/tail takeoff gear clash (nominally at 2710 Hz). Figure 10 shows the octave band sound pressure level in the untreated and the acoustically treated vehicle. The two higher frequency sources (first-stage planetary gear clash and main bevel/tail takeoff gear clash) were main sources of noise in the treated cabin, although their levels were significantly reduced by the acoustic treatment. First-stage planetary gear clash was judged subjectively to be the source which produced the most uncomfortable noise inside the treated cabin.

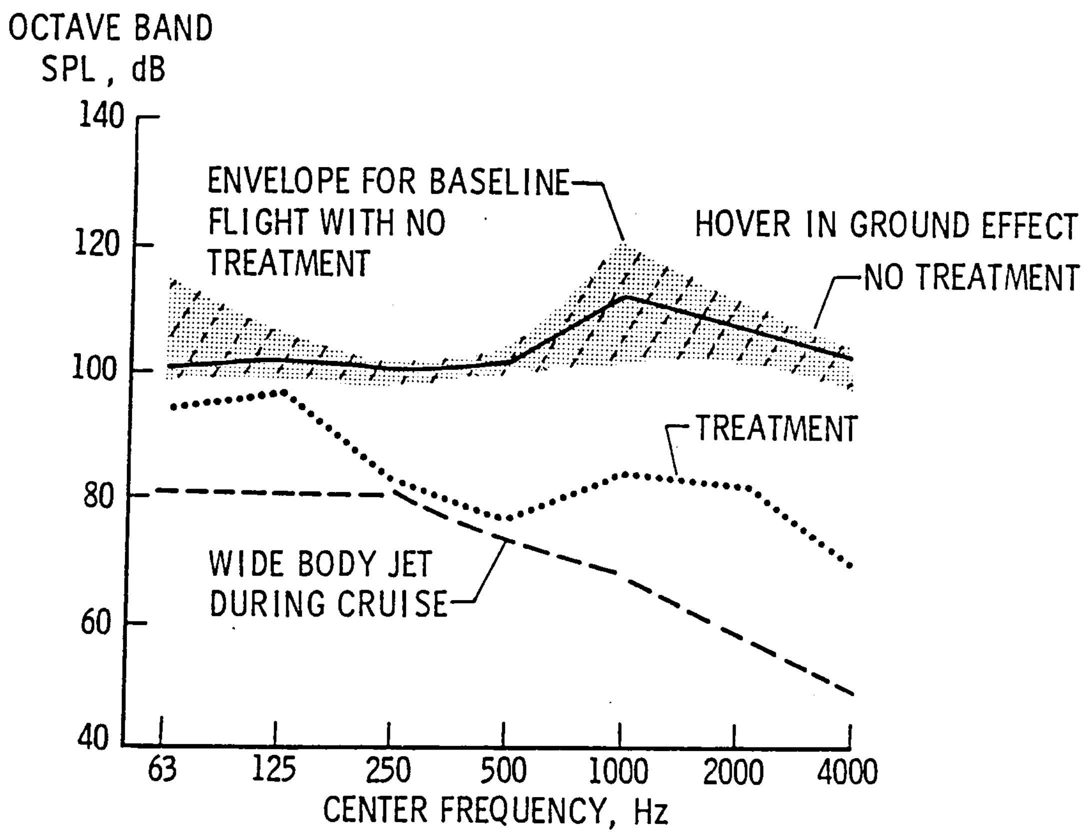

FIG 10 EFFECTIVENESS OF ACOUSTIC TREATMENT

The A-weighted sound pressure levels (L_A) were determined for the above data. The L_A in the untreated aircraft ranged from 108 dB to 122 dB with an average value of 115 dB for all flight conditions and microphone locations. The L_A in the treated cabin ranged from 83 dB to 90 dB with an average of 87 dB. The reduction of the average L_A values by 28 dB, from 115 dB in the untreated vehicle to 87 dB in the treated cabin, indicated a significant improvement in the cabin interior noise environment. This level was 3 dB less than levels in a medium-sized helicopter being used for passenger transportation (reference 22). As noted in reference 20, a 12 dB reduction in the first-stage planetary gear clash would result in interior noise levels which are about equal to those of current narrow-body jet transports.

4. CONCLUDING REMARKS

On a comparative basis, both the interior noise and vibration levels of helicopters are generally higher than those of conventional aircraft and surface vehicles. In order to evaluate the passenger acceptance of such an environment, a response model which incorporates the combined noise and vibration effects on comfort including within-axis and between-axis vibration is being developed. In addition to predicting passenger response, this model, when validated, should provide insight for more effective noise and vibration control. Future emphasis in the area of control will be on better diagnostics to identify the dominant sources and paths and better models to predict the transmission of airborne and structuralborne noise and vibration into the cabin.

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This material is to be presented, as an invited paper, at the Symposium on Internal Noise in Helicopters to be held July 17-20, 1979, Institute of Sound and Vibration Research, The University, Southampton, England.

16. Abstract
The passenger acceptance of aircraft interior noise and vibration as well as the control of the interior levels are being studied at the Langley Research Center (LaRC) as part of the NASA program in acoustics and noise reduction. Measurements to define and quantify the interior noise and vibration stimuli of aircraft, field and simulator studies to determine the subjective response to such stimuli, and theoretical and experimental studies to predict and control the interior environment are reviewed. In addition, ride quality criteria/standards for noise, vibration, and combinations of these stimuli are discussed in relation to the helicopter cabin environment. Data on passenger response are presented to illustrate the effects of interior noise and vibration on speech intelligibility and comfort of crew and passengers. Furthermore, the interactive effects of noise with multifrequency and multiaxis vibration are illustrated by data from the LaRC ride quality simulator. Constant comfort contours for various combinations of noise and vibration are presented and the incorporation of these results into a user-oriented model are discussed. With respect to aircraft interior noise and vibration control, ongoing studies to define the near-field noise, the transmission of noise through the structure, and the effectiveness of control treatments are described.

17. Key Words (Suggested by Author(s))
Aircraft interior noise, Vibration, Subjective response, Passenger acceptance

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