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SUMMARY

A simulator study was conducted to compare and validate various ride quality prediction methods for use in assessing passenger/crew ride comfort within helicopters. Thirty-five military pilots experienced and rated selected combinations of simulated helicopter interior noise and vertical vibration representative of that measured during routine flights. Results of this study indicated that crew ride comfort results from a complex interaction between vibration and interior noise. Reducing either noise or vibration alone provided little improvement in ride quality; reductions in both were required. The best metric for predicting crew comfort to the combined noise and vibration environment was the NASA discomfort index. The results were also used to derive tentative comfort criteria that account for the relative effects of both noise and vibration.

INTRODUCTION

The achievement of a "jet-smooth" ride within military and civilian helicopters has been identified as a primary goal of the helicopter industry (ref. 1). As stated in reference 1, this goal may not be economically or tactically feasible for certain utility missions but will be required for commercial transports, military gunships, and target acquisition helicopters of the future. Implicit in this goal is the imposition of more stringent requirements upon helicopter vibration and noise interior environments. It is anticipated that substantial reductions in interior noise and vibration levels, as compared with those present in current operational craft, may be required. This leads directly to two fundamental issues which must be addressed. The first involves the question of how to specify, in a usable and realistic manner, the levels, combinations of levels, or other ride parameters that constitute a "jet-smooth" ride. The second issue is concerned with the availability and adequacy of ride quality assessment methods applicable to the particular character of the helicopter ride environment. This environment is multidimensional in nature; that is, it contains multiple axes and multiple frequencies of vibrations combined with relatively high levels of interior noise.

A large body of literature dealing with vibration comfort criteria exists, but only a relatively small portion of the reported work has been identified as having direct applicability to helicopter ride quality (ref. 2). One such approach that may be applicable to helicopter environments has been developed by the National Aeronautics and Space Administration. The NASA approach utilized a realistic ride quality simulator and extensive psychophysical testing (approximately 3000 test subjects) to develop a general empirical model for prediction and assessment of human discomfort and acceptance of combined noise and vibration. (See refs. 3, 4, 5, and 6.) The NASA ride comfort model accounts for the interactive effects of interior noise and multiple frequency, multiple axis vibrations. Output of the NASA model is a single number scalar index of discomfort that relates directly to passenger acceptance.

Another approach of potential use in assessing helicopter ride quality is the absorbed power model developed by The U.S. Army Tank Automotive Command (TACOM) (refs. 7 and 8). This method also produces a single number scalar quantity (total absorbed power) derived from a summation of absorbed power for different frequencies and axes of vibration. It does not, however, account for the effects of noise. Both were applied to the noise and vibration measurements made on five operational U.S. Army helicopters in a recent joint NASA/Army study. The results of that study (ref. 9) indicate that each model predicted considerable variation in ride quality between the five helicopters and between flight conditions within each helicopter. The two models, however, did not always agree as to relative levels of ride quality between helicopters. Part of the lack of agreement may be attributable to the fact that the NASA model included the effects of the interior noise, whereas the absorbed power model did not.

To investigate this problem futher, an additional NASA/Army experimental investigation was conducted. The primary objective was to evaluate the capability of various ride quality metrics to predict pilot subjective comfort ratings of simulated helicopter interior noise and vertical vibration typical of routine military operational flights. A secondary objective was to investigate a possible ride quality criterion that accounts for the combined effects of noise and vibration. The Army absorbed power model was not considered and the study was not concerned with evaluation of individual helicopters or with comparisons between helicopters.

SYMBOLS AND ABBREVIATIONS

g acceleration due to gravity, g units ($1g = 9.81$ m/sec^2)

g_p peak acceleration, g units

g_{rms} root-mean-square acceleration, g units

L_A A-weighted sound pressure level, dB (re 20 μPa)

r linear correlation coefficient

Abbreviations:

DISC discomfort

IGE in ground effect

ISO International Standards Organization

max,min maximum, minimum

NASA National Aeronautics and Space Administration

OASPL overall sound pressure level

rms root mean square

SPL sound pressure level

EXPERIMENTAL METHOD

The objectives of this investigation were accomplished by applying selected combinations of simulated helicopter noise and vibration to a group of pilots and eliciting their subjective impressions of the discomfort associated with each exposure. The following sections describe the simulator used, subject characteristics, source of test stimuli, experimental design, subjective rating methods, test procedure, and data analysis.

Simulator

The simulator used was the passenger ride quality apparatus (PRQA) at the Langley Research Center shown in figure 1. The PRQA is an electrohydraulic three-degree-of-freedom motion simulator capable of exposing passenger subjects to complex vibration and noise inputs over a wide range of frequencies and amplitudes. The simulator is described in detail in references 10 and 11, and the reader is referred to those documents for details of simulator capabilities and operating characteristics. The interior of the PRQA is configured to closely resemble that of a modern jet transport; for the present study, it contained four first-class aircraft seats which allowed simultaneous testing of four subjects.

Subjects

The 35 military helicopter pilots used in this study were obtained from the local area with the assistance and cooperation of the Aviation Material Management Division of the U.S. Army Transporation School at Fort Eustis, Virginia, and NAVAIRLANT located at the Naval Air Station in Norfolk, Virginia. Their ages ranged from 23 to 43 years, with a median age of 31 years. The subject group consisted of 34 males and 1 female.

Source of Test Stimuli

The noise and vibration stimuli were obtained from a series of flight measurements described in reference 12. The particular environments selected for reproduction on the NASA ride quality simulator were those measured on the OH-58C, UH-1H, AH-1S, UH-60A, and CH-47C helicopters. These aircraft represented a set of vehicles having a large range of design gross weight (3200 to 33 000 lb).

The flight conditions selected for simulator reproduction were normal cruise and in-ground-effect (IGE) hover. For each of these conditions, only the measured vertical vibration and interior noise were used as inputs to the simulator. Lateral vibration was not used, since vertical axis vibration was usually dominant for the aircraft selected. Furthermore, the simulator could not accurately reproduce high-frequency (greater than 10 Hz) lateral vibration. The measured vibration signals were played directly into the simulator, but the noise signals were first applied to an equalizer which attenuated the signals in accordance with the SPH-4 helmet attenuation characteristics given in table I. (See ref. 13.) As a result, interior noise environments were roughly equivalent to those which the crew members actually heard in flight.

It is important to note that the noise and vibration environments evaluated by the subjects were simulator reproductions of the measured noise and vibration frequency spectra. That the simulated noise and vibration match flight noise and vibration levels was not a requirement of this study. The objectives required only that the subjects experience a range of noise and vibration sufficient to elicit a wide range of discomfort responses. Details of the actual simulator environments are given in the following sections.

Experimental Design

The experimental design is shown in table II. The factors that were varied include noise level, vibration level, flight condition, and helicopter type. Noise and vibration levels were varied for each frequency spectra defined by helicopter type and flight condition. Throughout this paper, helicopters are denoted as follows: H-1 for the AH-1S, H-2 for the CH-47C, H-3 for the UH-60A, H-4 for the UH-1H, and H-5 for the OH-58C. The noise levels were classified as being high, moderate, low, and ambient. The high noise level condition approximated the maximum levels measured in flight (suitably attenuated by the SPH-4 helmet characteristics). The moderate and low noise conditions correspond to 7 dB and 14 dB attenuations, respectively, of the high level. Thus, for each helicopter/flight condition combination, the shape of the noise spectrum remained constant and only level varied. The ambient noise condition ($L_A \approx 60$ dB) represented the case in which cabin noise input was removed and only the noise due to simulator operation was present.

The vibration levels were classified as being high, moderate, and low. The high vibration condition approximated the maximum levels measured in flight when possible. Man-rating requirements prevented the application of accelerations in excess of $0.5g_p$ to the subjects. In some cases this prevented achievement of full flight levels. The moderate and low vibration conditions correspond to 3 dB and 9 dB reductions from the highest test level. Vibration spectrum shape for each helicopter/flight condition combination also remained constant.

Each vibration and noise level combination was presented for each helicopter and both flight conditions. The flight conditions were normal cruise and IGE (in-ground-effect) hover. Each subject experienced all the noise and vibration combinations (a total of 120), which were randomized and counterbalanced to prevent presentation order effects. The root-mean-square floor acceleration levels (g_{rms}), overall sound pressure levels (OASPL), and A-weighted sound pressure levels (L_A) produced within the simulator cabin are given in tables III, IV, and V, respectively, for each condition of table II.

In addition to the stimuli of table II, the subjects also were given 10 calibration rides. These rides consisted of vibration only (except for ambient noise) and were used to determine whether the vibration discomfort sensitivity of the military pilots differed from that of the general passenger public. These calibration rides were vertical sinusoidal vibrations of various randomized levels applied at a frequency of 9 Hz. Responses to the calibration rides were further used to assist in interpreting the 9-point rating scale (see next section). The acceleration levels of each calibration ride are listed in table VI in the order presented to the subjects. A similar method for calibrating subjective discomfort responses to noise alone was not available.

Subjective Rating Methods

Subjective responses were obtained by use of two rating-scale methods. The first method required each subject to make an overall evaluation as to whether a ride segment was uncomfortable or not. The second rating method utilized a continuous 9-point unipolar discomfort scale and required that evaluation marks be placed along the scale to indicate the degree of discomfort associated with a ride segment. The instructions given to the subjects explaining how to use the scale are given in appendix A. A sample rating sheet showing the rating scales is shown in appendix B.

Test Procedure

Prior to the start of each test, the subjects were thoroughly instructed in the use of the rating scales as well as other pertinent information related to test procedures and protocol. Upon entering the simulator, they were first exposed to the 10 calibration rides, then the rating sheets were collected and new rating sheets were issued for use in the remainder of the test. This was followed by application of the first 60 helicopter ride combinations. The first half of testing took approximately 45 minutes, whereupon a 15-minute break was taken before completing the remaining 60 ride segments. Each ride segment lasted approximately 20 seconds and included ramp-up and ramp-down times of about 2.5 seconds each. Intervals between rides averaged about 8 seconds.

Data Analysis

Vibration data.- The vertical vibration level at the floor of the simulator cabin was measured during each ride segment and recorded on 1-inch magnetic tape. The tapes were digitized and processed through the Langley Research Center's Signal Analysis Program (SAP) and Acoustics Analysis Program (AAP). These programs, described in reference 14, are general purpose programs for the analysis of random, stationary time series. For the present study the SAP output options utilized were the summary statistics (max, min, mean, rms) and the power spectral density estimators. These estimators were used to quantify the frequency content of the vibration spectra and to verify that the simulator accurately reproduced the flight noise and vibration spectra.

Noise data.- The interior noise within the simulator cabin was measured at head level and midway between the two rear seats, that is, directly above the middle armrest. This location was selected on the basis of previous noise surveys within the simulator passenger cabin which indicated that this location approximated reasonably well (±2 dB) the space-averaged sound pressure level within the cabin. The noise was recorded on an audio recorder and subsequently analyzed through the AAP to obtain one-third octave spectra. Results of both the noise and vibration analyses were also applied as input to the NASA ride comfort model, as discussed in detail in the results section.

Subjective data.- The subjective ratings were tabulated, and the mean and standard deviation of the 9-point scale values were computed for each ride segment; these are given in tables VII and VIII. The means were then used in correlation analyses to determine the relative effectiveness of various ride quality metrics in accurately estimating the obtained discomfort responses. The percent of pilots rating each ride segment as uncomfortable was also determined (table IX) and used to assist in interpreting the 9-point scale values.

RESULTS

Simulator Physical Environment

Vibration.- The root-mean-square acceleration levels on the simulator cabin floor for each ride segment are presented in table III. These, however, provide no information regarding the fidelity with which the simulator reproduced the frequency content of the flight measurements. This information is presented in figure 2 in which the simulator output spectrum shape is compared with the input (flight) spectrum shape. The spectra shown correspond to the cruise condition. Hover is not shown since the results are similar. When considering the spectra of figure 2, it should be recalled that the simulator levels were not necessarily matched with flight levels. Consequently, the various spectral peaks should not be expected to coincide in amplitude. It was important, however, to achieve good fidelity between input and output frequency content. The results in figure 2 do indicate that the simulator closely matched and reproduced the dominant frequency components measured in flight, providing assurance that the reproduced environments within the passenger cabin would "feel" the same as the flight environments. This was confirmed by spontaneous remarks and comments made by the subjects both during and after the tests. The output spectra also show that the simulator was unable to reproduce the very low-frequency portion (less than 2 Hz) of the flight spectra. The stroke limitations of the hydraulic actuators that drive the simulator prevented full reproduction of vibration at frequencies below 1 Hz.

Noise.- The overall and A-weighted sound pressure levels within the simulator cabin for each ride segment are given in tables IV and V, respectively. Samples of the overall interior noise levels for the cruise condition measured in flight (dashed lines) and within the simulator cabin (solid lines) are presented in figure 3 for each aircraft. These data indicate that the noise spectra within the simulator cabin approximated the flight spectra reasonably well. Differences between the two likely resulted from equalization of the flight spectra (prior to playback into the cabin speaker system) according to the SPH-4 helmet attenuation characteristics and different physical interior characteristics of the simulator cabin (e.g., reverberation, size, absorption). Although the reproduced noise spectra differed somewhat from the actual flight spectra, the noise maintained its realistic character and was readily perceived and identified by the pilots as helicopter interior noise with which they were familiar.

Subjective Response

Calibration rides.- The purpose of the calibration rides was to determine whether the helicopter pilots' subjective responses to vibration differed from those of the general public upon which the NASA discomfort model was based. Any differences would have to be accounted for when applying the NASA model to predict helicopter crew/passenger comfort. Results of the pilots' evaluation of the calibration rides are summarized in figure 4, which shows the percent of pilots who rated each calibration ride uncomfortable as a function of rms vertical acceleration level. The line in the figure is a linear least-squares fit to the data points. Indicated on this figure is the acceleration level corresponding to the discomfort threshold (where 50 percent of the pilots were uncomfortable). This acceleration level is 0.057g. The discomfort threshold for the general public was previously determined to be 0.061g. (For example, see ref. 6.) Since the two values are close (within 7 percent), it is reasonable to conclude that the helicopter pilots evaluated vibration ride comfort the same as the general public. This implies that highly trained operators (pilots in this case) may have the same comfort expectations as the general passenger.

Helicopter rides.- The pilots' mean subjective ratings and standard deviations resulting from each of the 120 helicopter noise and vibration environments (as reproduced by the simulator) are summarized in tables VII and VIII for the 9-point scale. The percent uncomfortable values are given in table IX. The relationship between the two rating scales is shown in figure 5. This figure provides a basis for interpreting the numbers on the category scale in terms of a readily understandable parameter (percent uncomfortable). For example, scalar ratings of 1.84, 3.29, and 4.46 correspond to 50, 75, and 90 percent uncomfortable, respectively. For scalar ratings above approximately 4.5, it is not possible to relate the two scales because of the "ceiling" effect of the 9-point scale.

Vibration ratings with ambient noise.- The mean subjective ratings as a function of rms vertical acceleration level (in g units) are presented for the ambient noise condition at cruise in figure 6(a) and for hover in figure 6(b). The dashed lines indicate the 50, 75, and 90 percent uncomfortable rating-scale values. The reader should recall that the ambient noise condition refers to the test condition in which helicopter noise was absent from the simulator cabin and only the noise produced by cabin vibration was present. Thus, figure 6 represents the effect upon subjective comfort response of changes in cabin vertical vibration. Observe that the discomfort increased substantially over the acceleration range investigated and that this increase was roughly linear. The largest discomfort response occurred for the cruise condition because of the higher levels of acceleration used. For the range of acceleration common to both conditions, the discomfort responses were similar. This would be observed if the two figures (figs. 6(a) and 6(b)) were overlaid.

It is useful to consider some implications of these data with respect to helicopter passenger ride quality. For example, if a ride quality criterion states that no more than 50 percent of the passengers should be uncomfortable, then the data on figure 6 indicate the levels for each helicopter simulation that should not be exceeded. These levels are helicopter dependent because of the varying spectral characteristics between helicopters. To illustrate this, consider the data for aircraft H-1 and H-2. Figure 6 shows that the acceleration level at which 50 percent of the subjects were uncomfortable is much less for aircraft H-1 than for aircraft H-2. Examining the spectra indicates that the dominant vibration peak for aircraft H-1 occurs at about 11 Hz (fig. 2(a)), whereas the dominant peak for aircraft H-2 is at 24 Hz (fig. 2(b)). Thus, for equal rms acceleration levels the subjects in aircraft H-1 would perceive and evaluate an environment having a predominantly lower frequency content. Since human comfort response is most sensitive to lower vibration frequencies, it would be expected that aircraft H-1 would be evaluated as most uncomfortable. This is a very important point since it illustrates quite well that comparative ride quality evaluations cannot be made simply on the basis of an overall measure such as rms acceleration.

Noise rating with low vibration.- The comfort responses to the simulated helicopter noise are shown in figures 7(a) and 7(b) as a function of A-weighted noise level L_A for low values of cabin floor vibration. These data indicate that the spread in comfort ratings due to helicopter type is much less for a given value of

L_A than that obtained for vibration only (fig. 6). This implies that the character of the interior noise, at least as perceived by the subjects, varied only slightly from helicopter to helicopter. Further, if the curves of figures 7(a) and 7(b) are overlaid (not shown), it can be seen that the comfort responses for the cruise and hover conditions are similar. Exceptions are aircraft H-1 and H-3 at values of L_A less than approximately 75 dB.

If 50 percent uncomfortable is considered as discomfort threshold, the data of figure 7 imply that discomfort threshold ranges from approximately $L_A = 67$ to 77 dB for cruise and $L_A = 74$ to 78 dB for hover. These values are similar to annoyance-threshold results obtained in earlier studies (e.g., ref. 15) of human response to simulated aircraft interior noise due to boundary layer and propeller tones. It should be noted that the discomfort threshold levels shown in figures 7(a) and 7(b) reflect the effects of tonal components within the measured environments. Reference 15 indicated that annoyance penalties as large as 6 dB can result from the presence of tones within an interior noise environment. Thus, the relatively low values of L_A corresponding to discomfort threshold are probably due in large part to the high tonal content of helicopter interior noise. It is also possible that discomfort threshold may not be synonymous with annoyance threshold or that the pilots are far more critical of the noise environment than were the subjects used in reference 15. In assessing these results, the reader should keep in mind that the levels shown in figure 7 approximate those that would be heard with SPH-4 helmets on. The actual interior noise levels would be much higher.

Rating of combined noise and vibration.- The simulated helicopter environments of most interest are those containing both interior noise and vibration. The mean subjective discomfort responses to vibration combined with the high and moderate noise levels are presented in figure 8 for each aircraft. Also shown for comparison are the responses for the ambient noise condition. The solid lines represent the best-fit linear regression lines for each noise condition. The scatter about each regression line due to helicopter type is indicative of the effect of the frequency content associated with the noise and vibration spectra of each aircraft. Inspection of the data in figure 8 indicates several important features relevant to helicopter ride quality. For example, at high levels of vertical vibration (e.g., greater than $0.10g_{rms}$) the presence of high noise levels increased the discomfort ratings only slightly relative to the ambient noise condition. At lower values of vertical acceleration, however, the addition of the same high noise levels resulted in substantial increases in discomfort. Furthermore, for high interior noise levels the discomfort was relatively unaffected by the level of vibration present. These results clearly indicate the presence of interactive effects between the noise and vibration components of the environment. Specifically, the contribution to total discomfort response of one of the parameters (say noise) depends upon the level present within the environments of the other parameter (say vibration). Thus, in the assessment of helicopter passenger ride quality and in ride quality trade-off analyses, it will be important to understand and account for these interactive effects. In particular, it appears that reduction of one parameter only may not be sufficient to significantly improve ride quality. Instead a reduction in both parameters may generally be required. This result illustrates the need for a means of accurately and reliably estimating ride comfort in the combined environment.

Evaluation of Ride Quality Metrics

Unweighted and weighted acceleration.- The most fundamental metric that might be expected to correlate with subjective discomfort response is the unweighted rms acceleration level. The actual correlation of the obtained ratings with this metric is illustrated in figure 9(a), where the data are widely scattered, with a low positive linear correlation ($r = 0.551$) between the two parameters. Thus, it would be difficult to predict discomfort based upon unweighted rms vertical acceleration only. In an attempt to improve the correlation, human sensitivity frequency weighting was applied to each vibration spectrum and a weighted rms acceleration level was determined for each ride segment. The frequency weighting function (shown in fig. C1) approximates the inverse shape of the NASA discomfort threshold curve given in reference 10 and is similar to frequency weighting derived from the ISO criteria for vertical vibration (ref. 16). These weightings are intended to heavily weight the frequencies that most influence ride comfort and to minimize those that are less important. The scatter diagram for the weighted rms acceleration level is shown in figure 9(b). Application of the weighting function did not improve the linear correlation ($r = 0.535$) for this case. No significant improvement in correlation was obtained by attempting higher order curve fitting. This lack of improvement may be due to the fact that the dominant vibration frequencies were above 10 Hz and, therefore, not appreciably affected by the relative weighting. Both of the above results, however, imply that passenger ride quality in the combined environment was not accurately predicted by simple, physically derived, vibration metrics alone.

A-weighted noise level.- The relationship between A-weighted noise level and subjective discomfort is illustrated in figure 9(c). This figure does not contain the data of figure 5 corresponding to levels of L_A less than 60 dB. The correlation with L_A was somewhat higher ($r = 0.650$, second-order polynomial fit), although considerable scatter still remained. The higher correlation indicates that the use of the simple noise metric L_A provided a slight improvement in predictive ability. It is of interest to compare figures 9(a) and 9(c) with figures 6 and 7, respectively. Recall that figure 6 presented the mean discomfort responses as a function of rms vertical acceleration for the ambient noise condition and figure 7 showed discomfort as a function of noise level in the absence of vibration. In both cases the scatter of the data was greatly reduced, indicating that the correlation of the individual physical parameters with discomfort was higher. (Correlation coefficients were not obtained for these cases.) This implies that the use of the simple physical vibration or noise metrics may be adequate when only a single parameter is present. However, when both physical parameters are present, it will be necessary to resort to use of a metric that incorporates both parameters. Such a metric is the NASA discomfort index, whose application to the present data is discussed in the following section.

NASA discomfort index.- The inability of metrics based upon a single vibration or noise parameter to accurately predict subjective response to the combined noise and vibration environments led to the application of the NASA ride comfort model to the present data. The NASA model has been implemented on the Langley computer system and requires as input the recorded noise and vibration environments. Details of the model computational process and the procedure used to generate predicted discomfort levels are given in appendix C. Results of applying the model are presented in table X, which shows the predicted discomfort values, and in figure 9(d), which shows the relationship between the obtained pilots' discomfort ratings and the NASA discomfort (DISC) index. The DISC index is the basic output parameter of the NASA model and has units of subjective discomfort. For example, a DISC value of 1 represents the amount of discomfort associated with discomfort threshold. As seen in figure 9(d), the use of the NASA discomfort index greatly reduced the scatter and correlated much higher with the subjective ratings ($r = 0.914$, second-order fit).

The higher correlation is a result of the capability of the NASA model to account for the interactive effects of noise and vibration. This capability is discussed in detail in the next section.

Detailed Comparison of Ratings With NASA Model Predictions

Comparison of NASA ride comfort model predictions to the subjective ratings obtained in the present study could be done on an approximate basis only because of scale differences between the 9-point scale used in the present study and the ratio scale upon which the NASA discomfort index is based. The 9-point scale is subject to a "ceiling" effect, whereas the ratio scale is unbounded. Thus, in order to make reasonable comparisons, it was necessary to adjust the predicted responses to correct for scale differences. The procedure used is described in appendix C. The adjustment was valid over a range of predicted discomfort values up to about 4.0 DISC; that is, predicted DISC indices in excess of 4.0 could not be reliably expressed in equivalent 8-point scale values. This means that, in many cases, comparisons could not be made at the highest noise and/or vibration levels. For aircraft H-2, no meaningful comparisons could be made.

Comparisons of predicted DISC indices versus obtained subjective discomfort ratings (for the range over which such comparisons were considered valid) are illustrated in figures 10(a) to 10(d). These figures show the obtained and predicted discomfort as a function of L_A for low, moderate, and (where applicable) high vibration at the simulated cruise condition. Similar results were obtained for the hover condition. Figures 10(a) to 10(d) indicate that the NASA discomfort index performed well and predicted with good accuracy the discomfort due to the various combinations of interior noise and vibration. Such a capability has heretofore been unavailable. Its potential for assessing ride comfort and determining relative trade-offs between noise and vibration is readily apparent. For example, the relative contribution of noise and vibration to total predicted discomfort is illustrated in detail in figure 11 for the cruise condition of aircraft H-4. The discomfort ratings obtained from the subjects are indicated by the open bars. The predicted vibration discomfort component is indicated by the shaded bars, and the predicted noise component is indicated by the hatched bars. The total predicted discomfort is the sum of shaded and hatched bars. Values are presented for high and low interior noise levels, each of which is combined with high, moderate, and low vibration levels. The interplay of noise and vibration and their subsequent relative influence upon total discomfort is well illustrated in figure 11. At the high noise level the reduction of vibration from high to low levels resulted in little change in predicted total discomfort. This is consistent with the obtained ratings. Intuitively, total discomfort would be expected to decrease when vibration level decreased. The reason it did not is explained by examining the model estimates of the individual noise and vibration contributions to total discomfort. For high noise and high vibration the dominant contributor to the total predicted discomfort response was vibration. As vibration level decreased, the vibration discomfort component decreased, but the noise discomfort component increased and became the dominant factor. The result was little change in total discomfort. The reason for this was explained in reference 6 as being the ability of high levels of vibration to divert (or mask) attention from the noise. As vibration decreased, the subjects placed more emphasis upon the noise, as reflected by increased discomfort response to the noise. These predicted results again indicate that little benefit would be gained by reducing vibration in the presence of high interior noise levels. However, when the interior noise level is low (right half of fig. 11), reduction of vibration affords significant improvement in total subjective discomfort. The same relative interactive effects between noise and vibration that were present for high noise are also present here. The difference is that low noise contributes to total discomfort to a much lesser degree.

The data obtained in this study could also be used to derive approximate constant comfort criteria for the simulated helicopter environments. This was accomplished by applying a contour-generating computer program to the data of tables III, V, and X. This program, using best-fit least-squares methods, determined values of A-weighted noise level and rms floor acceleration that produce constant values of discomfort. The results are presented in figure 12, which gives the values of L_A and rms vertical acceleration that produce constant values of percent uncomfortable. The usefulness of these curves lies in the fact that they provide a possible format for future helicopter ride comfort criteria that incorporate the effects of both noise and vibration. It should be emphasized that the criteria curves of figure 12 are very tentative, since they were derived from ratings of simulated helicopter environments by a single group of helicopter pilots. More extensive data obtained during actual flights and from additional simulator testing would be required in order to derive improved criteria curves. A set of such curves, combined with the analysis/assessment capabilities of the NASA ride comfort model would provide a powerful new approach to the evaluation and specification of helicopter ride quality.

CONCLUSIONS

Results have been presented of a research investigation to quantify discomfort responses of helicopter pilots to helicopter interior noise and vibration typical of routine flights, to assess various ride quality metrics including the NASA ride comfort model, and to examine possible criteria approaches. The more important conclusions and implications are summarized as follows.

1. The subjective discomfort responses to vibration of the helicopter pilots were approximately the same as the discomfort responses obtained in earlier ride quality studies in which subjects were obtained from the general public. This indicated that training and flying experience with the various aircraft did not affect their comfort expectations, implying that pilot evaluation of ride comfort may be used as an indicator of passenger acceptance.

2. Overall measures such as unweighted and weighted root-mean-square acceleration level and A-weighted noise level were not good predictors of discomfort. Accurate prediction required a metric incorporating the interactive effects of both noise and vibration. It was demonstrated that control and/or reduction of either noise or vibration alone may not be sufficient to significantly improve ride quality. Instead, a reduction of both parameters may be required. Thus, any ride quality assessment method must be capable of accounting for the combined effects of noise and vibration.

3. The best prediction of discomfort response was the NASA discomfort index obtained by application of the NASA ride comfort model. Because of its ability to handle both noise and vibration, the NASA model accurately predicted discomfort in the presence of various combinations of these parameters. This makes it a potentially valuable tool for use in the prediction and assessment of total ride quality, as well as the relative discomfort trade-offs between noise and vibration components of a ride environment. A set of approximate and tentative constant comfort contours were presented as an example of a possible format for specifying allowable levels of interior noise and vibration. These contours incorporated the interactive effects of

noise and vibration and could be used to obtain an immediate indication of whether individual noise and vibration levels, acting in combination, would meet a specified acceptance criterion. Such contours, used in conjunction with the NASA ride comfort model, may provide a powerful design tool for the ride quality engineer.

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February 6, 1984

APPENDIX A

INSTRUCTIONS EXPLAINING USE OF DISCOMFORT SCALE

Subject Instructions

You have volunteered to participate in a research program to investigate ride quality within helicopters. Specifically, we wish to identify the helicopter environments which most influence a person's sense of comfort or discomfort. To assess the influence of these environments, we have built a simulator which can expose passengers to realistic sounds and vibrations. 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 noises or vibrations 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 environments that you will experience today are representative of those you may have encountered in helicopters. You will enter the simulator, take a seat, fasten the seatbelt, and assume a comfortable position with both feet on the floor. Selected helicopter environments 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 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 or environments 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 discomfort 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. There will be several seconds between successive ride segments to allow you to mark your evaluations.

Evaluations.- There are three requirements you should use in your evaluations. First, your evaluations should be based upon the environment experienced during the ride segment that you are rating. Second, please rate each ride segment in terms of the level of comfort or discomfort experienced during the ride segment, not on whether you notice differences of vibration and noise. This requirement is important because we are interested in differences of comfort, not merely in your ability to detect differences of vibrations and noises. Third, please base your evaluations upon how you would feel as a passenger or crew member, not upon your ability to perform flight tasks. You will be asked to make two evaluations of the comfort associated with each ride segment. First, please indicate your overall opinion of whether the ride segment is uncomfortable by marking the appropriate space on the evaluation sheet. If the ride is uncomfortable, mark "YES" and if not uncomfortable mark "NO." Secondly, you should record your evaluation of the discomfort associated with each ride segment by placing a checkmark (✓) upon the scale. For example, a ride segment causing little discomfort should be scored toward the "0 - zero discomfort" end of the scale. Similarly, if you judge a ride segment to cause a large amount of discomfort, you would place your checkmark toward the "8 - maximum discomfort" end of the scale.

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

Are there any questions?

APPENDIX B

SAMPLE RATING SHEET

Subject Number ___
Aviation Rating ___

Date ___ a.m. ___ p.m. ___
Age ___ Weight ___ Sex ___

Ride Number	Uncomfortable No	Uncomfortable Yes	Zero Discomfort — Maximum Discomfort (0 1 2 3 4 5 6 7 8)
21	___	___	0 1 2 3 4 5 6 7 8
22	___	___	
23	___	___	
24	___	___	
25	___	___	
26	___	___	
27	___	___	
28	___	___	
29	___	___	
30	___	___	
31	___	___	
32	___	___	
33	___	___	
34	___	___	
35	___	___	
36	___	___	
37	___	___	
38	___	___	
39	___	___	
40	___	___	

APPENDIX C

COMPUTATION OF PREDICTED DISCOMFORT

Description of NASA Model

A series of experimental studies using approximately 3000 test subjects has led to the development of a general, comprehensive model for estimating passenger ride discomfort/acceptance in the presence of complex interior noise and vibration environments. This model (see ref. 6) accounts for the effects upon subjective comfort of multiple frequency and multiple axis vibrations combined with interior noise. In the present paper, however, only vertical axis vibration and interior noise were of interest. The procedure used to compute estimated discomfort is a simplification of the approach given in reference 6. Whereas reference 6 required detailed evaluation of the spectral content (i.e., detailed identification of dominant spectral peaks and associated levels), the approach used in the present study utilized frequency weighting of the vibration spectra in accordance with human vibration frequency sensitivity characteristics. The frequency weighting curve for the vertical axis of vibration is shown in figure C1. This curve was derived from the equal discomfort contour corresponding to discomfort threshold for narrowband (2 Hz bandwidth) random vibration.

The basic outputs of the NASA model are a set of discomfort indices that represent total absolute discomfort (or acceptance) of a given environment as well as indices reflecting the relative contributions of noise and vibration to total discomfort. It is important to note that the NASA discomfort indices (called DISC's) are measured in terms of subjective discomfort units. This characteristic allows summation of discomfort due to different modalities such as noise and vibration. The NASA discomfort indices are measured along a ratio scale of discomfort (DISC scale) such that the numerical values of the indices bear a direct ratio relationship to one another. For example, a discomfort value, say DISC = 2, corresponds to twice the discomfort associated with DISC = 1. Similarly, a value of DISC = 0.5 represents one-half the discomfort corresponding to DISC = 1.0. For the NASA laboratory studies a value of DISC = 1.0 was selected to represent discomfort threshold, i.e., the discomfort level which 50 percent of the subject population rated as being uncomfortable.

Correction for Scale Differences

In the present investigation the subjects evaluated helicopter ride comfort using a numerical category scale. (See appendixes A and B.) Thus, in comparing results obtained from the category scale with estimated discomfort predicted by the NASA model, it was necessary to adjust for scale differences. These differences are due to the fact that the category scale values are limited by the selected range of the scale (0 to 8 in this case) and by the tendency of subjects to fill the midportion of the scale. The NASA discomfort scale, however, is unbounded. Thus, at the higher scale values the model predictions become increasingly disparate from category scale ratings.

These scale differences were accounted for in the present study by determining the relationship between the mean subjective ratings obtained from the pilots and the predicted discomfort levels obtained from the NASA model. This relationship is shown in figure C2, which contains the mean subjective ratings and discomfort predictions for each condition of table II. The curve shown in the figure is a second-order polynomial fit to the data which shows a "ceiling" effect when the obtained ratings are plotted against predicted discomfort values. Thus, in order to compare model predictions with obtained discomfort ratings, it is necessary to correct for these scale differences. This was done by applying the following equation, which is the polynomial curve shown in figure C2:

$$D_{adj} = -0.882 + 2.1017D_{pred} - 0.1749D_{pred}^2 \qquad (C1)$$

where

D_{adj} predicted discomfort adjusted for scale differences

D_{pred} discomfort predicted by NASA ride comfort model (uncorrected for scale differences)

Procedure

The actual procedure used to compute adjusted discomfort estimates for each ride segment using the NASA model approach is summarized in the following steps:

(1) Compute the power spectral density (psd) of vertical simulator vibration and determine the A-weighted cabin noise levels within the 63, 125, 250, 500, 1000, and 2000 Hz octave bands, for each ride segment.

(2) Apply the weighting function of figure C1 to each vibration psd. Note: This involves squaring each value of figure C1.

(3) Integrate the result to obtain a weighted rms vertical acceleration (g_{wtd}) level for each ride segment.

(4) Compute the vertical vibration discomfort component D_{vib} for each ride segment by using the following equations:

$$D_{vib} = 68.772g_{wtd} \qquad (g_{wtd} < 0.01) \qquad (C2a)$$

$$D_{vib} = 0.241 + 44.672g_{wtd} \qquad (g_{wtd} \geq 0.01) \qquad (C2b)$$

(5) Compute discomfort due to noise within each of the octave bands of step (1) by using the following equation:

$$D_N(i,L_A) = (a_i + b_i D_{vib})(WF_i) \qquad (C3)$$

where

$D_N(i,L_A)$ noise discomfort due to ith octave band having A-weighted noise level L_A

a_i,b_i empirically determined constants listed in table CI

WF_i weighting factor that corrects for effect of ith noise octave band (see table CII)

For values of $L_A < 65$, set $D_N(i,L_A) = 0$; for values of $L_A > 100$, use $L_A = 100$ in the computation of $D_N(i,L_A)$. Also, if $D_N(i,L_A) < 0$, set $D_N(i,L_A) = 0$.

(6) Compute total noise discomfort contribution using

$$D_{N,tot} = D_N(i,L_A)_{max} + 0.3\left[\sum D_N(i,L_A) - D_N(i,L_A)_{max}\right] \tag{C4}$$

where $D_{N,tot}$ is the total noise discomfort resulting from noise in one or more of the six octave bands.

(7) Compare total predicted discomfort using

$$D_{pred} = D_{vib} + D_{N,tot}$$

(8) Adjust predicted discomfort D_{adj} for scale differences using equation (C1). The results of step (8) are the estimated discomfort indices used in figure 9(d).

TABLE CI.- VALUES OF SLOPE AND INTERCEPT FOR EQUATION (C3)

Noise level, L_A	Intercept, a_i	Slope, b_i	Noise level, L_A	Intercept, a_i	Slope, b_i
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 CII.- OCTAVE BAND WEIGHTING FACTORS

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

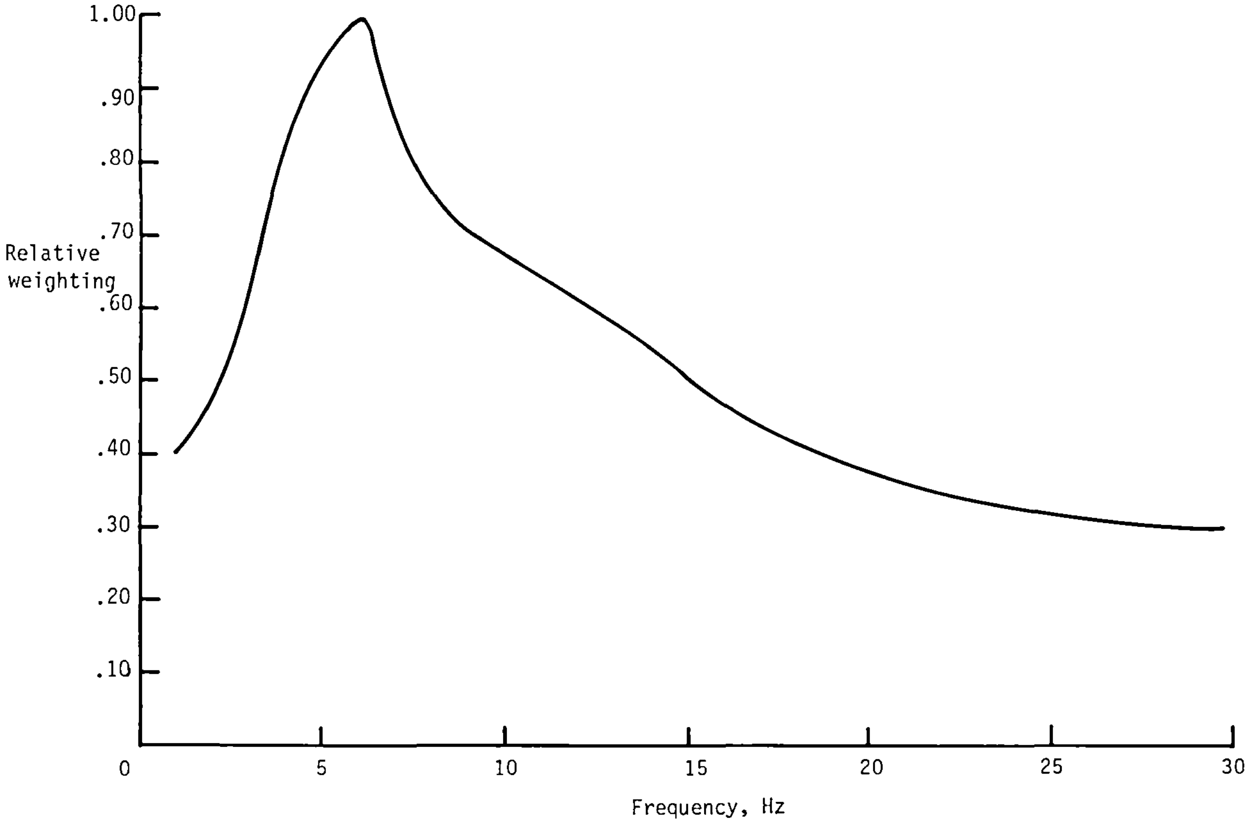

Figure C1.- Relative frequency weighting for vertical-axis vibration.

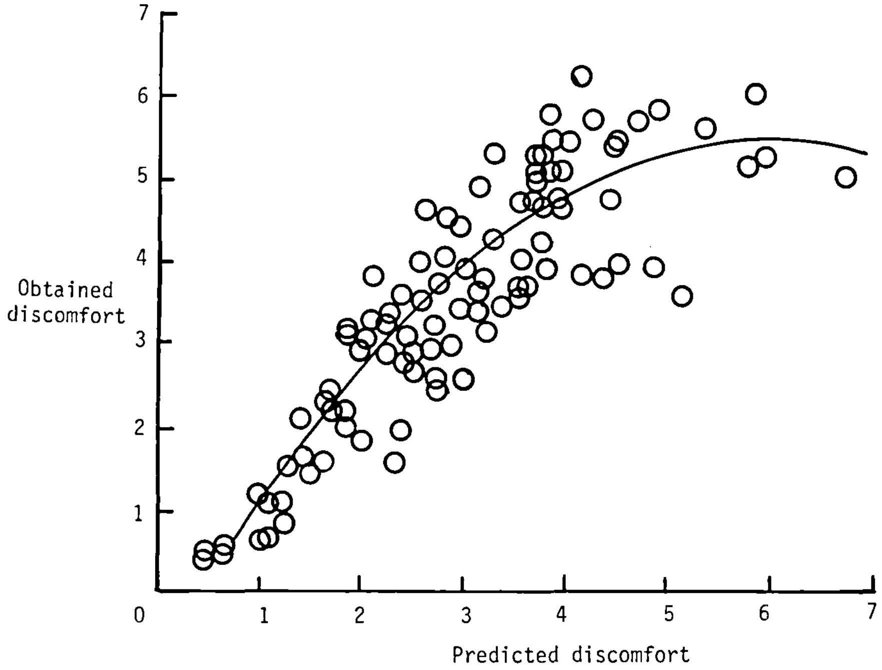

Figure C2.- Relationship between category scale ratings (obtained discomfort) and predicted discomfort.

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TABLE I.- ATTENUATION CHARACTERISTICS OF SPH-4 HELMET

Frequency, Hz	Attenuation, dB
75	17
125	16
250	14
500	25
1000	24
2000	30
3000	40
4000	43
6000	44
8000	36

TABLE II.- EXPERIMENTAL DESIGN

Vibration level (a)	Noise level (b)	H-1	H-2	H-3	H-4	H-5	H-1	H-2	H-3	H-4	H-5
		Cruise					Hover				
High	1 2 3 4										
Moderate	1 2 3 4										
Low	1 2 3 4										

[a]High: full; moderate: -3 dB; low: -9 dB.
[b]1: full; 2: -7 dB; 3: -14 dB; 4: ambient; includes attenuation of SPH-4 helmet characteristics.

TABLE III.- ROOT-MEAN-SQUARE ACCELERATION LEVELS FOR EACH STIMULUS CONDITION

[Averaged over all runs[a]]

Vibration level	Noise level	rms acceleration levels of aircraft -									
		H-1	H-2	H-3	H-4	H-5	H-1	H-2	H-3	H-4	H-5
		Cruise					Hover				
High	1	0.115	0.142	0.115	0.096	0.089	0.060	0.086	0.050	0.061	0.031
	2	.117	.124	.094	.096	.089	.061	.092	.049	.061	.031
	3	.121	.124	.114	.095	.089	.061	.091	.050	.062	.031
	4	.117	.084	.111	.096	.088	.061	.085	.046	.061	.031
Moderate	1	0.064	0.069	0.061	0.050	0.050	0.034	0.024	0.027	0.033	0.018
	2	.066	.073	.063	.052	.049	.033	.043	.029	.034	.018
	3	.066	.076	.061	.051	.050	.033	.045	.028	.034	.029
	4	.065	.074	.064	.052	.051	.033	.046	.027	.033	.018
Low	1	0.023	0.023	0.024	0.018	0.020	0.014	0.016	0.013	0.012	0.007
	2	.028	.024	.026	.019	.019	.012	.016	.010	.013	.007
	3	.024	.024	.023	.019	.019	.013	.017	.010	.012	.007
	4	.025	.025	.024	.020	.019	.025	.015	.011	.012	.007

[a]Standard deviations for vertical acceleration are typically 12.4 percent of the mean values.

TABLE IV.- OVERALL SOUND PRESSURE LEVELS FOR EACH STIMULUS CONDITION

[Averaged over all runs[a]]

Vibration level	Noise level	OASPL of aircraft -									
		H-1	H-2	H-3	H-4	H-5	H-1	H-2	H-3	H-4	H-5
		Cruise					Hover				
High	1	97	98	99	97	95	96	96	97	94	95
	2	93	94	97	93	91	91	93	93	89	89
	3	91	93	97	89	87	89	92	91	88	85
	4	90	91	96	90	86	87	90	92	85	83
Moderate	1	96	97	97	97	95	96	96	97	94	95
	2	91	93	94	91	89	90	90	92	89	89
	3	88	90	92	88	86	86	88	90	85	85
	4	86	89	93	85	83	84	88	86	83	81
Low	1	95	97	96	96	95	96	95	96	94	95
	2	90	91	92	90	89	90	90	90	88	90
	3	85	87	86	86	84	84	86	86	85	84
	4	83	85	85	85	80	81	82	82	82	78

[a]Standard deviations within ±2 dB.

TABLE V.- A-WEIGHTED SOUND PRESSURE LEVELS FOR EACH STIMULUS CONDITION

[Averaged over all runs[a]]

Vibration level	Noise level	L_A of aircraft -									
		H-1	H-2	H-3	H-4	H-5	H-1	H-2	H-3	H-4	H-5
		Cruise					Hover				
High	1	87	91	91	89	88	88	90	90	87	89
	2	81	86	85	83	83	81	85	84	80	83
	3	75	80	79	76	75	74	78	77	73	76
	4	<60	66	67	62	<60	<60	64	<60	61	<60
Moderate	1	87	91	91	89	89	87	90	90	87	88
	2	81	85	85	83	82	81	83	84	80	83
	3	74	79	78	76	76	74	77	77	73	76
	4	<60	65	<60	<60	60	<60	<60	<60	<60	<60
Low	1	87	92	91	89	88	87	90	90	86	89
	2	81	85	85	82	83	81	84	84	80	83
	3	74	78	79	76	75	74	78	77	73	76
	4	60	<60	<60	<60	<60	<60	<60	<60	<60	<60

[a]Standard deviations within ±2 dB.

TABLE VI.- ACCELERATION LEVELS OF CALIBRATION RIDES

[Sinusoidal vibration applied at 9 Hz]

Ride	Acceleration level, g_p
1	0.109
2	.222
3	.200
4	.086
5	.245
6	.131
7	.063
8	.154
9	.177
10	.040

TABLE VII.- MEAN RATINGS OF ARMY AND NAVY PILOTS

[Averaged over all subjects]

Vibration level	Noise level	Mean ratings for aircraft -									
		H-1	H-2	H-3	H-4	H-5	H-1	H-2	H-3	H-4	H-5
		Cruise					Hover				
High	1	4.70	6.03	5.72	5.72	6.28	5.48	5.62	5.25	4.00	4.76
	2	5.31	5.80	4.22	4.68	4.73	3.94	3.93	3.75	4.06	3.74
	3	5.09	5.30	4.28	4.88	3.75	3.09	3.40	3.07	2.92	2.89
	4	5.07	3.20	4.63	3.65	4.52	3.32	3.16	2.48	3.12	2.16
Moderate	1	5.79	6.04	5.44	4.94	5.44	3.93	5.17	4.82	3.64	5.30
	2	3.55	3.92	3.44	3.82	4.40	3.23	3.74	4.00	2.72	2.99
	3	3.52	2.80	3.36	3.20	2.96	2.18	2.76	1.81	2.12	2.29
	4	3.58	2.39	2.54	3.13	2.46	2.12	1.55	1.12	1.47	.87
Low	1	4.67	5.01	5.48	5.07	5.54	3.65	5.28	4.97	3.14	4.64
	2	2.51	3.53	3.37	2.58	3.44	2.84	3.82	2.63	2.00	2.93
	3	2.32	1.83	1.94	1.62	1.62	1.22	1.55	1.82	1.23	1.65
	4	1.10	.45	1.22	.64	.67	.45	.53	.47	.35	.56

TABLE VIII.- STANDARD DEVIATIONS OF SUBJECTIVE DISCOMFORT RATINGS

Vibration level	Noise level	Standard deviation for aircraft -									
		H-1	H-2	H-3	H-4	H-5	H-1	H-2	H-3	H-4	H-5
		Cruise					Hover				
High	1	1.78	1.31	1.94	1.77	1.46	1.40	1.23	1.45	1.72	1.60
	2	1.39	1.30	1.75	1.49	1.38	1.40	1.70	1.56	1.40	1.32
	3	1.59	1.55	1.43	1.59	1.71	1.40	1.44	1.46	1.26	1.50
	4	1.76	1.52	1.65	1.42	1.47	1.66	1.52	1.49	1.62	1.16
Moderate	1	1.49	1.24	1.38	1.62	1.82	1.52	1.46	2.06	1.77	1.58
	2	1.37	1.71	1.51	1.27	1.32	1.68	1.18	1.76	1.65	1.91
	3	1.43	1.13	1.37	1.63	1.46	1.20	1.52	.96	1.52	1.52
	4	1.81	1.39	1.35	1.30	1.42	1.74	1.08	1.02	1.34	1.12
Low	1	1.73	1.83	1.99	1.90	1.78	1.63	1.97	2.00	1.87	1.96
	2	1.22	1.93	1.74	1.77	1.64	1.70	1.84	1.63	1.40	1.57
	3	1.49	1.51	1.23	1.18	1.19	1.09	1.25	1.88	1.16	1.35
	4	1.20	.66	1.33	.76	.79	.57	.84	.73	.54	1.34

TABLE IX.- PERCENT OF PILOTS RATING EACH HELICOPTER RIDE SEGMENT AS UNCOMFORTABLE

Vibration level	Noise level	Percent uncomfortable for aircraft -									
		H-1	H-2	H-3	H-4	H-5	H-1	H-2	H-3	H-4	H-5
		Cruise					Hover				
High	1	91.4	97.1	97.1	97.1	100.0	97.1	100.0	97.1	88.6	97.1
	2	91.4	97.1	82.8	82.8	91.4	91.4	82.8	88.6	82.8	91.4
	3	97.1	91.4	82.8	97.1	91.4	71.4	80.0	77.1	80.0	51.4
	4	91.4	82.1	97.1	82.8	97.1	77.1	80.0	60.0	82.8	62.8
Moderate	1	97.1	100.0	97.1	97.1	97.1	91.4	97.1	97.1	82.8	97.1
	2	82.8	82.8	80.0	91.4	91.4	68.6	77.1	97.1	62.8	62.8
	3	80.0	51.4	88.6	77.1	68.6	48.6	80.0	42.8	57.1	71.4
	4	82.8	62.8	68.6	80.0	68.6	60.0	42.8	22.8	37.1	11.4
Low	1	91.4	97.1	97.1	91.4	91.4	91.4	97.1	97.1	68.6	97.1
	2	68.6	80.0	80.0	68.6	82.8	71.4	88.6	62.8	42.8	82.8
	3	51.4	40.0	57.1	37.1	40.0	28.6	22.8	37.1	28.6	51.4
	4	20.0	2.8	31.4	15.7	11.4	11.4	8.6	2.8	8.6	11.4

TABLE X.- DISCOMFORT LEVELS PREDICTED BY NASA MODEL

[Adjusted for differences between scales]

Vibration level	Noise level	DISC levels for aircraft -									
		H-1	H-2	H-3	H-4	H-5	H-1	H-2	H-3	H-4	H-5
		Cruise					Hover				
High	1	4.99	5.38	5.13	4.90	4.80	4.63	5.36	4.57	4.39	4.68
	2	4.74	5.22	4.55	4.56	4.48	3.90	5.04	3.57	3.66	3.72
	3	4.70	4.16	4.13	4.00	4.03	3.22	3.80	2.70	3.32	2.59
	4	4.56	2.61	3.44	4.02	3.68	2.75	2.42	2.14	2.76	2.03
Moderate	1	4.61	5.43	5.02	4.64	4.76	4.57	5.42	4.62	4.35	4.51
	2	4.41	5.21	4.25	3.86	3.85	3.54	4.95	3.35	3.29	3.72
	3	3.38	3.87	3.03	2.96	3.17	2.27	3.23	2.41	2.33	2.14
	4	3.17	2.26	2.48	2.41	2.39	1.70	1.52	1.22	1.91	1.45
Low	1	4.36	5.34	5.03	4.48	4.53	4.41	5.43	4.52	4.06	4.70
	2	3.60	5.29	4.00	3.57	3.40	3.00	4.82	2.77	2.42	3.48
	3	2.08	2.61	3.14	1.77	2.09	1.26	3.05	1.75	1.24	1.64
	4	1.37	.45	.99	1.04	1.13	.45	.03	.43	.03	.43

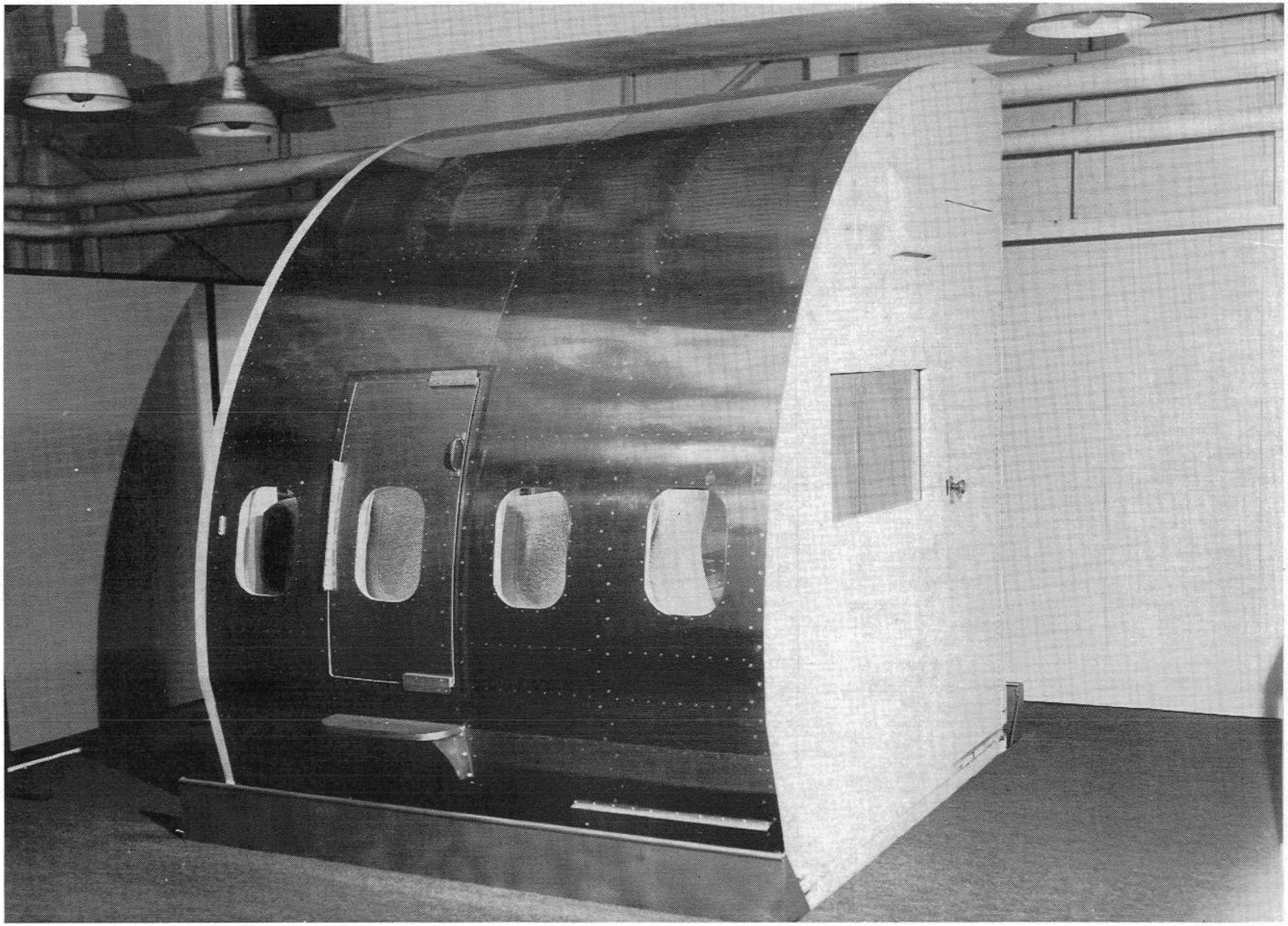

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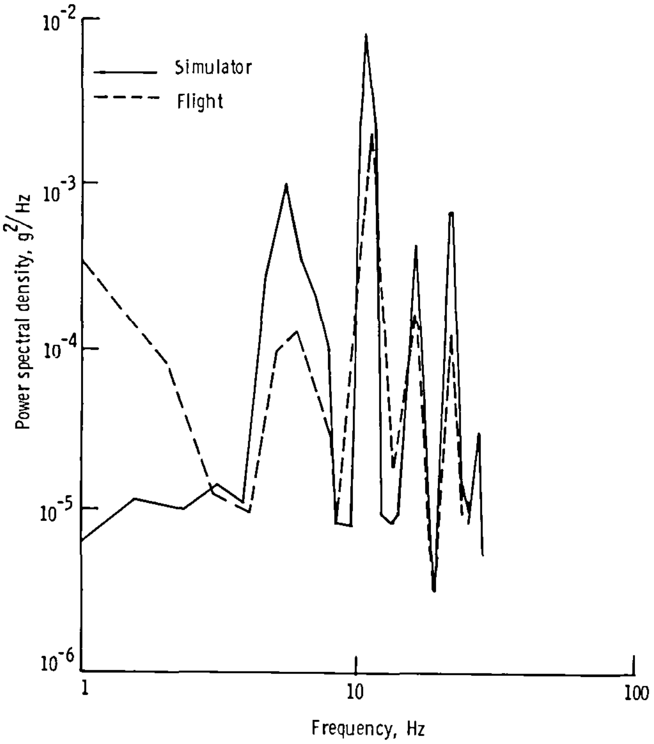
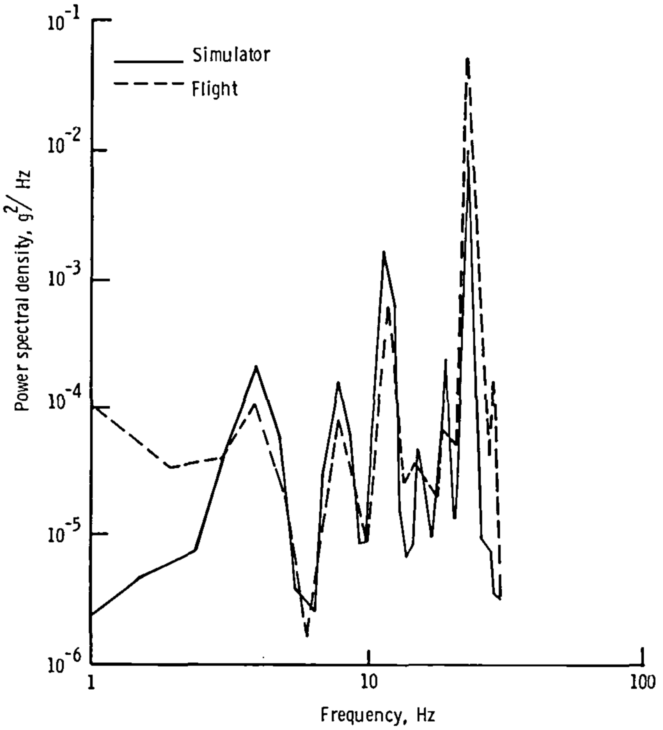
Figure 1.- Exterior view of passenger ride quality apparatus at the Langley Research Center.

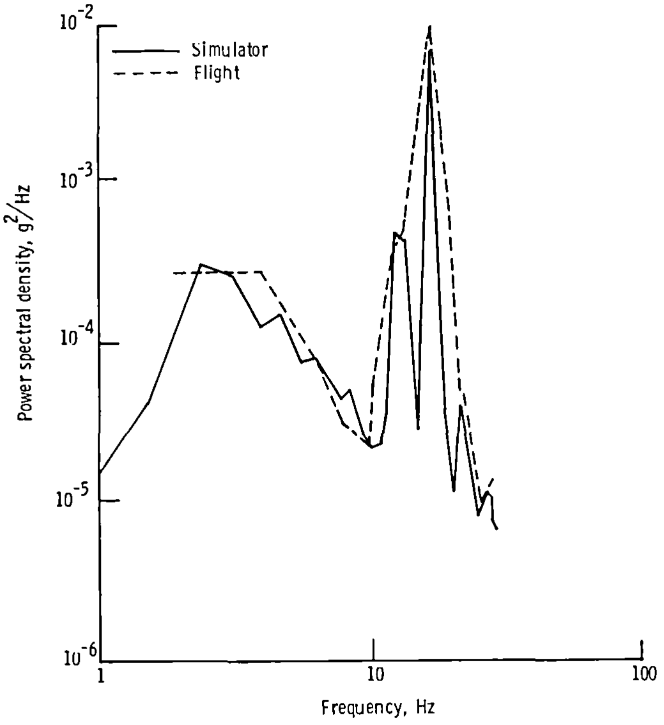


(a) Aircraft H-1.

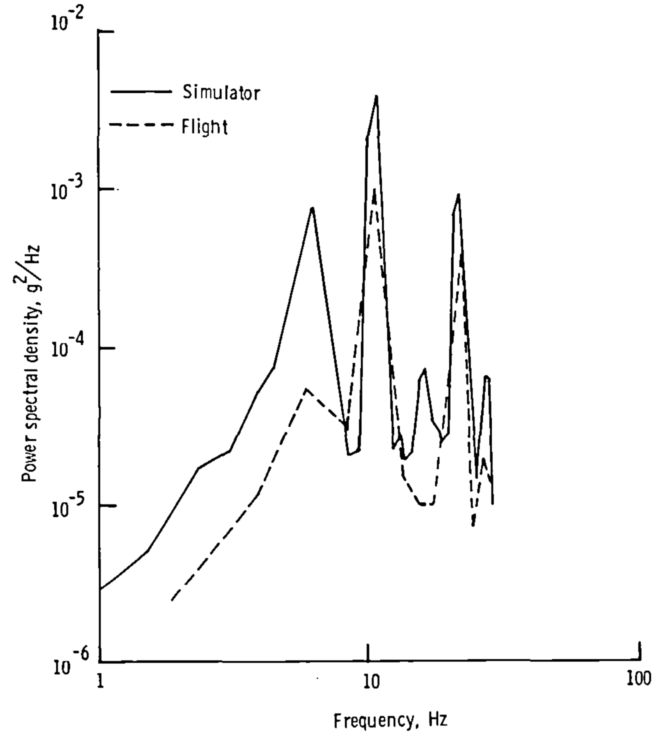


(b) Aircraft H-2.

Figure 2.- Comparisons of simulator output acceleration spectra with measured helicopter acceleration spectra for cruise condition.

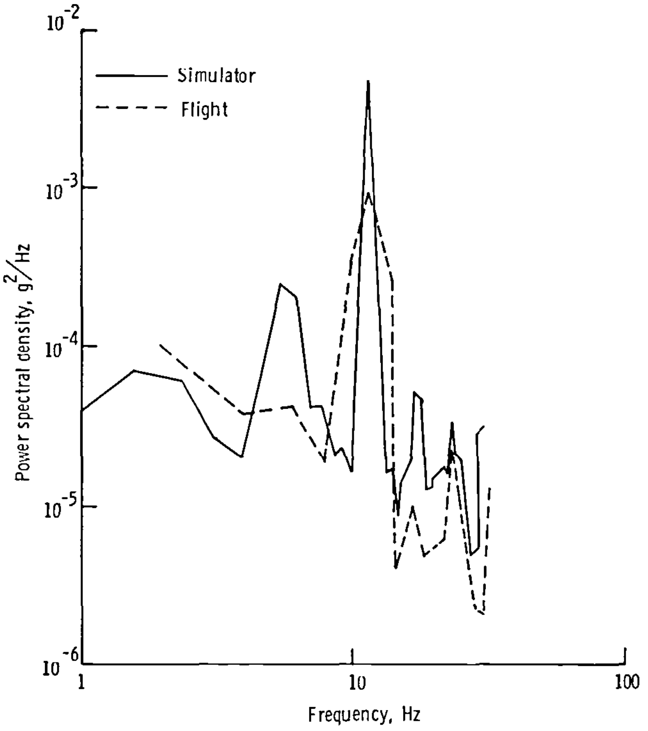


(c) Aircraft H-3.



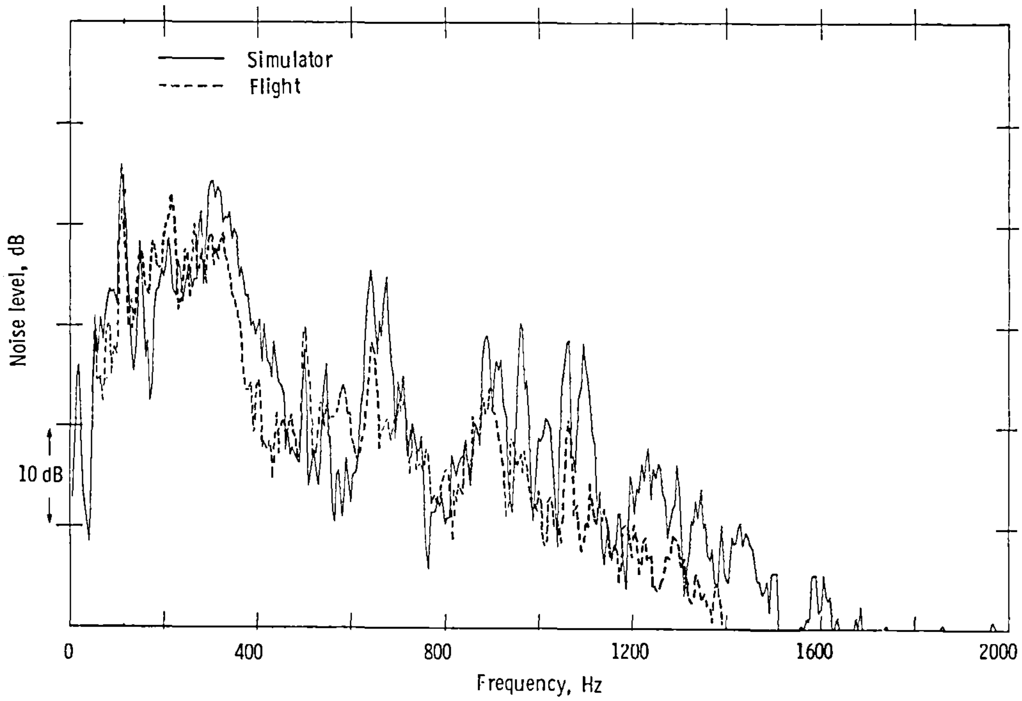
(d) Aircraft H-4.

Figure 2.- Continued.

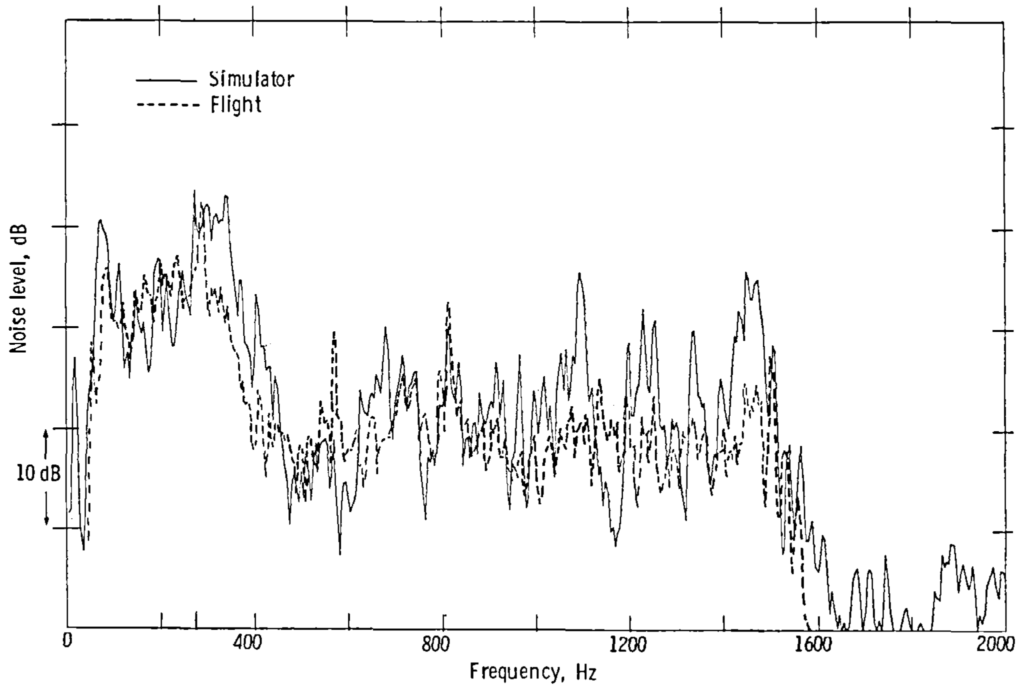


(e) Aircraft H-5.

Figure 2.- Concluded.

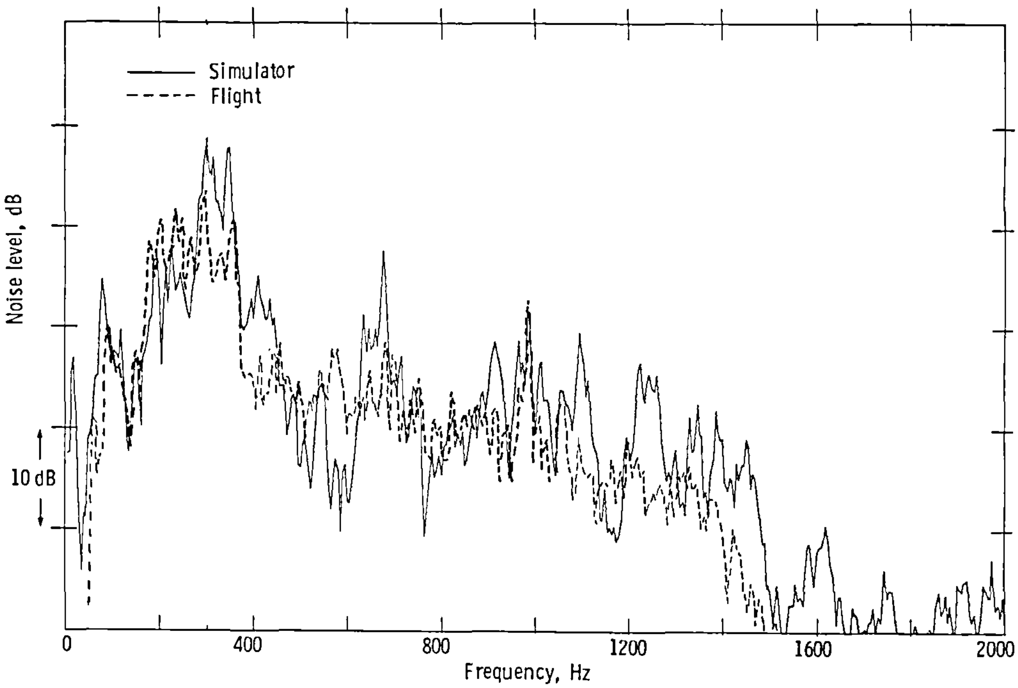


(a) Aircraft H-1.

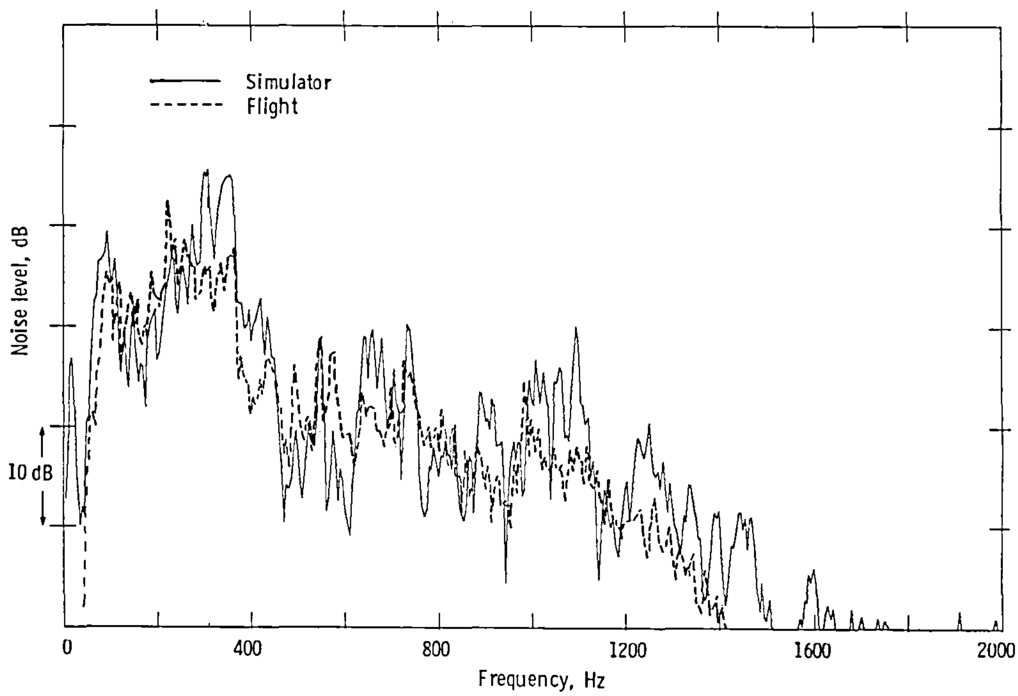


(b) Aircraft H-2.

Figure 3.- Comparisons of helicopter overall noise spectra with measured helicopter overall noise spectra for cruise condition.

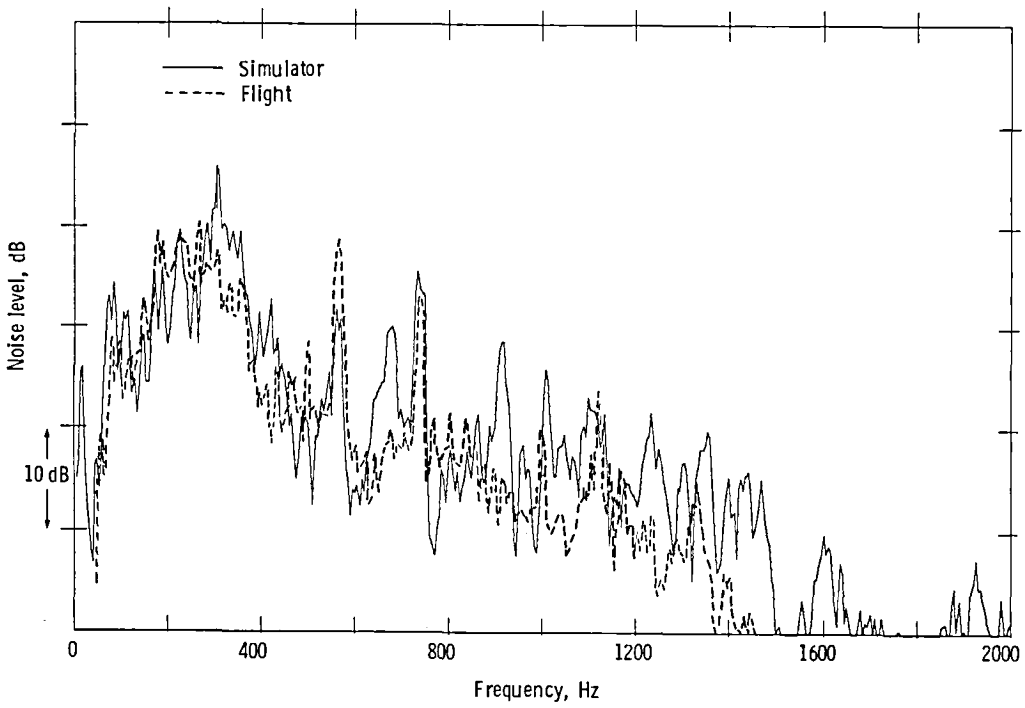


(c) Aircraft H-3.



(d) Aircraft H-4.

Figure 3.- Continued.



(e) Aircraft H-5.

Figure 3.- Concluded.

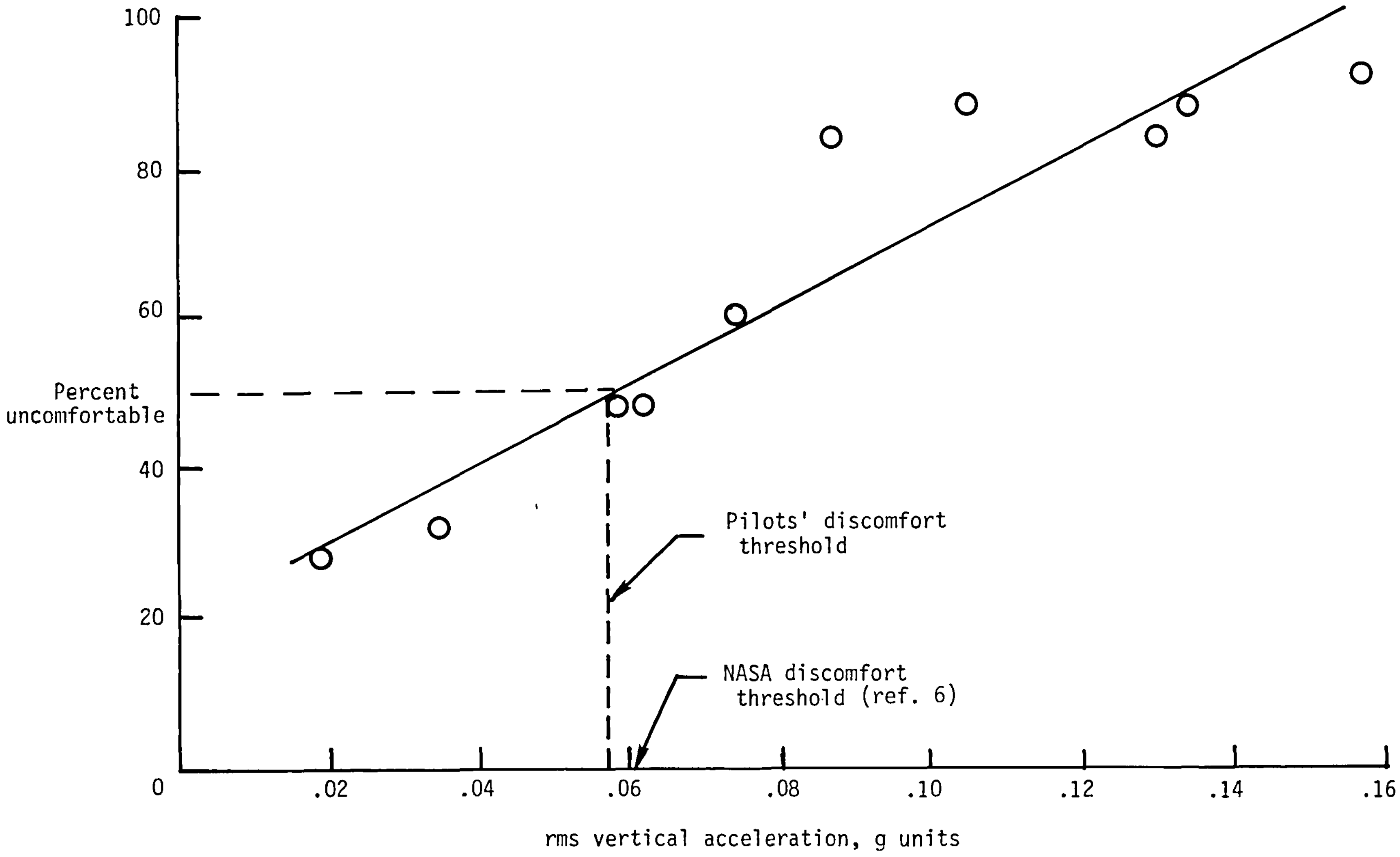


Figure 4.- Discomfort threshold of pilots.

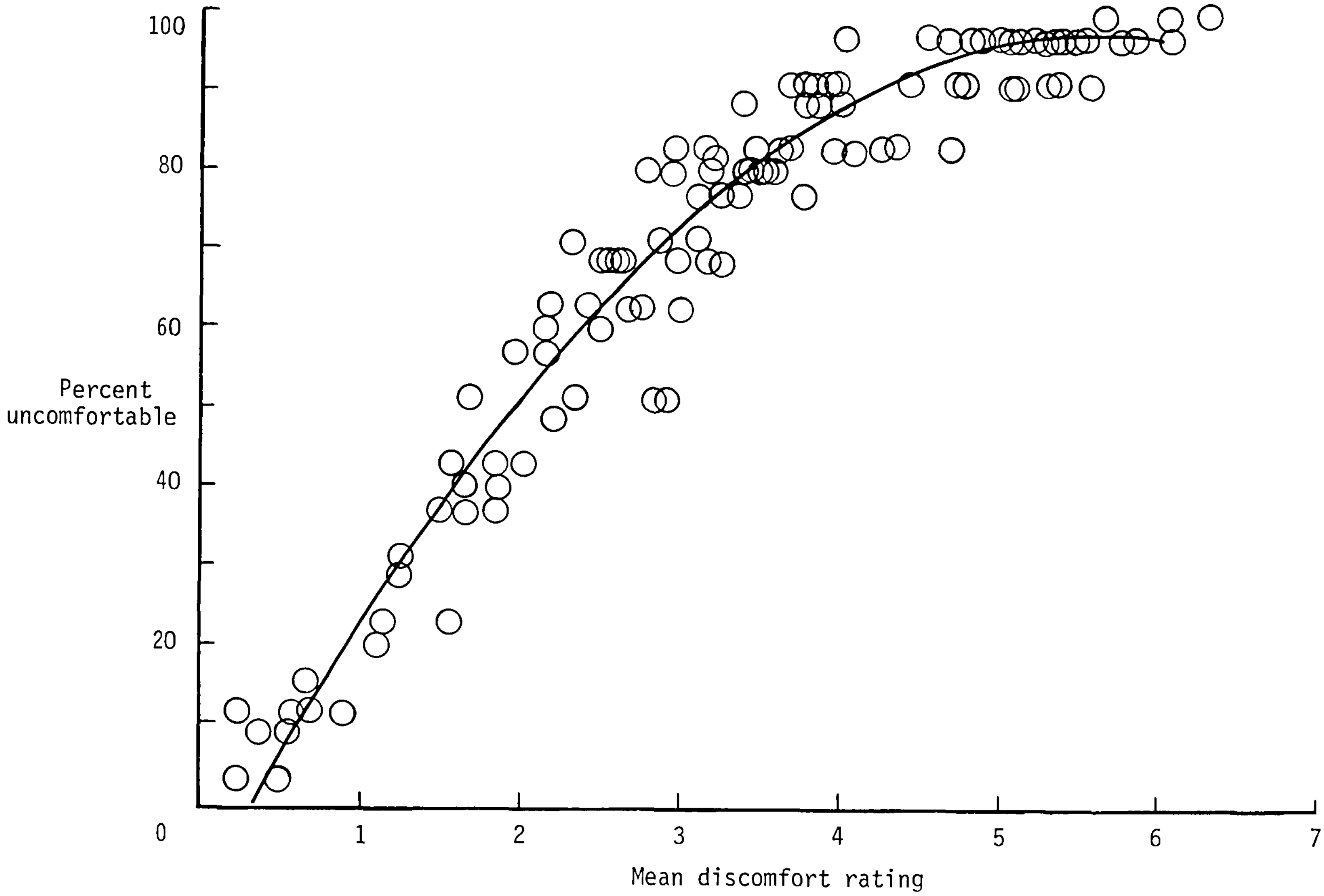
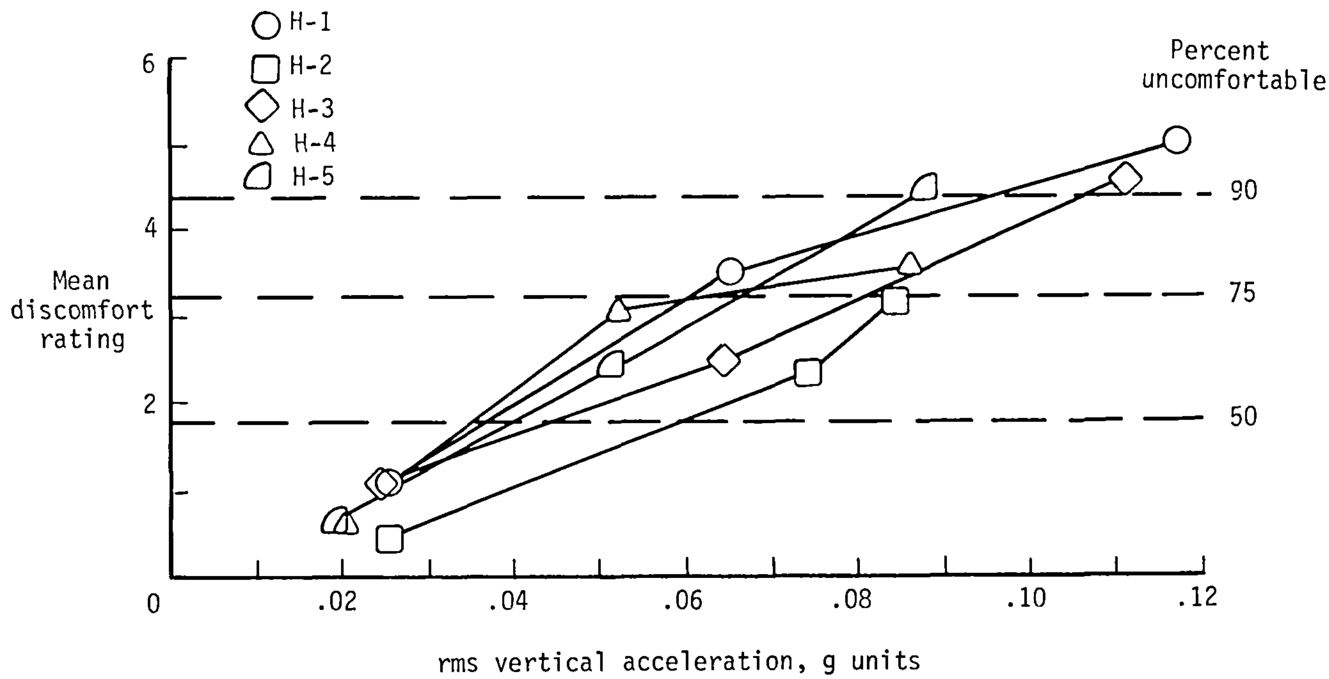
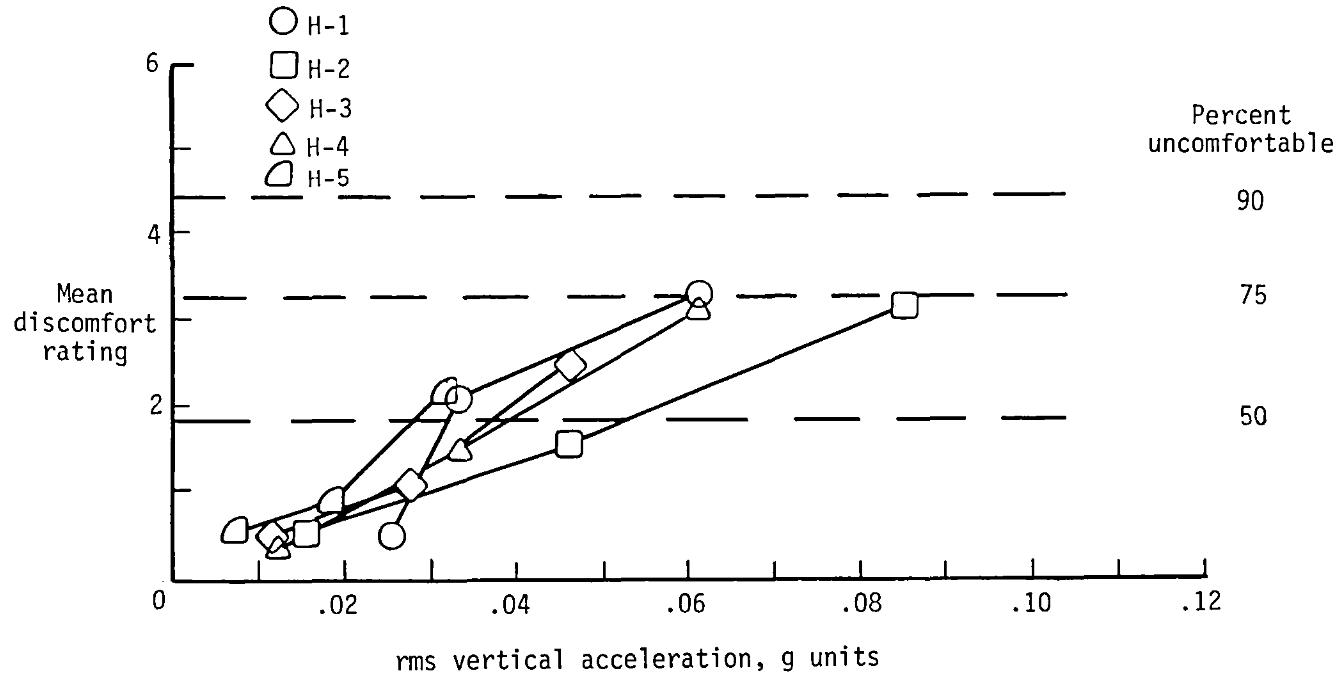


Figure 5.- Relationship between percent uncomfortable and 9-point rating scale.

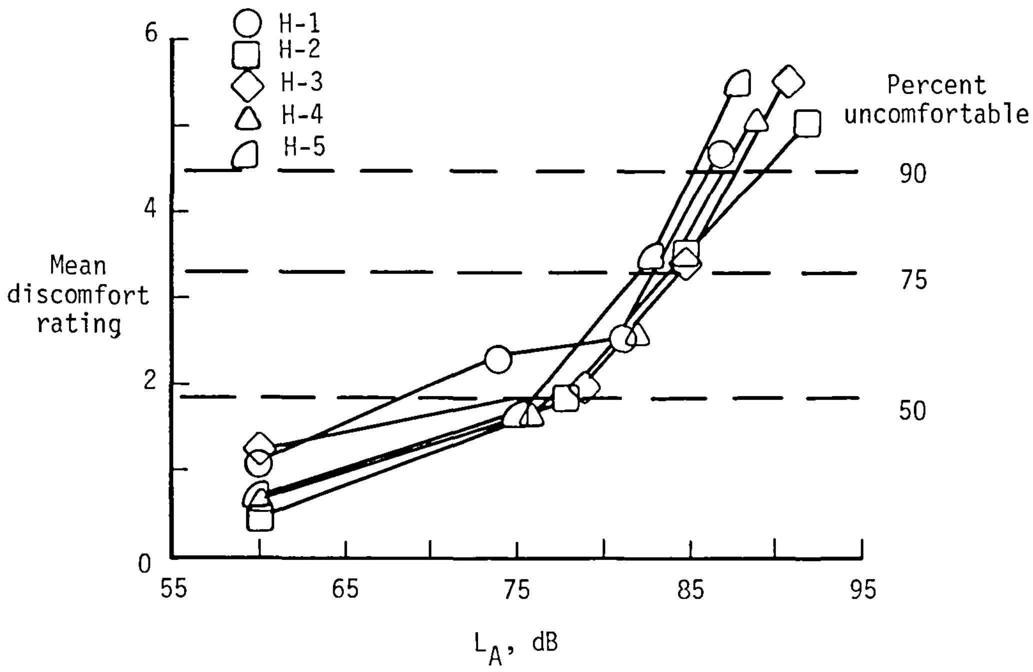


(a) Cruise.

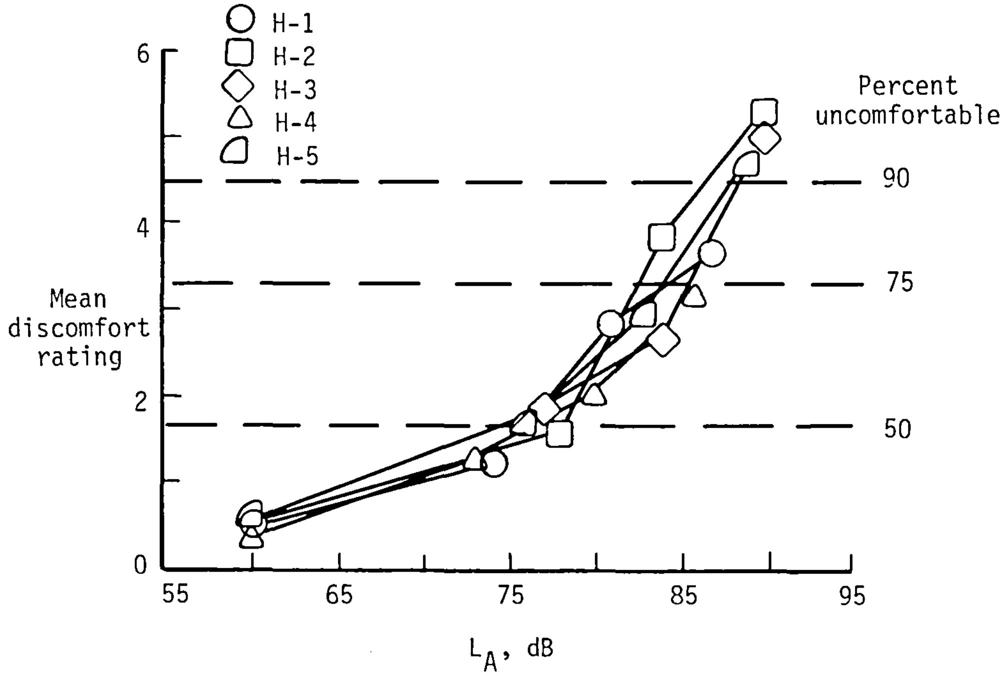


(b) Hover.

Figure 6.- Mean discomfort rating as function of rms vertical acceleration for cruise and hover conditions (ambient noise only).



(a) Cruise.



(b) Hover.

Figure 7.- Mean discomfort rating as function of A-weighted noise level for low vibration.

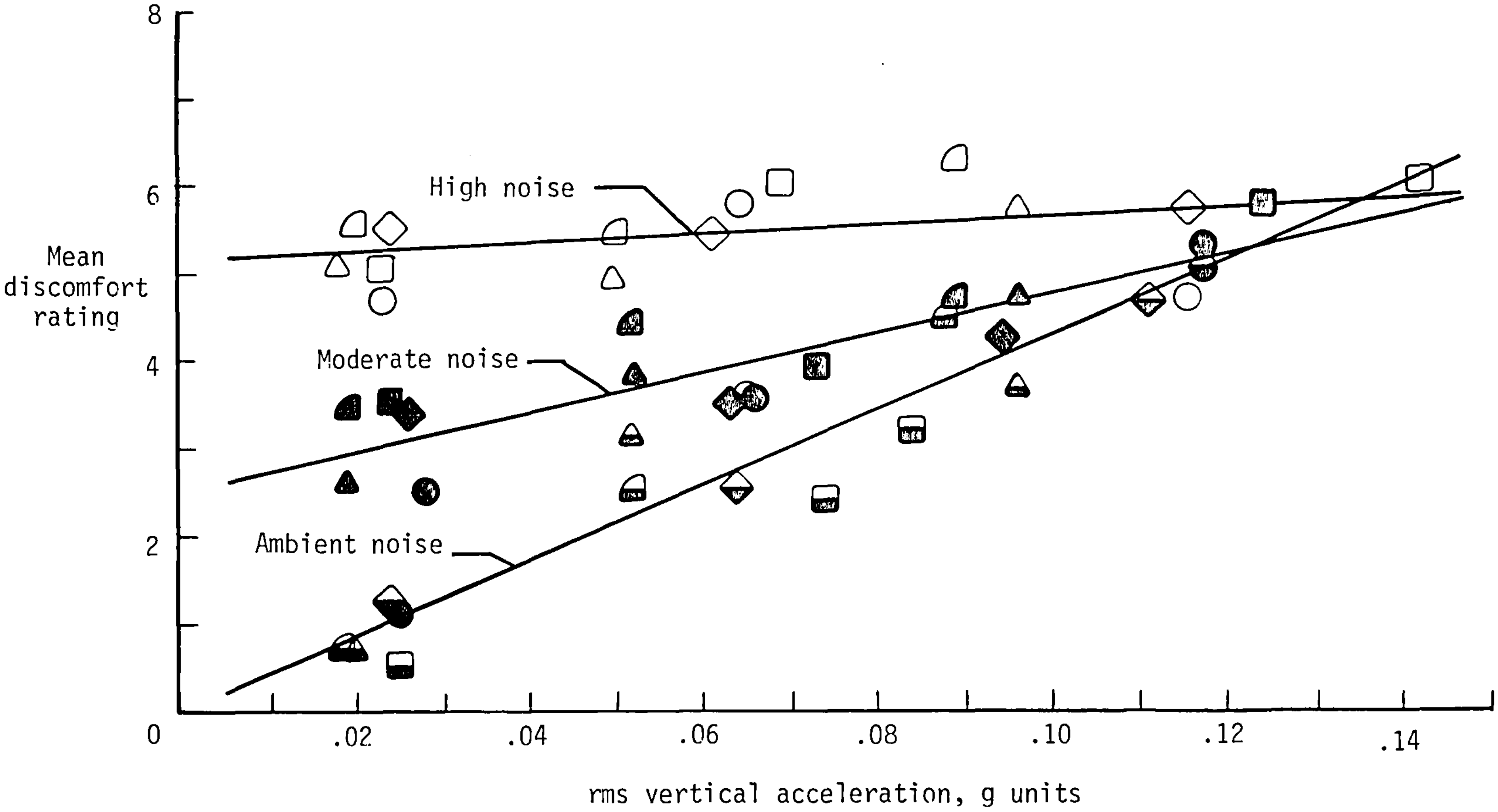
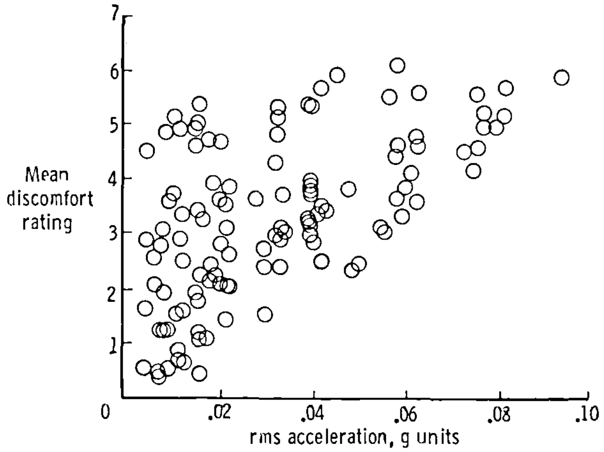
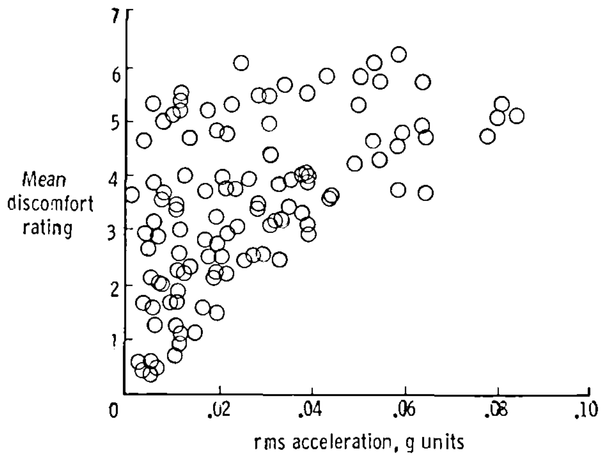


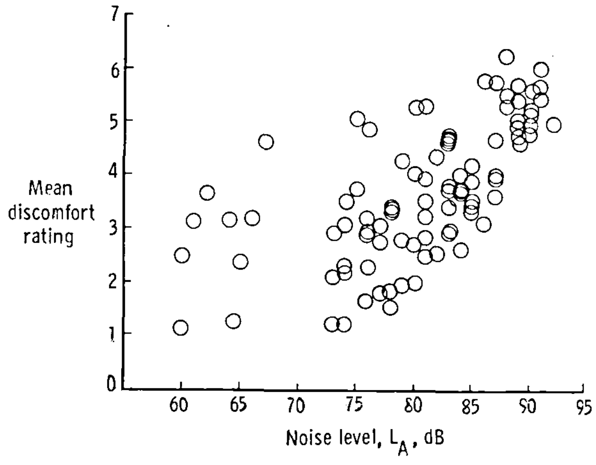
Figure 8.- Mean discomfort response to high, moderate, and ambient noise in presence of vibration.



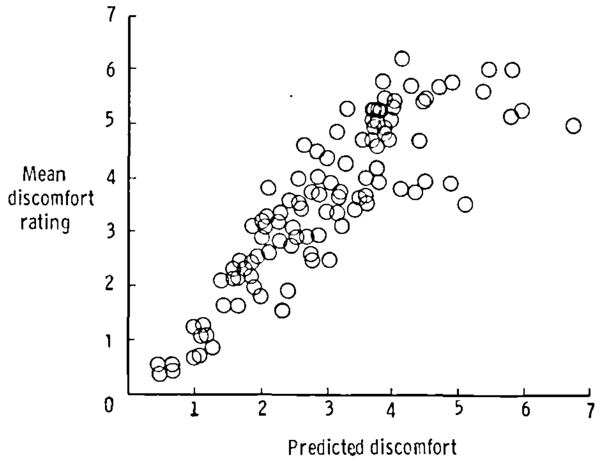
(a) Unweighted acceleration; r = 0.551.



(b) Weighted acceleration; r = 0.535.

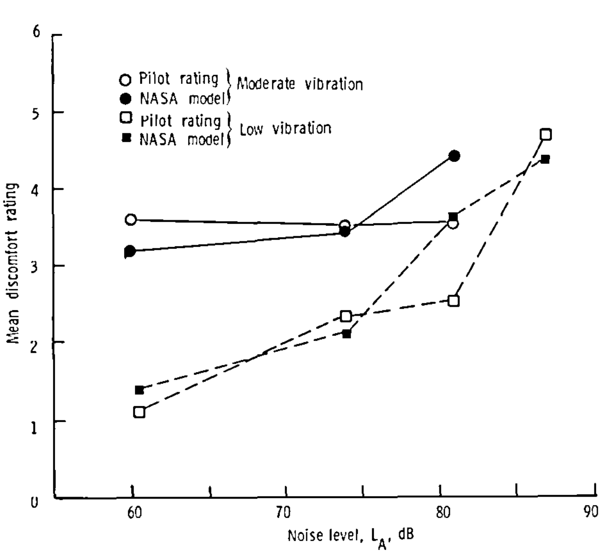


(c) A-weighted noise; r = 0.650.

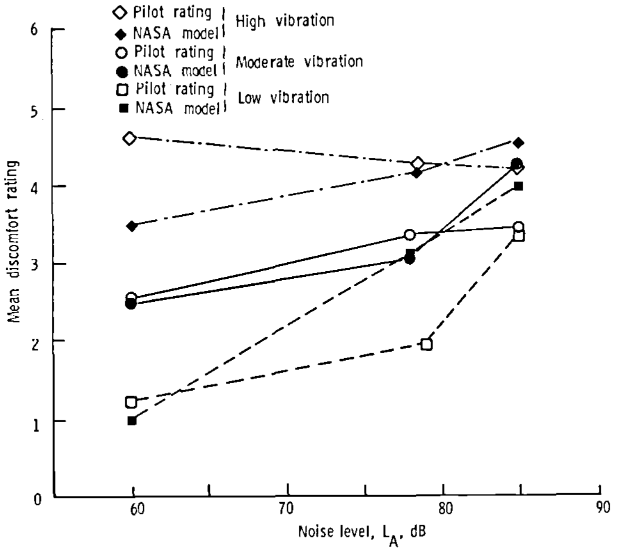


(d) NASA discomfort index; r = 0.914.

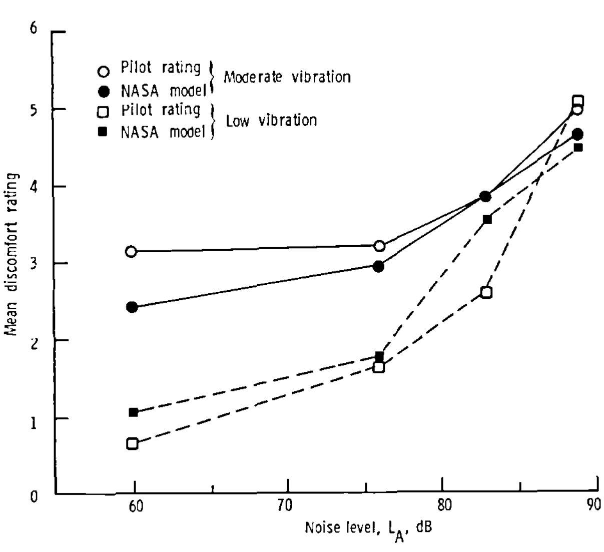
Figure 9.- Correlation of obtained discomfort ratings with various ride quality metrics.



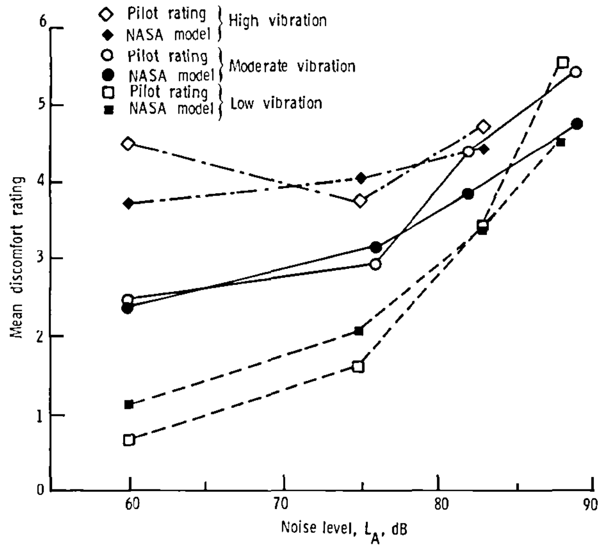
(a) Aircraft H-1.



(b) Aircraft H-3.



(c) Aircraft H-4.



(d) Aircraft H-5.

Figure 10.- Comparison of obtained discomfort ratings with predicted NASA discomfort indices for cruise condition.

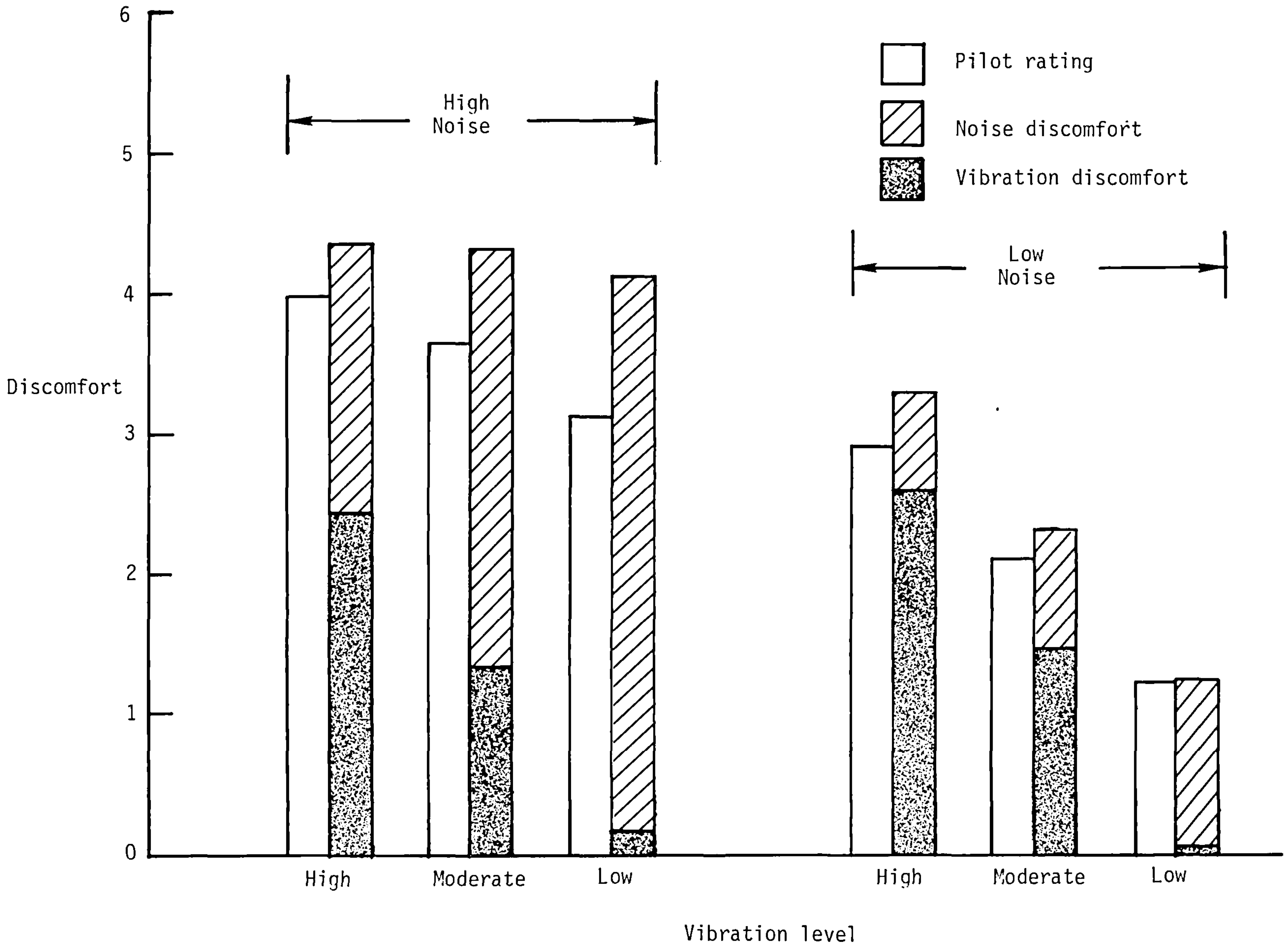


Figure 11.- Relative contribution of noise and vibration to total predicted discomfort for aircraft H-4 in cruise condition.

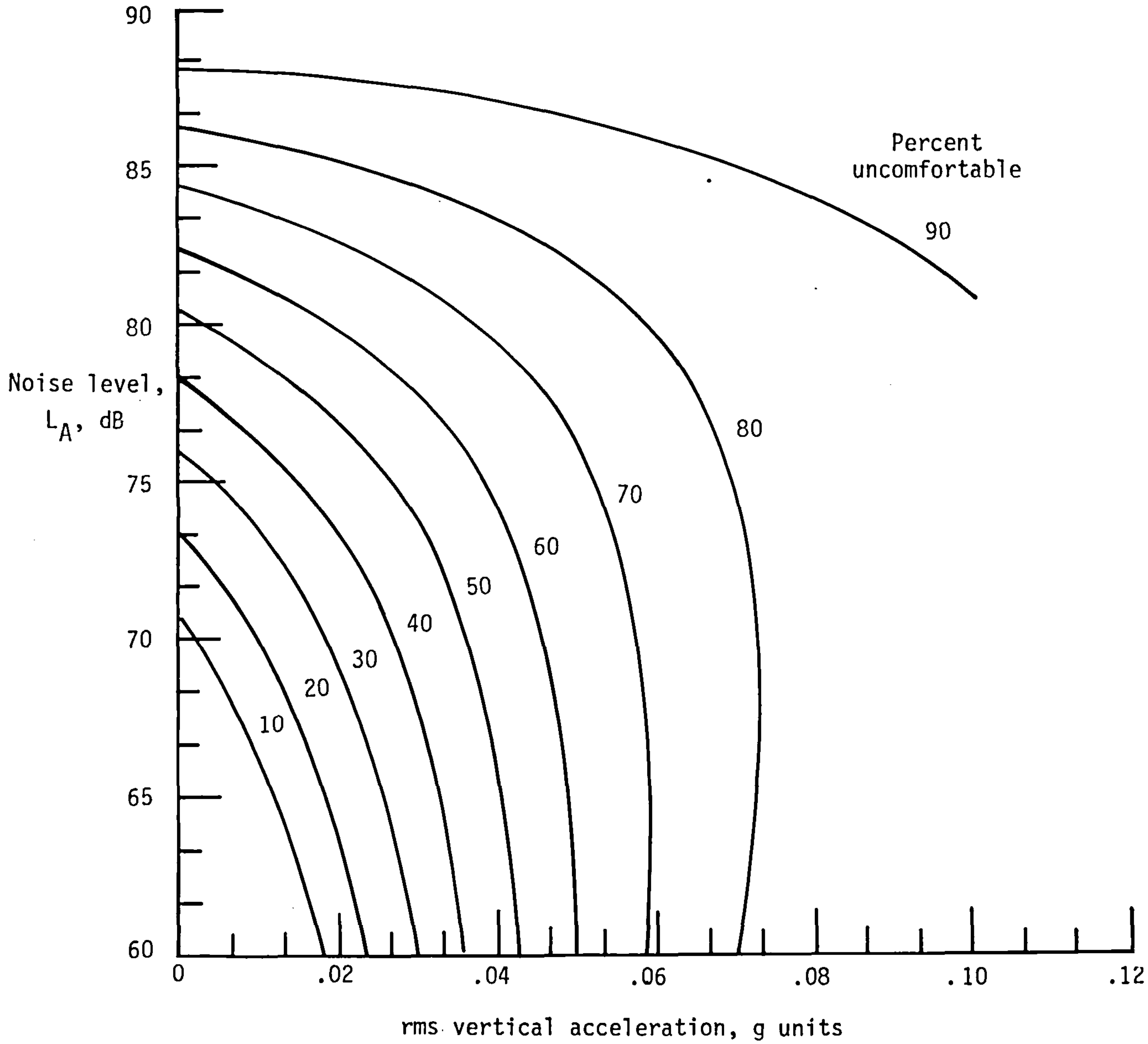


Figure 12.- Values of A-weighted noise level and rms vertical acceleration that produce constant values of discomfort.

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15. Supplementary Notes

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Daniel D. Hollenbaugh: Applied Technology Laboratory, USAAVSCOM Research and Technology Laboratories.

16. Abstract

This paper presents the results of a simulator study conducted to compare and validate various ride quality prediction methods for use in assessing passenger/crew ride comfort within helicopters. Included are results quantifying 35 helicopter pilots' discomfort responses to helicopter interior noise and vibration typical of routine flights, assessment of various ride quality metrics including the NASA ride comfort model, and examination of possible criteria approaches. Results of the study indicated that crew discomfort results from a complex interaction between vibration and interior noise. Overall measures such as weighted or unweighted root-mean-square acceleration level and A-weighted noise level were not good predictors of discomfort. Accurate prediction required a metric incorporating the interactive effects of both noise and vibration. The best metric for predicting crew comfort to the combined noise and vibration environment was the NASA discomfort index.

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