NASA Technical Memorandum 84515

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Sherman A. Clevenson

AUGUST 1982

NASA

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Sherman A. Clevenson
Langley Research Center
Hampton, Virginia

NASA
National Aeronautics
and Space Administration

Scientific and Technical
Information Branch

1982

SUMMARY

The effect of cabin and/or armrest vibration on passenger annoyance in the presence of synthesized turboprop interior noise was investigated in a realistic laboratory simulator. Passenger annoyance responses to a wide range of potential turboprop interior noise environments were obtained under three conditions: no vibration, armrest vibration, and armrest-plus-cabin vibration. The interior noise consisted of components caused by boundary-layer noise combined factorially with tonal components caused by a range of fundamental blade passage frequencies and associated harmonics.

Results indicate that passenger annoyance for the particular set of vibration conditions used in the study was unaffected by the presence of armrest vibration but was consistently lowered when cabin vibration was added. These results are shown to be consistent with predictions of the NASA ride quality model.

INTRODUCTION

Recent emphasis on fuel conservation measures has led to an increased interest in aircraft powered by advanced turboprop propulsion systems for commuter as well as medium-haul applications. The propeller proposed for this application is a high-speed, multibladed propeller with an advanced blade geometry that results in high blade loading (ref. 1). A potential problem of such a propeller is that passengers are subjected to additional acoustical and vibrational energy compared with conventional turbofan aircraft. Therefore, considerable effort is being devoted to the prediction and control of the noise and vibration to which passengers may be exposed. This is particularly important because the increased fuel efficiency could be offset if passenger acceptance necessitates increased aircraft weight for purposes of reduction of acoustic and vibration levels. One question that has been posed is whether the presence of perceptible levels of vibration of the armrests and of the cabin plus the armrests would affect passenger assessment of annoyance within the expected interior acoustic environment of the proposed turboprop aircraft. The combined effects of interior acoustic noise and vibration upon passenger discomfort have been studied (refs. 2 through 4), and it has been determined that passenger evaluations of total subjective discomfort were affected by the relative levels of each stimulus present in the environment. In particular, the results of these studies indicated that passenger objections to interior noise were lessened by the presence of whole-body vibration transmitted through the seats and/or floor of a passenger cabin.

Since the advanced turboprop system is still in the design stage, there are many prospective interior acoustic and vibration stimuli that must be considered in an effort to study the above question. This paper was written in order to present the results of an experimental pilot investigation to determine whether a perceptible level of vibration transmitted through the seat armrests, both with and without cabin vibration in the presence of simulated turboprop cabin acoustic environments, alters subjective assessments of annoyance. The vibration was combined with a wide range of simulated interior acoustic environments that were developed and used in a previous unpublished study. Only a single perceptible level of armrest vibration was used, and this level was based upon measurements made during the flight of a current turboprop aircraft. Thus, the results presented herein are strictly applicable for armrest/floor vibration characteristics used in this study.

The approach used in the current study was to obtain annoyance ratings of passengers exposed to simulated advanced turboprop cabin interior noise both with and without vibration. The vibrations were presented for a wide range of interior acoustic levels obtained as described previously. Results are presented to illustrate the effects on passenger annoyance of the selected vibration conditions for interior acoustic levels consisting of variations of simulated boundary-layer noise level and blade passage frequency components.

SYMBOLS AND ABBREVIATIONS

f_n blade passage frequency, Hz

L_n acoustic sound pressure level within cabin, dB(A)

n number (1, 2, 3, ...)

R_n roll-off ratio, decrease in level per harmonic for first 10 harmonics of amplitudes of BPF, dB

T_n ratio of one-third-octave band level of BPF to one-third-octave band level of simulated boundary layer containing BPF

BL simulated boundary layer

BPF blade passage frequency, Hz

PRQA passenger ride quality apparatus

SPL sound pressure level

EXPERIMENTAL METHOD

Passenger-subjects were exposed to simulated turboprop aircraft interior noise and vibration. The noise consisted of two components: a simulated boundary-layer (BL) spectrum and simulated propeller tones caused by the fundamental blade passage frequency (BPF) and its associated harmonics. The vibration consisted of either armrest vibration or armrest-plus-cabin vibration. The following sections provide a review of the simulator, subject characteristics, subjective evaluations, noise and vibration stimuli, test design, and test procedures used in the investigation.

Simulator

The facility used to generate the noise and vibration environments was the passenger ride quality apparatus (PRQA) at the Langley Research Center (refs. 5 and 6). The PRQA is shown in figure 1 with the front bulkhead removed. This facility is a three-degree-of-freedom, man-rated motion simulator with the interior configuration of a modern jet transport. It has been used extensively in the development of a passenger ride-comfort vibration model (ref. 4). Loudspeakers are mounted in the doors at either end of the cabin, above the luggage racks, and beneath the seats.

For this study, the cabin was fitted with two rows of first-class seats (two abreast) with an electrodynamic shaker located beneath each set of seats (fig. 2). The electrodynamic shaker was used to drive the steel tubular structure of the seats in order to produce armrest vibration similar to that measured in flight. The 3-in. foam cushion and seat backing isolated the passenger from the seat vibration except for the component transmitted through the armrests. Cabin vibration was provided by using the vertical-vibration capability of the PRQA. All speakers within the cabin were utilized for all tests during this study.

Subjects

A total of 144 passenger-subjects (20 males and 124 females) participated in the study. The subjects were obtained from a contractual pool and were paid for their participation. The ages of the subjects ranged from 18 to 68 years, with a median age of 35 years. The weights of the subjects ranged from 102 to 272 pounds with a median weight of 148 pounds. All subjects were audiometrically screened and were required to have hearing losses of no greater than 20 dB at frequencies up to 6000 Hz.

Subjective Evaluations

A continuous, nine-point unipolar scale was used by each subject to evaluate the annoyance of a test condition (see appendix). The scale was anchored at zero with the words "ZERO ANNOYANCE" and at the opposite end of the scale with the words "MAXIMUM ANNOYANCE." Thus, the scale of increasing numbers was interpreted as representing increasing degrees of annoyance. The subjects were instructed (see appendix) to evaluate their annoyance on this scale and to base their annoyance judgments upon the sound they experienced within each test condition. They were also instructed to keep their arms on the armrests at all times.

Noise and Vibration Stimuli

This study involved the determination of whether a perceptible level of vibration would affect the annoyance ratings of passengers who simultaneously experienced interior acoustic environments of a simulated turboprop aircraft. This was accomplished by using three separate subject groups. The first group was exposed to no vibration; the second group was exposed to armrest vibration; and the third group was exposed to armrest and cabin vibration. All three groups experienced identical factorial combinations of noise.

The armrest vibration used in these tests was derived from acceleration measurements made on the armrest during the flight of a current turboprop aircraft. A control spectrum (see fig. 3(a)) based on these measurements was used to drive the underseat shakers shown in figure 2. The armrest vibration was identical for every test point of armrest vibration or armrest-plus-cabin vibration and consisted of a discrete frequency (and its harmonics) superimposed on a shaped broadband noise.

Flight measurements made in the vertical direction on the floor of the turboprop aircraft indicated a spectrum similar to that measured on the armrest but with greater magnitude. However, limitations of the simulator drive system precluded use of that spectrum for cabin excitation. As a compromise, the cabin was vibrated at its highest usable frequency (30 Hz). The resulting spectrum of cabin vibration is shown in figure 3(b). For this case, the cabin rms acceleration level at a frequency of 30 Hz was 0.15g (1g = 9.807 m/sec^2). The acoustic level produced by the cabin vibration was less than 80 dB(A).

The basic acoustical components required to simulate the acoustic noise environment of the turboprop interior are the simulated broadband turbulent boundary-layer (BL) noise spectrum and the discrete-frequency components caused by the blade passage frequency and its harmonics. In the remainder of this paper the interior-noise components caused by the propeller blade passage frequency are referred to as tonal components (or tones). Due to some of the unknowns in the advanced turboprop systems (engine speed, number of blades, blade sweep, structural and acoustical transmissions, etc.) various overall acoustic noise levels L_n, tonal frequencies f_n, tone-to-noise ratios T_n and harmonic roll-off ratios R_n were incorporated in this study. These variables were investigated in a previous unpublished research study and the test tapes from that study were used in the present investigation. The variable T_n is defined as the difference (in dB) between the one-third-octave level of a tone and the one-third-octave level of the simulated boundary-layer noise band containing the tone. (See fig. 3(c).) The variable R_n is defined as the decrease in level per harmonic for the first 10 harmonics of the fundamental tone. (See fig. 3(c).) The simulated boundary-layer noise approximated that expected at the mid-cabin position on a medium-haul aircraft traveling at Mach 0.8 and an altitude of 35 000 ft, and then transformed to the cabin interior. For this study, the experimental condition that resulted from a parametric combination of L_n, f_n, T_n, and R_n, either with or without vibration, constituted a single-stimulus condition.

Test Design

The test design (fig. 4) consisted of three separate subject groups exposed to either no vibration, armrest vibration, or armrest-plus-cabin vibration in conjunction with the acoustic stimuli. Although the separate groups were relatively homogeneous in terms of subject demographics (age, sex, weight), no attempt was made to control for other possible sources of group differences. Furthermore, the large sample size tends to minimize group effects. It is assumed, therefore, that the results of this investigation reflect the effect of vibration and are only minimally influenced by group differences.

A total of 128 stimuli were provided to passengers for their evaluation. These stimuli consisted of 120 factorial combinations of 5 fundamental tone frequencies (f_n = 50, 80, 100, 125, and 200 Hz), 2 harmonic roll-off rates (R_n = 0 and 10 dB/harmonic), 3 tone-to-noise ratios (T_n = 0, 10, and 20 dB), and 4 overall sound pressure levels L_n. The nominal values of L_n were 71, 79, 87, and 95 dB(A) for acoustic stimuli only; 73, 79, 87, and 95 dB(A) for acoustic stimuli with armrest vibration; and 80, 84, 88, and 95 dB(A) for acoustic stimuli with armrest and cabin vibration. In addition to the 120 stimuli described above, the simulated boundary-layer noise only was presented twice at each of the 4 levels as a control condition. These stimuli were randomly assigned to 8 tapes containing 16 sounds each. The order of presentation of tapes to subject groups was counterbalanced.

Test Procedures

A typical test consisted of instructing the subjects in the use of the rating sheets, escorting them into the cabin, and exposing them to the selected stimuli over a test period of approximately 1 1/2 hours. The test period was divided into

2 halves with a 15-minute rest period in the middle. The subjects were exposed to 64 stimuli during each half of the test. The task for each subject (four subjects concurrently) was to experience and evaluate each stimulus and to use the annoyance scale described previously. The order of presentation of stimuli was balanced and randomized. Each stimulus consisted of 3 seconds of rise time, 15 seconds of acoustic noise (with or without vibration), 3 seconds of decay time, and an inter-stimulus interval of 9 seconds.

RESULTS AND DISCUSSION

The results of this investigation are shown in figures 5 through 10. Figures 5 through 7 illustrate the effects of adding vibration to a range of possible interior acoustic noise environments for a turboprop aircraft. Figure 8 illustrates the effect of adding vibration where the tone conditions are grouped together, whereas figure 9 shows the effect of adding vibration to a simulated boundary-layer-only environment. In figure 10, the results of the present experiment are compared with the predictions of the NASA ride quality model. The discussion that follows is predicated on the assumption that the three groups of subjects were from the same homogeneous population and that between-group differences were less than differences due to vibration.

Mean annoyance ratings for each of the three vibration conditions for each value of f_n used in this study are presented in figure 5. The ratings were averaged over all values of T_n and R_n taken at 82 dB(A). The level of 82 dB(A) was selected because previous unpublished data indicated that this level corresponded to annoyance threshold for the boundary-layer spectrum used in this study. To obtain annoyance values at 82 dB(A), regression lines between annoyance ratings and dB(A) levels were first determined for each set of R_n, f_n, and T_n values (fig. 4), and then the annoyance value was calculated for 82 dB(A). The circles in figure 5 represent no vibration, the squares represent armrest vibration, and the triangles represent the armrest-plus-cabin vibration. The figure shows that the annoyance ratings for the passenger-subjects exposed to armrest vibration were slightly lower than the ratings obtained in the absence of armrest vibration, but the small difference was not statistically significant (from t-test). Passenger annoyance responses to cabin-plus-armrest vibration, however, was approximately one unit of annoyance lower than the ratings for the no-vibration condition, and these differences were found to be statistically significant. These results imply that the vibration of the armrests at the level used in this study does not add to annoyance and does not interact with tone frequency. Cabin-plus-armrest vibration, however, resulted in consistently lower annoyance values. On the surface, this appears to be contrary to what would intuitively be expected to happen. However, this result is predictable in terms of a ride quality model to be discussed subsequently.

Mean annoyance ratings for the three vibration conditions are shown as a function of T_n in figure 6. In this case, the annoyance ratings are averaged over values of f_n and R_n for the 82-dB(A) noise level. This figure shows that the annoyance ratings for the passenger-subjects exposed to armrest vibration were again slightly lower than the ratings obtained in the absence of vibration. Also, the small difference was again not statistically significant for the range studied. Passenger annoyance responses to cabin-plus-armrest vibration were again about one unit lower than the ratings for the no-vibration conditions, and this difference was found to be statistically significant. These results have the same implications as stated in the previous paragraph and show, in addition, that vibration does not interact with T_n. It should be noted that the overall noise level is 82 dB(A) for each value of T_n.

Mean annoyance ratings for the three vibration conditions are shown for the two values of R_n in figure 7. In this case the ratings were averaged over values of f_n and T_n at 82 dB(A). This figure shows similar results as the previous two figures and indicates no interaction of vibration with R_n.

Regression lines of annoyance responses averaged over f_n, T_n, and R_n versus A-weighted noise level of the combined tone and simulated boundary layer for each vibration condition are shown in figure 8 and for the simulated boundary layer noise only in figure 9. The solid line corresponds to the no-vibration condition, the long-dashed line to the armrest vibration condition, and the short-dashed line to the cabin-plus-armrest vibration condition in both figures. As would be expected, these lines indicate increased annoyance for increased noise level. Statistical comparison of the regression lines of figure 8 with the comparable regression lines of figure 9 showed that the trends were not affected by the presence of tones in the boundary layer. These results imply that, for the level of vibrations and noises considered in this study, the passengers responded to vibration in the same manner whether or not propeller tonal components were present in the interior noise environment.

Tests of slope and intercept differences between the regression lines of figures 8 and 9 for no vibration and armrest vibration showed no significant difference between the two. This is additional support for the data indicating the lack of significant effects of armrest vibration described previously. However, the regression line for cabin-plus-armrest vibration was significantly different from the other two regression lines and produced lower annoyance ratings in the range studied. This result is consistent with the results of prior NASA ride quality research described in reference 4, which is briefly summarized in the following paragraph.

The NASA ride quality model predicts passenger discomfort within complex vehicle environments containing both interior noise and vehicle vibration. This model contains empirical equations derived from laboratory testing of more than 2200 test subjects for estimating the contributions of individual vibration and noise to total passenger discomfort. The model is valid for vibrations in the range of 1 to 30 Hz, for acoustic levels in octave bands from 65 to 2000 Hz, and for A-weighted noise levels ranging from 65 to 100 dB(A). One facet of the model that is applicable to the present study is the delineation of the interactive effects of combined vibration and noise in determining total subjective discomfort response. The NASA model indicates that the noise contribution to the total subjective discomfort in the combined environment decreases as vibration level increases. (See ref. 4.) This effect can be best illustrated by considering the following example. Assume that the interior noise level in a vehicle cabin is held constant, but vibration level of the cabin varies over a given range. Assume also that the passengers are asked to rate their discomfort (or annoyance) to the noise within the vehicle. The NASA ride quality model predicts that the subjective ratings of the noise by the passengers will decrease as vibration level increases. This is because an increasingly larger level of cabin vibration tends to divert attention from the noise. Thus, the results obtained in the present study are explainable by the ride quality model (ref. 4) if the subjects are assumed to be evaluating the acoustic noise environment rather than the total vibration and noise environment. Previous experience has shown that passenger-subjects rate annoyance and discomfort essentially the same on a nine-point scale. Although the subjects were instructed to rate the annoyance of each ride segment (see appendix), they were also instructed, "Listen to all of the sound before making your judgment." Thus, it can be assumed that the subjects were giving their responses primarily to the noise environment when they were subjected to both cabin vibration and noise.

A comparison of the results of the present study with predictions of the ride quality model is shown in figure 10. The model predicts passenger acceptances in terms of DISC (discomfort) units, which had to be transferred into annoyance ratings used in the present investigation. This was accomplished by using data from a previous NASA study where subjects rated both acceptability (to obtain DISC units) and discomfort. The results of the model computations are indicated by the dashed lines in figure 10. Also shown in figure 10 are the lines representing the average of the acoustic noise only and the noise and armrest vibration condition (average of solid line and long-dashed line of fig. 9) and noise with cabin-plus-armrest vibration condition (short-dashed line of fig. 9). It can be seen that the results of the ride quality model predict a lower annoyance rating in the range of 75 to 85 dB(A) for the condition where cabin vibration was added to the acoustic noise environment.

CONCLUDING REMARKS

The effect of armrest vibration and cabin-plus-armrest vibration on annoyance for a range of synthesized propeller-driven-aircraft interior noise has been investigated. The investigation was conducted in the passenger ride quality apparatus at the Langley Research Center and used three separate groups of subjects (144 total). The subjects evaluated synthesized propeller-driven-aircraft noises only, these noises combined with armrest vibration, or these noises combined with armrest-plus-cabin vibration. The noises, ranging from 71 to 95 dB(A), consisted of a turbulent-boundary-layer noise with a factorial combination of five blade passage (tone) frequencies (50 to 200 Hz), two harmonic roll-off rates, and three tone-to-noise ratios. Although three separate groups of subjects were used, it is believed that differences due to groups were small. Results of this investigation indicate that the noise parameters (fundamental blade passage frequency, harmonic roll-off rate, tone-to-noise ratio) did not interact with the vibration parameters. This permitted direct attention to be focused on the main effects resulting from application of the three particular vibration conditions used in this study. For these conditions it was determined that the presence of armrest vibration did not significantly affect subjective annoyance judgments in the simulated turboprop interior-noise environment. Addition of cabin vibration, however, reduced annoyance responses by approximately one unit on the nine-point rating scale. This result was consistent with predictions of the NASA ride quality model, and it implies that the presence of cabin vibration tends to divert attention from, or perhaps mask, the effects of the interior noise. This is an interesting result that would be worthy of further investigation for a wider range of vibration parameters. The present results, because of the limited vibration conditions used, should be applied to other vibration conditions with caution.

Since no significant interaction of noise parameters with vibration occurred, the design of additional experiments need not be concerned with detailed specification of the noise parameters.

Langley Research Center
National Aeronautics and Space Administration
Hampton, VA 23665
July 19, 1982

APPENDIX

INSTRUCTIONS TO SUBJECTS

Preliminary Instructions

You have volunteered to participate in a research program to investigate the quality of rides. Specifically, we wish to identify the types of sound in transportation vehicles which most influence a person's sense of well-being. To assess the influence of these sounds, we have built a simulator which can expose passengers to realistic sounds. The simulator essentially provides no risk to passengers since it has been designed to meet stringent safety requirements such that it cannot expose subjects to sounds which are known to cause injury. It contains many built-in safety features which automatically shut the system down if it does not perform properly.

The sounds that you hear today are representative of sounds you may experience in an airplane. You will enter the simulator, take a seat, fasten the seatbelt, and assume a comfortable position with both hands on the armrests and both feet on the floor. Selected sounds will then be applied to the cabin. You are to make yourself as comfortable and relaxed as possible while the test is being conducted. During the tests you will at all times be in two-way communication with the test conductor.

You have the option at any time and for any reason to terminate the tests in any of three ways: (1) by pressing the overhead button labeled "STOP," (2) by voice communication with the test conductor, or (3) by pressing downward on the toggle switch located at the front of each right-hand armrest. Because of individual differences in people, there is always the possibility that someone may find the sounds objectionable and may not wish to continue. If this should happen to you, please do not hesitate to stop the tests by one of the above methods.

Test Instructions

The task you will be required to perform today is to evaluate the annoyance associated with various helicopter ride segments. Each ride segment, to be evaluated by yourself, will be presented to you for a total of 15 seconds. Listen to all of the sound before making your judgment. There will be several seconds between successive ride segments to allow you to mark your evaluation.

You should record your evaluation of the annoyance associated with each ride segment by placing a check mark (✓) upon the scale. For example, a sound causing little annoyance should be scored towards the "0 - zero annoyance" end of the scale. Similarly, if you judge a sound to cause a large amount of annoyance, you would place your check mark towards the "8 - maximum annoyance" end of the scale.

There are no right or wrong answers. Your ratings should reflect only your <u>own</u> opinion of the sound.

Are there any questions?

APPENDIX

Score Sheet

Subject Number __________ Date __________ a.m. ___ p.m. ___

Session Number __________ Age _____ Weight _____ Sex _____

Ride Number — Zero Annoyance … Maximum Annoyance

Ride Number	0 (Zero Annoyance)	1	2	3	4	5	6	7	8 (Maximum Annoyance)
1									
2									
3									
4									
5									
6									
7									
8									
9									
10									
11									
12									
13									
14									
15									
16									

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L-81-3715

Figure 1.- Passenger ride quality apparatus at the Langley Research Center with front bulkhead removed.

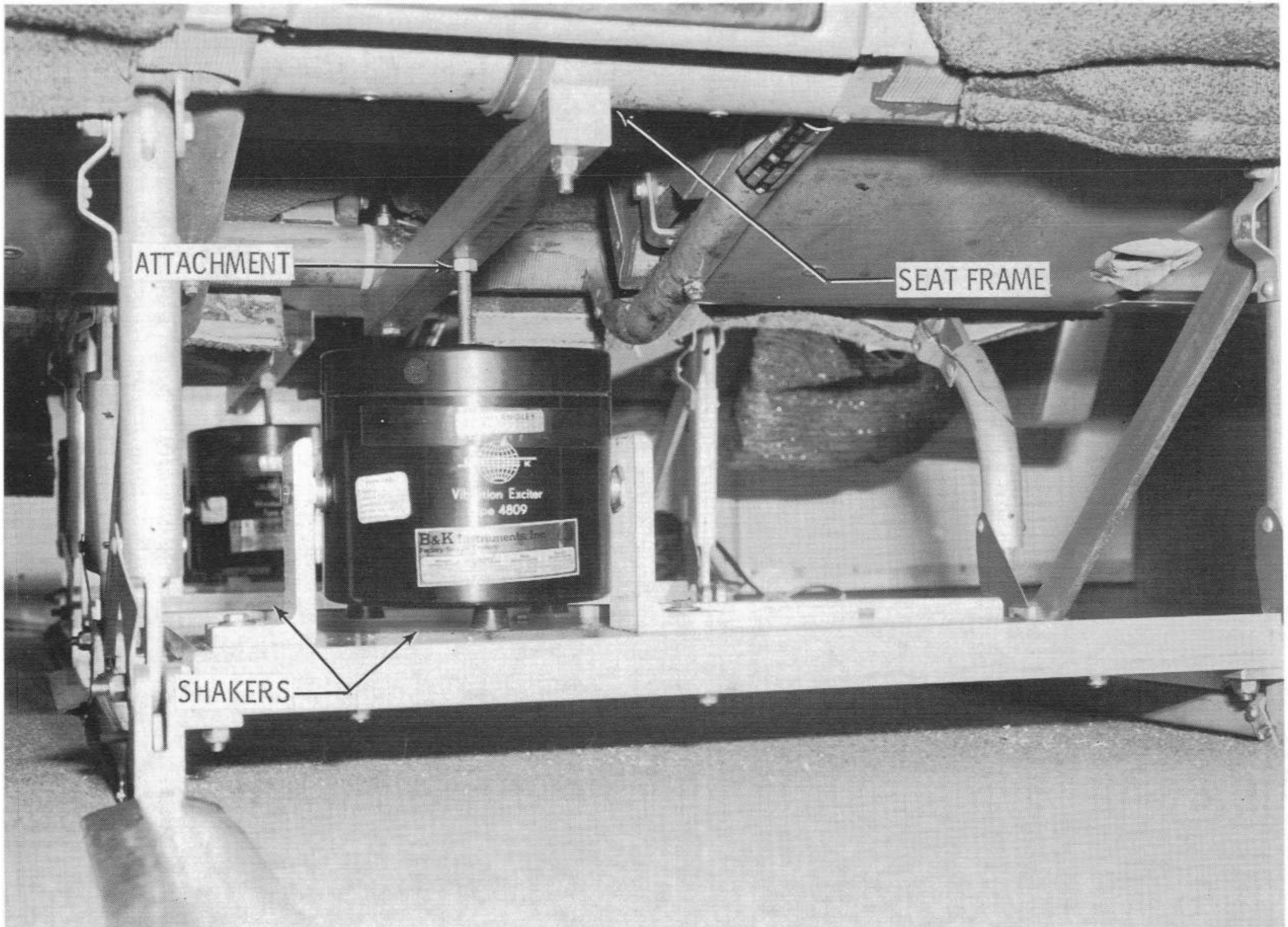

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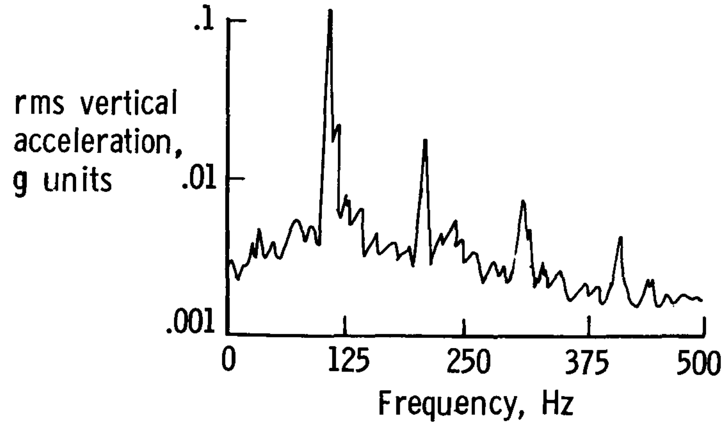
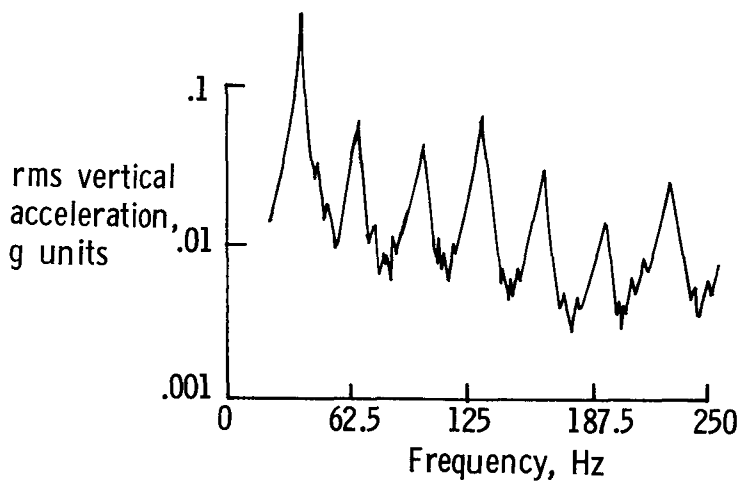
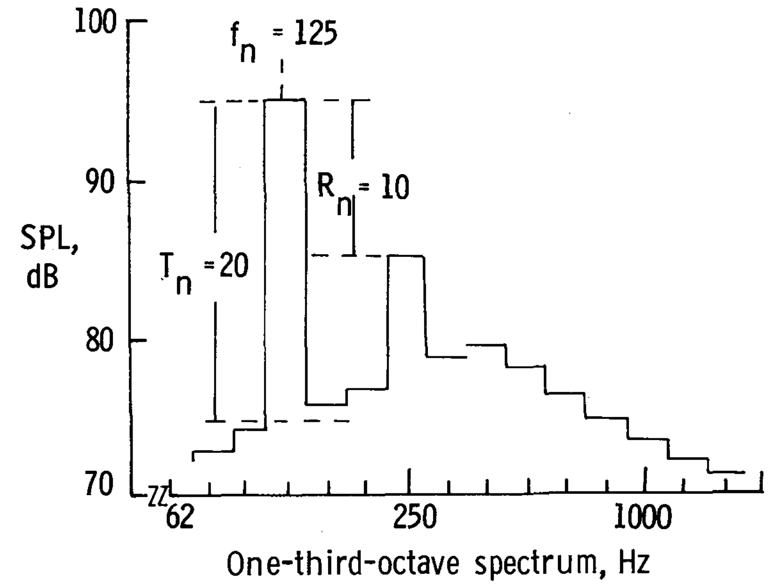
Figure 2.- Shaker installation under seats.



(a) Armrest vibration.



(b) Cabin vibration.



(c) Cabin interior noise.

Figure 3.- Spectral examples of armrest vibration, cabin vibration, and cabin interior noise.

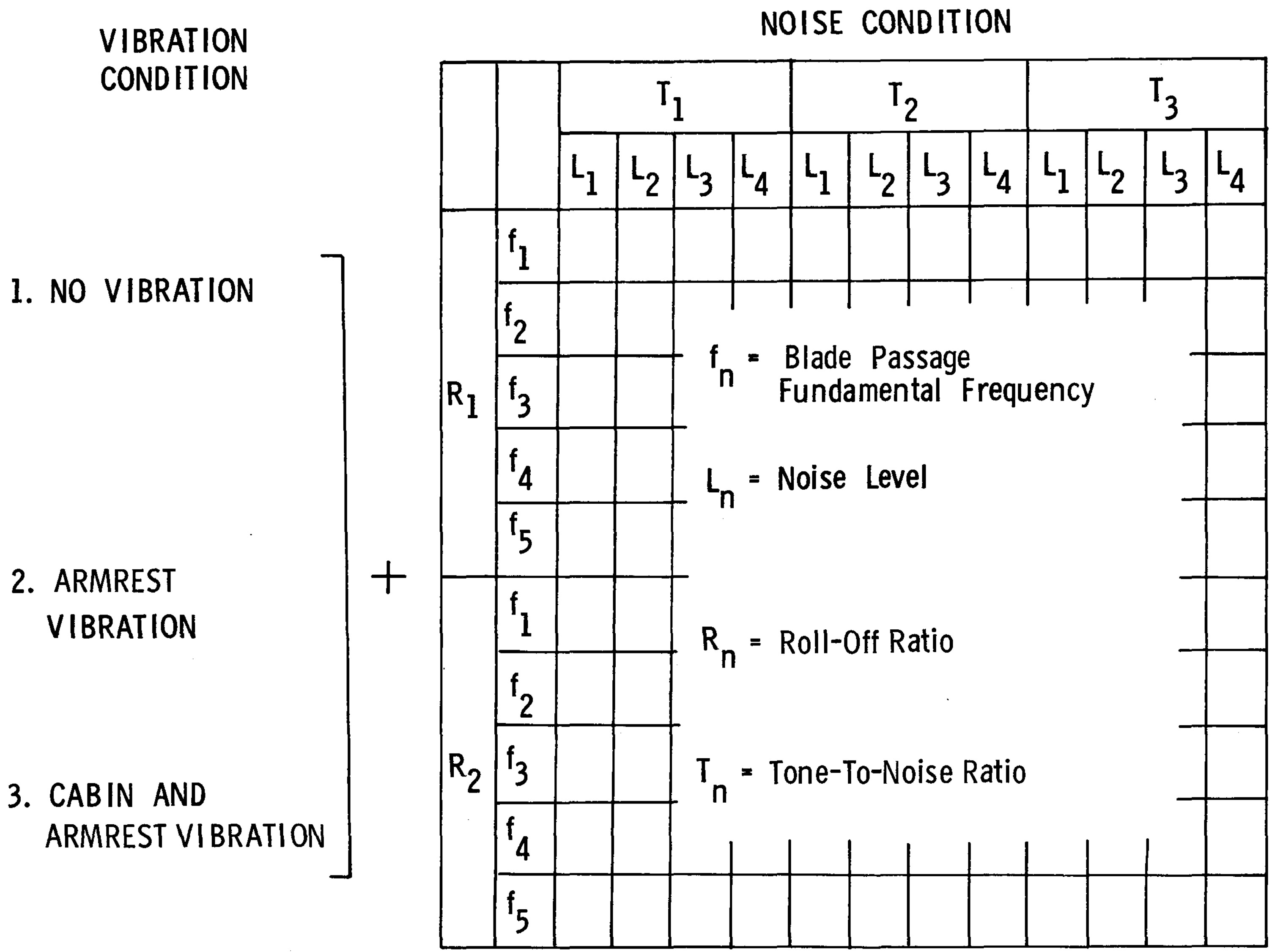


Figure 4.- Experimental design.

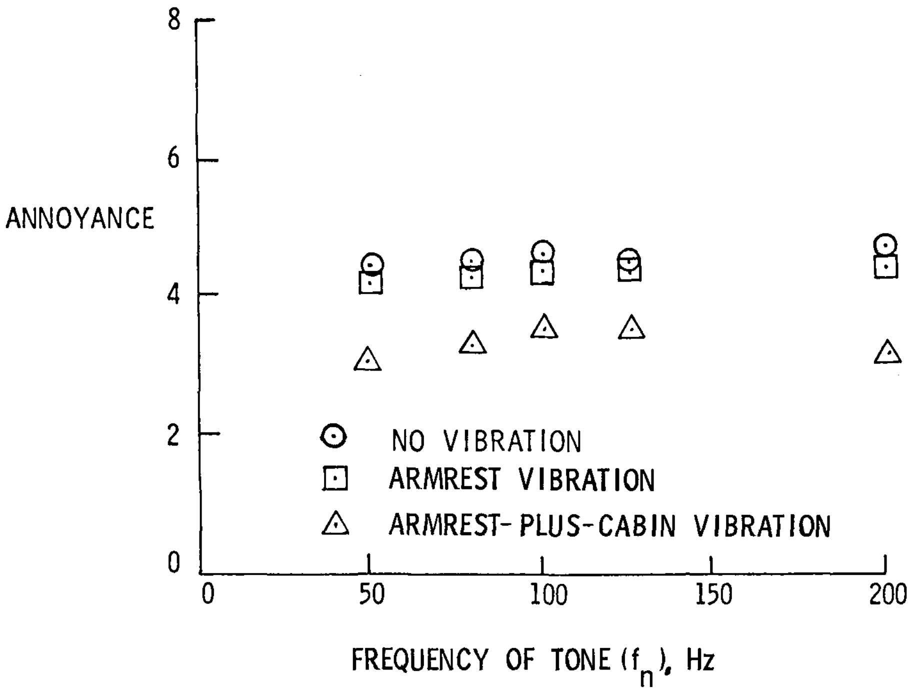


Figure 5.- Annoyance ratings for the three vibration conditions at each tone frequency. Noise level of 82 dB(A) for all data.

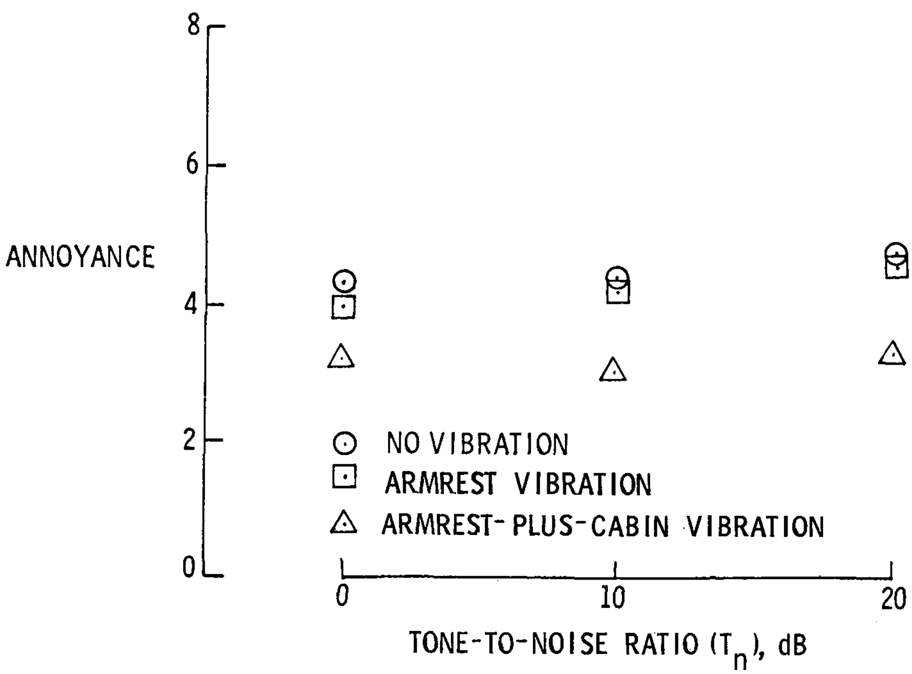


Figure 6.- Annoyance ratings for the three vibration conditions at each tone-to-noise ratio. Noise level of 82 dB(A) for all data.

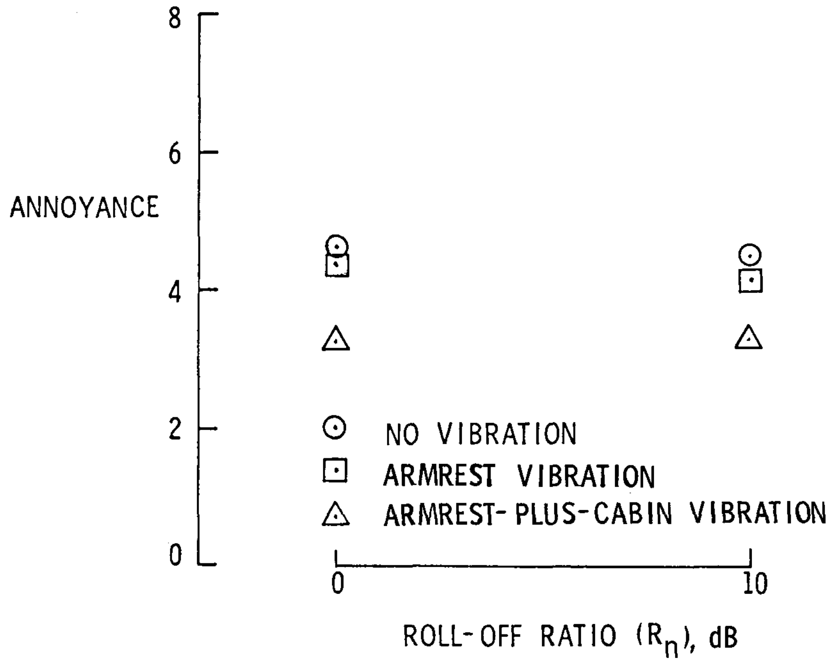


Figure 7.- Annoyance for the three vibration conditions at each roll-off ratio. Noise level of 82 dB(A) for all data.

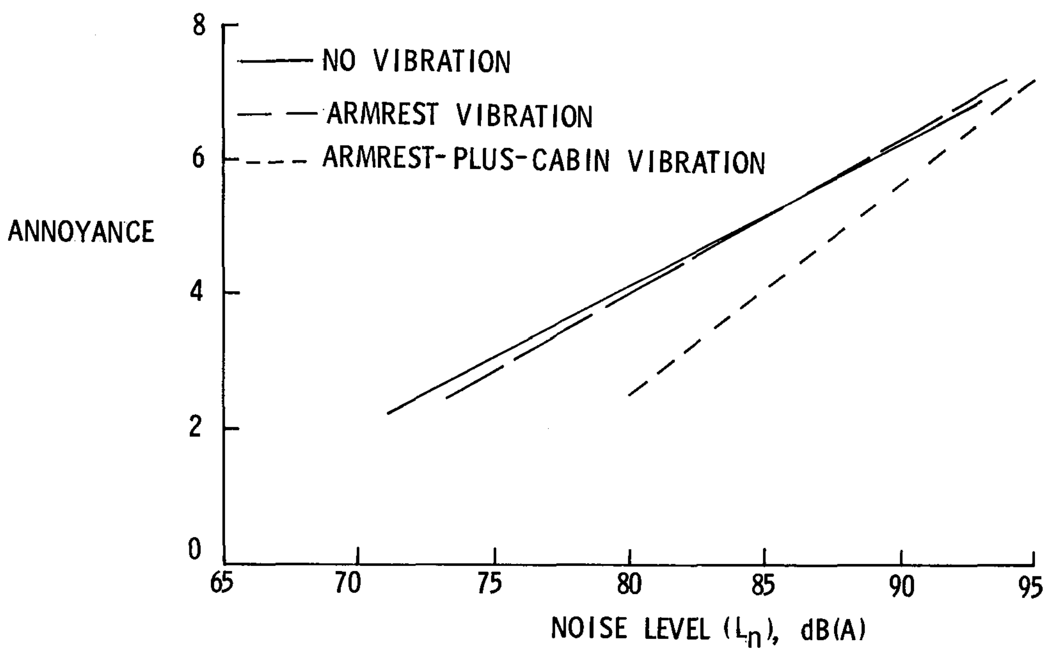


Figure 8.- Annoyance for the three vibration conditions as a function of A-weighted noise level for all tones.

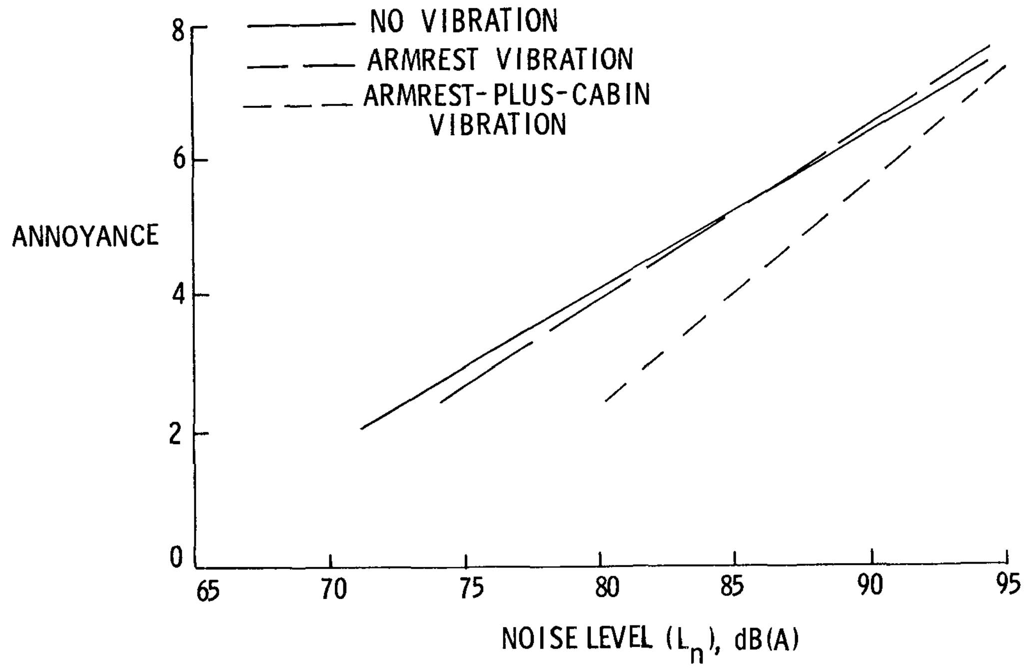


Figure 9.- Annoyance for the three vibration conditions as a function of A-weighted noise level for boundary layer only.

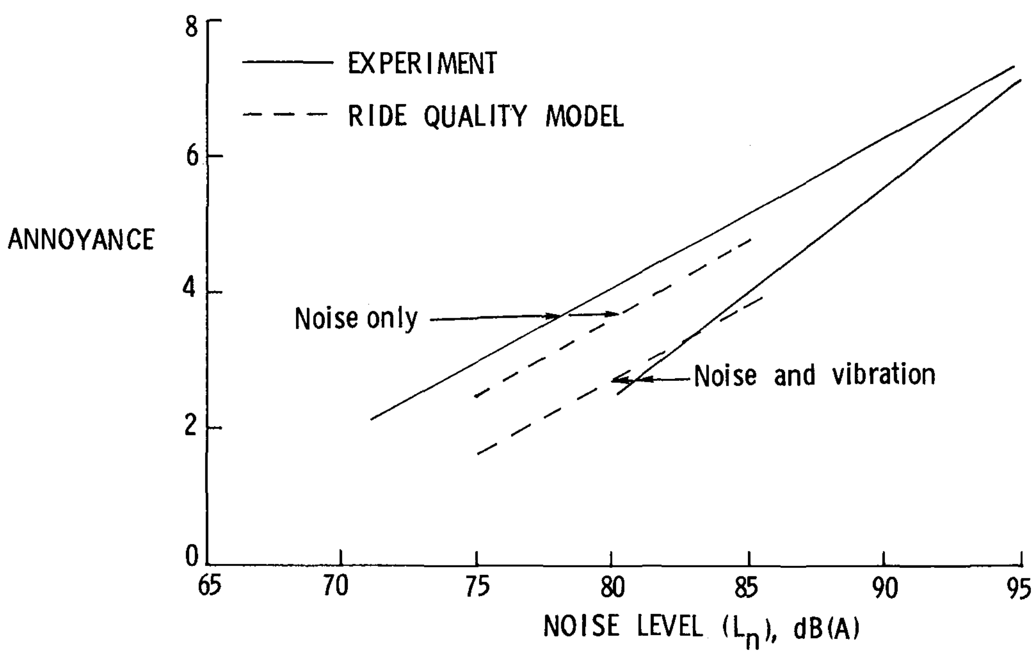


Figure 10.- Comparison of ride quality model prediction with experimental data for noise and vibration conditions.

1. Report No. NASA TM-84515	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle EFFECT OF SYNTHESIZED PROPELLER VIBRATION ON PASSENGER ANNOYANCE IN A TURBOPROP INTERIOR NOISE ENVIRONMENT		5. Report Date August 1982
		6. Performing Organization Code 505-35-13-01
7. Author(s) Sherman A. Clevenson		8. Performing Organization Report No. L-15298
9. Performing Organization Name and Address NASA Langley Research Center Hampton, VA 23665		10. Work Unit No.
		11. Contract or Grant No.
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, DC 20546		13. Type of Report and Period Covered Technical Memorandum
		14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

The effect of synthesized propeller vibration on passenger annoyance to aircraft noise has been investigated in the passenger ride quality apparatus at the Langley Research Center. Passenger reactions of annoyance to a wide range of potential turboprop interior-noise environments were obtained under three simulated vibration conditions: no vibration, armrest vibration, and armrest-plus-cabin vibration. The noises, ranging from 71 to 95 dB(A) consisted of a turbulent boundary layer with a factorial combination of five blade passage frequencies (50 to 200 Hz), two harmonic roll-offs, and three tone-to-noise ratios. Results indicate that passenger annoyance to noise in the presence of armrest vibration did not significantly change. However, those passengers exposed to cabin-plus-armrest vibration while being exposed to noise apparently rated their discomfort to only the noise environment. This resulted in a lower rating for the combined cabin vibration and noise environment compared with the rating for the noise-alone environment. This result is predicted by the NASA ride quality model.

17. Key Words (Suggested by Author(s)) Passenger annoyance Ride quality Human response		18. Distribution Statement Unclassified - Unlimited Subject Category 53	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 18	22. Price A02

For sale by the National Technical Information Service, Springfield, Virginia 22161

NASA-Langley, 1982