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A MODEL FOR PREDICTION OF RIDE QUALITY IN A MULTIFACTOR ENVIRONMENT

By

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16. Abstract

Recently a ride quality comfort model has been proposed at Langley Research Center which accounts for the effect of both multifrequency and multiaxes vibratory inputs, as well as nonvibratory inputs such as noise, on human comfort response. This paper describes in general terms the proposed NASA ride quality model and presents selected results of several experimental investigations that have contributed to the development of the model and to a more comprehensive understanding of human comfort response to vibration. Human subjective response to vertical vibration, combined vertical-lateral vibrations, and roll vibrations are discussed and a set of vertical constant discomfort curves is presented.

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INTRODUCTION

Environmental factors such as vibration, noise, temperature, etc., are important to the design and improvement of transportation systems since these factors can adversely affect passenger acceptability (ride quality) of the system. These factors will become even more important with the advent of future transportation systems such as STOL aircraft, civil helicopters, and high-speed ground vehicles which are expected to generate larger vibration and noise levels than most currently acceptable systems. Thus, it is important to have an understanding of passenger acceptability of noise and vibration in order to (1) predict passenger acceptance of any given environment, (2) determine sources of vibration and/or noise that cause passenger discomfort, and (3) provide a "fix" to a ride quality problem by knowing how much reduction in noise and/or vibration is required to achieve acceptability.

Numerous investigations, e.g., refs. 1-5, have been conducted to determine the effects of vibration on passenger acceptability. There remains, however, a lack of information on the empirical relationship between human comfort response and vibration. Particular attention needs to be focused on collecting data regarding the integrative effect of random (multifrequency and multiaxis) vibration inputs and other interactive factors such as noise, temperature, etc. In general, most of the previously proposed passenger acceptance criteria utilize some form of equal comfort contours characterized by adjectives of various meanings. The most widely recommended criteria is that proposed by ISO (International Standards Organization, see ref. 6) which is an acceleration-frequency contour based upon sinusoidal testing of subjects in one axis at a time. ISO, however, does not adequately account for multiple frequency and multiple axis vibrations and it does not account for the interactive effects of vibration combined with noise. Furthermore, ISO defines their proposed comfort contour in terms of "reduced comfort boundary" which is somewhat difficult to interpret with respect to passenger acceptance.

Recently, a ride quality comfort model has been proposed at Langley Research Center (ref. 7) which accounts for the effect of both multifrequency and multiaxis vibratory inputs, as well as nonvibratory inputs such as noise, on human comfort response. This paper outlines this model and contains some of the more important experimental results obtained to date from a variety of methodological and model-oriented studies of human comfort response to vertical, combined vertical-lateral, and roll vibrations.

The specific purposes of this paper are to (1) describe the NASA ride quality model and (2) to present selected results of several experimental investigations that have contributed to the model and to provide a more comprehensive understanding of human comfort response to vibration.

SIMULATOR

A series of photographs of the simulator used in this study are presented in figure 1. The simulator is called the Passenger Ride Quality Apparatus (PRQA) and is configured to resemble the interior of a typical jet transport aircraft. It can produce vibratory motions in either of two combinations of degrees of freedom. The first combination is simultaneous vertical, lateral, and roll vibrations and the second combination is vertical, longitudinal, and pitch. The peak-to-peak stroke capability of the simulator is 6 inches and the linear accelerations are limited to ±0.5g for frequencies from 1.3 to 30 Hz. Maximum angular displacement capability is ±0.1 radian up to 1.3 Hz and the limiting roll acceleration levels are ±6.3 rad/sec^2 up to 5 Hz.

Figure 1(a) shows the waiting room where subjects receive instructions, are briefed, etc. Figure 1(b) is a model of the PRQA showing the support and drive system and figure 1(c) is an exterior view of the PRQA. Figure 1(d) shows the interior (with front bulkhead removed) equipped with first-class aircraft seats. Figure 1(e) illustrates the control console and figure 1(f) is a view looking from inside the PRQA onto a visual display. In figure 1(f) the first-class seats have been replaced by tourist-class seats.

DESCRIPTION OF MODEL APPROACH

The basic approach followed in this paper is to develop a model that integrates the effect of the several key factors that may adversely affect passenger comfort and that also has general applicability to any transportation system. The ride quality model concept and the many factors involved are presented in block diagram form in figure 2. To the extreme left of figure 2 the input to a vehicle is shown as being applied to the vehicle transfer function. The inputs can be noise and/or vibration and the vehicle transfer function can be its frequency response and/or noise transmission characteristics. The output of the vehicle transfer function is the ride spectra (or environment) to which passengers are exposed. At this point, the ride spectra are applied to the various computational aspects (indicated by the dashed box) of the ride quality model. These include the empirical relationships governing vibration frequency masking/summation both within an axis and between axes, the development of equal comfort curves to account for the discomfort contributions due to single frequencies, the interactive effects of noise and vibration, and model correction due to other factors such as duration, transients, anxiety, etc. The end result is a final scale of discomfort which gives a number (ride quality index) that indicates the degree of acceptability of the ride environment. The model can be reduced to the meter concept shown at the bottom of figure 2. A multiaxis ride spectra is input to the ride quality meter whose output is the ride quality index that gives the level of passenger acceptance. The ride quality meter which is under development is a practical hardware implementation of the components within the dashed box. It should be emphasized that the model described above is a predictive model and all that is required to provide passenger comfort evaluation is knowledge of the ride environment. The model (or meter) is being developed from both laboratory and field studies using a large number of test subjects.

APPLICATION OF RIDE QUALITY MODEL

The application of the ride quality model to new or existing vehicle designs is presented in figure 3. Estimated or measured inputs are applied to an experimental or estimated vehicle transfer function to give the ride environment at the passenger locations of the vehicle. This ride environment is provided as input to the ride quality meter (model), the output of which gives the passenger acceptability of the vehicle. If the acceptability level is sufficient, then the design or modification is complete, if not, then the model will diagnose the problem source so that a vehicle modification can be made. The process is then repeated until the required level of passenger acceptability is achieved.

PSYCHOPHYSICAL LAWS

An experimental study (ref. 8) using the PRQA was conducted to (1) determine in a systematic manner the psychophysical relationships governing human assessment of the intensity and discomfort due to whole-body vertical vibration and (2) determine if intensity and discomfort responses differ from one another. A total of 48 subjects were used in this study with 24 subjects performing discomfort evaluations and 24 different subjects performing intensity evaluations. A total of 10 frequencies were investigated and a magnitude estimation procedure was used to obtain subjective evaluations. The candidate psychophysical laws were: linear, power, exponential, and logarithmic.

Results of statistical analysis indicated that a linear law should be selected for description of the relationship between subjective ratings of intensity or discomfort and vibration level. Using a least squares linear fit to the magnitude estimation data for both discomfort and intensity at each frequency and testing for differences of slope between the two sensations, it was determined that 3 of the 10 frequencies displayed significant differences in slope. Thus, caution should be used when applying results from vibration intensity evaluation studies to the problem of developing discomfort response criteria. Figure 4 shows a typical example of the magnitude estimates and the fitted least squares lines for intensity and discomfort at a frequency of 5 Hz (one of the most critical frequencies affecting discomfort). For this frequency, the slopes of the intensity and discomfort curves did not differ significantly.

METHODOLOGICAL CONSIDERATIONS

Several experiments were conducted on the PRQA in order to derive information related to the methodology to be used in development of the ride quality model. These experiments utilized a total of 296 subjects and involved vertical vibration, roll vibration, and combined vertical-lateral vibrations. Some of the specific objectives of these studies were to (1) explore the adequacy of frequency averaging of vibration data to obtain discomfort predictors, (2) determine the relative importance of seat and floor vibration in the selection of a measurement and criteria specification location, (3) explore the affect upon human comfort of roll vibrations and in particular the effects of roll frequency, roll acceleration level, and seat location, e.g., distance from axis of rotation, and (4) examine the effects of combined vertical-lateral vibrations. Supporting data and conclusions for each of the above objectives will now be discussed.

Frequency Averaging

The problem of interest in this section is to determine whether the prediction of passenger discomfort can be based upon a frequency averaging process (such as overall rms acceleration level) or whether information on the frequency content of the spectrum is also necessary. An analysis of variance applied to the data indicated a significant interaction between acceleration and frequency. This is displayed graphically in figure 5 which presents the mean discomfort ratings (based upon a nine-point unipolar scale) as a function of frequency for five levels of seat acceleration. Note that the mean discomfort ratings vary with frequency for each acceleration level and at each frequency the ratings are dependent upon acceleration level. Thus in order to determine the degree of discomfort, it is necessary to have knowledge of both the frequency and acceleration content of a ride. The case where many frequencies are present simultaneously requires further analysis and will be discussed in a later section.

Seat-Floor Considerations

The question frequently arises as to what location to use for specification of ride quality criteria and as a measurement location for sensor packages. The fact that floor and seat responses differ has been demonstrated in reference 9 and is illustrated by the seat transfer function shown in figure 6. This section discusses the relative contribution of vibrations at the seat and floor (when the vibrations are simultaneously experienced) to the total discomfort of a passenger. The discussion herein will be concerned with tourist-class aircraft seats although the results have been shown to apply to first-class aircraft seats as well as bus seats (ref. 9).

The average correlation coefficient between measured seat and floor accelerations for the study considered herein yielded a value of 0.87, indicating a high degree of correlation. Thus these measures are not independent measures and, therefore, cannot be used to compute weighting factors for the relative contribution of floor and seat accelerations to discomfort response. In addition, t-test comparisons between the floor and seat correlation coefficients of discomfort response with acceleration were made and indicated that for practical purposes there is no significant difference in the contribution of vibration at the floor or at the seat to the total discomfort of a passenger. These results are illustrated graphically in figure 7 which shows the mean discomfort ratings as a function of floor and seat acceleration levels for three values of vertical sinusoidal frequency. In evaluating the data of figure 7, it should be noted that the seat transmissibility characteristics (ratio of seat to floor acceleration) of figure 6 tend to amplify floor vibrations at frequencies below 9 Hz, is approximately unity at 9 Hz, and attenuates floor vibration at frequencies above 9 Hz. The data of figure 7 illustrate the high level of correlation existing between mean discomfort ratings for both floor and seat accelerations. This is evidenced by the parallel trends of each pair of solid and dashed curves. The spread between the parallel curves is due to the seat transmissibility characteristics mentioned earlier and indicates that, even though either location will give equal predictability, the measurement location for specifying absolute values of acceleration must be given. For simplicity and convenience, it is therefore recommended that the floor be used as the location for measurement and criteria specification.

Roll Vibrations - Frequency and Acceleration Effects

A study was conducted in which a total of 72 subjects were exposed to roll vibrations at selected roll acceleration levels (0.48 to 2.88 rad/sec^2), frequencies (1 through 4 Hz), and in several seat locations (window, center, and aisle seats). This study constitutes the first known systematic investigation of human response to roll vibrations in a realistic environment. An analysis of variance applied to the results indicated that the effects of roll acceleration and frequency, as well as their interaction, were significant. The effect of seat location was found to be not significant. An example of the interaction between roll acceleration level and roll frequency is displayed in figure 8. Figure 8 shows the mean discomfort ratings as a function of roll acceleration level with frequency as a parameter. These curves demonstrate a basic linearly increasing trend of discomfort response with roll acceleration level which is in accord with the previous discussion regarding the selection of a linear psychophysical law for vertical vibration. Also the effect of frequency is apparent, especially at the higher levels of roll acceleration.

Roll Vibration - Seat Location

The analysis of variance indicated that the effect of seat location on subjective evaluations was not significant for the particular seat arrangement and roll axis used in this study. The overall effect of seat location is illustrated in figure 9 which shows the mean ratings (averaged over roll frequency) for each seat location as a function of roll acceleration level. Although this graph shows some spread between the points (for each roll acceleration level) corresponding to each seat location, these differences are not statistically significant.

Combined Axes - Vertical With Added Lateral

A study was conducted in which subjects were exposed to combined vertical and lateral vibrations at several combinations of input frequencies which ranged from 1 to 20 Hz for both axes. All vibration levels were equal to 0.15 g. Some typical results for vertical vibration with added lateral vibration are presented in figure 10. This figure shows the mean discomfort ratings (based upon a nine-point unipolar discomfort scale) of the subjects as a function of vertical input frequency with added lateral input frequency as a parameter. This set of curves shows that all lateral frequencies contribute to subjective discomfort when combined with any of the vertical frequencies and, furthermore, the lateral axes tend to have a dominant effect at the lower values of lateral frequency. For example, the mean discomfort rating for vertical alone peaks at approximately 4.6 whereas the mean ratings when lateral vibrations 1, 2, and 3 Hz are present range generally between 6 and 7.5.

Combined Axes - Lateral With Added Vertical

Figure 11 presents the mean discomfort ratings as a function of lateral input frequency with vertical input frequency as a parameter. This figure further emphasizes the point that lateral axis motions dominate at the lower frequencies implying that the presence of low-frequency lateral vibrations may tend to effectively mark the presence of vertical vibrations at comparable levels. At the higher frequencies (above 3 Hz) the vertical vibrations do contribute to the discomfort ratings.

EQUAL DISCOMFORT CURVES

Study A

A total of 186 subjects and three experiments were involved in the development of a set of constant discomfort curves. The first study, called Study A, was directed towards the determination of the acceleration level at different frequencies that produces identical discomfort. The method utilized was to require the subjects to evaluate successive "comparison ride segments" according to a modified method-of-limits task. Specifically, a subject's task was to determine if a ride segment (a vibration applied at a selected frequency and amplitude) provided greater or less discomfort than a ride segment termed the "standard ride." The standard ride was selected on the basis of previous studies to be 0.15 g at 9 Hz. At each frequency the percentage of rides rated greater than the standard was computed and transformed into z-scores (standard normal scores). Thus, a z-score of 0.0 corresponds to 50 percent of the comparison rides being evaluated as having more discomfort than the standard ride. Typical results are shown in figure 12 which presents the z-score transformations obtained from 5 Hz comparison rides as a function of the floor acceleration level. The acceleration level at z = 0.0 is interpreted as being equal in discomfort to the standard ride. For the data of figure 12, an acceleration level of 0.115 g at 5 Hz was taken as equal in discomfort to the standard ride of 0.15 g at 9 Hz.

Initial Discomfort Curve

Repeating the method of the preceding section for all frequencies and plotting the z = 0.0 point gives the curve shown in figure 13. The left ordinate is the peak floor acceleration level and the right ordinate is the root-mean-square acceleration level that gives constant values of discomfort along the curve of figure 13. Although the curve of figure 13 is a constant discomfort curve, its absolute level of discomfort remains to be determined. The procedure for doing this is described in the next section.

Study B

The objective of this study was to derive equal discomfort curves that can be assigned absolute levels of discomfort. The procedure used was to obtain magnitude estimates of discomfort for successive ride segments at each particular frequency. As an example, the magnitude estimation results for the standard frequency of 9 Hz is displayed in figure 14. A least-squares line was fit to the data and normalized to a value of unity at a floor acceleration level of 0.08 g which was determined from a previous study to be the approximate threshold of discomfort at 9 Hz. Thus using figure 14, we find that the standard ride of Study A (0.15 g at 9 Hz) has a mean discomfort level of 2.47 and, therefore, determines the level of discomfort of the curve of figure 13 relative to the threshold of discomfort. Knowledge of the normalized magnitude estimates for 9 Hz combined with the discomfort value of the curve of figure 13 now allows the mean magnitude estimates at each frequency to be properly adjusted for direct correspondence with each other. A typical example is shown in figure 15 for a frequency of 5 Hz. Curves similar to figure 15 were generated for all frequencies and used to compute the peak and rms floor accelerations required to produce discomfort levels ranging from 1 (threshold) to 12 (very high discomfort). Thus the set of constant discomfort curves displayed in figure 16 was produced. The dips in the curves correspond to the frequencies of maximum human discomfort and range from about 4 to 6 Hz. These curves and the associated magnitude estimations for each frequency provide the basis of the ride quality model.

Yet to be accounted for are the masking/summation effects of combined frequencies and axes and the development of equal discomfort curves for other axes. Studies have been completed to provide this information and will be the subject of future publications.

CONCLUDING REMARKS

This paper has presented the outline of a comprehensive model approach to the development of ride quality criteria and predictive capability. Results from several related studies have been presented which contribute to the development of such a model as well as to a more comprehensive understanding of human comfort response to vibration. The major points of interest are summarized as follows:

(1) A linear relationship can be used to describe the psychophysical law governing human response to vibration.

(2) Caution should be used in applying results from vibration intensity evaluation studies to the problem of human discomfort response.

(3) In order to accurately assess the level of discomfort of a ride a knowledge of both frequency and acceleration amplitude is required. Frequency averaging of vibration data provides at best only a crude predictor of discomfort.

(4) The floor location in a vehicle can be used as the point for making vibration measurements and specifying ride quality criteria. If it is desired to specify criteria at the seat, then the floor criteria can be corrected by applying the seat transfer function to the floor input.

(5) Subjective response to roll vibration was found to depend significantly on roll frequency, roll acceleration level, and their interaction. Furthermore, subjective response varied linearly with roll acceleration amplitude which is in accord with comment (1) for vertical vibrations.

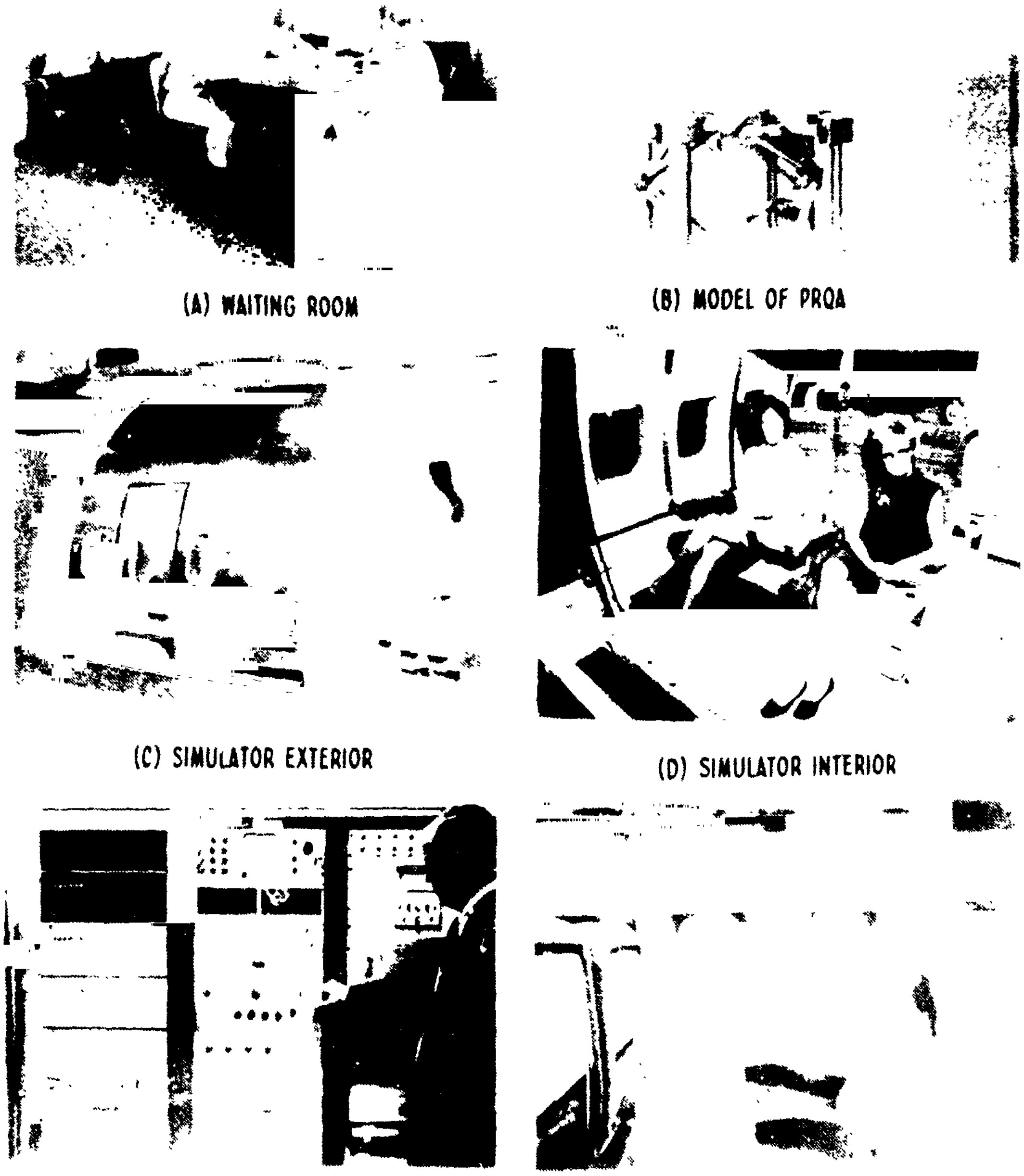
(6) For the particular seat arrangement and roll axis used in these studies, the effect of seat location was unimportant.

(7) Combined axes (vertical and lateral) studies indicated that the addition of lateral vibrations to vertical vibrations resulted in increased subjective discomfort regardless of the frequencies involved. Of particular importance was the indication that low-frequency lateral (1 to 2 Hz) vibrations tended to dominate subjective ratings thus implying that under certain conditions, between axis masking does occur.

(8) A set of equal discomfort curves for vertical vibration were developed.

REFERENCES

1. Anon.: Symposium on Vehicle Ride Quality. NASA TM X-2620, 1972.
2. Hanes, R. M.: Human Sensitivity to Whole-Body Vibration in Urban Transportation Systems - A Literature Review. The Johns Hopkins University, APL/JHU TPR 004, May 1970.
3. Guignard, J. C.: Human Sensitivity to Vibration. J. Sound & Vib., 15, 1971, pp. 11-16.
4. Guignard, J. C.; and King, P. F.: Aeromedical Aspects of Vibration and Noise. AGARD-AG-151, 1972.
5. Anon.: 1975 Ride Quality Symposium. NASA TM X-3295, DOT-TSC-OST-75-40, Nov. 1975.
6. Anon.: Guide for the Evaluation of Human Exposure to Whole-Body Vibrations. Draft International Standard, ISO/DIS, 2631, 1972.
7. Dempsey, Thomas K.: A Model and Predictive Scale of Passenger Ride Discomfort. NASA TM X-72623, 1974.
8. Leatherwood, J. D.; and Dempsey, T. K.: Psychophysical Relationships Characterizing Human Comfort Response to Whole-Body Sinusoidal Vertical Vibration. NASA TN D-8188, 1976.
9. Leatherwood, J. D.: Vibrations Transmitted to Human Subjects Through Passenger Seats and Considerations of Passenger Comfort. NASA TN D-7929, June 1975.



(A) WAITING ROOM

(B) MODEL OF PRQA

(C) SIMULATOR EXTERIOR

(D) SIMULATOR INTERIOR

(E) CONTROL CONSOLE

(F) TOURIST TYPE SEATS

[illegible] PASSENGER RIDE QUALITY APPARATUS (PRQA)

PASSENGER RIDE QUALITY MODEL

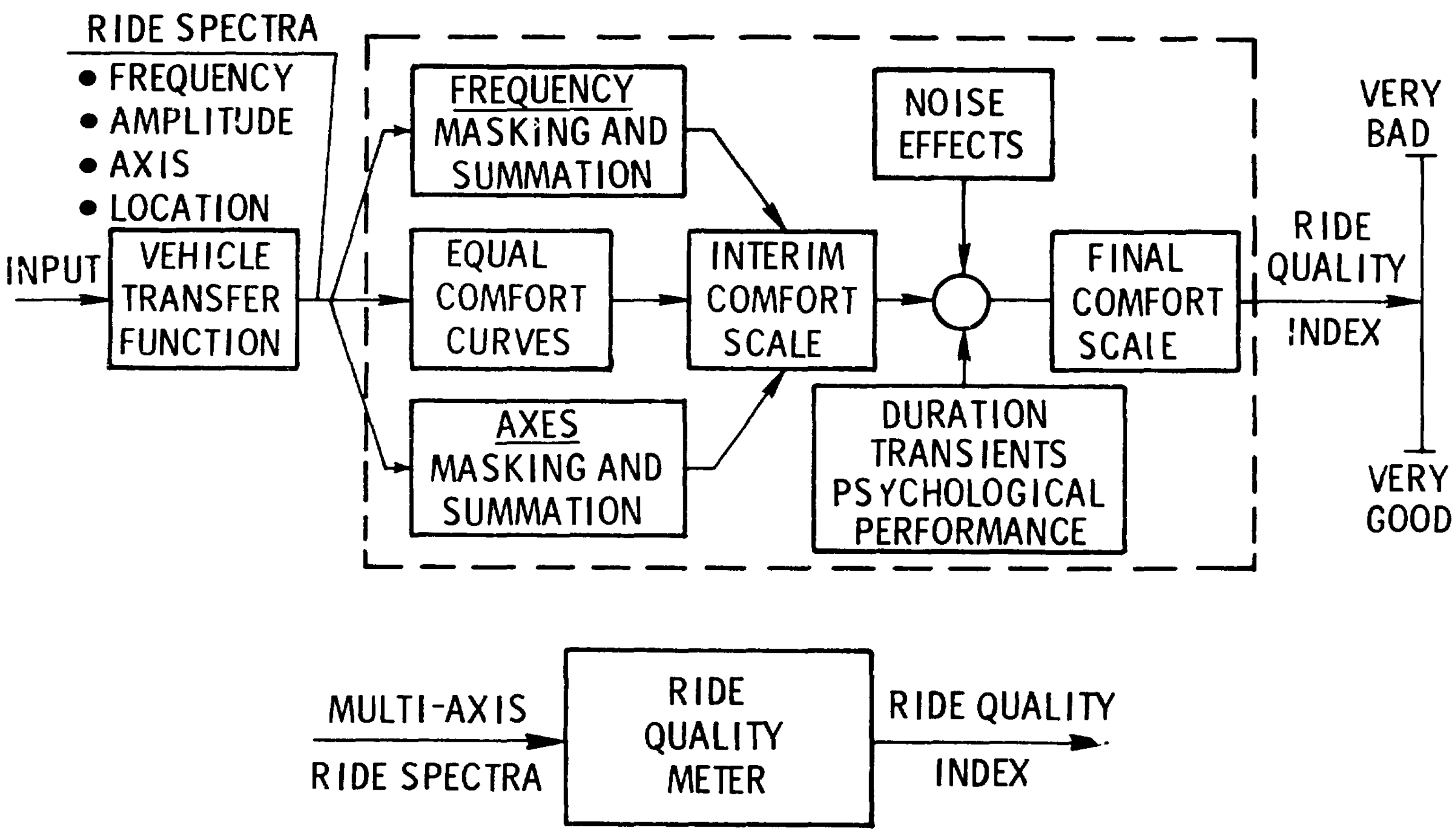


Figure 2

APPLICATION OF RIDE QUALITY MODEL

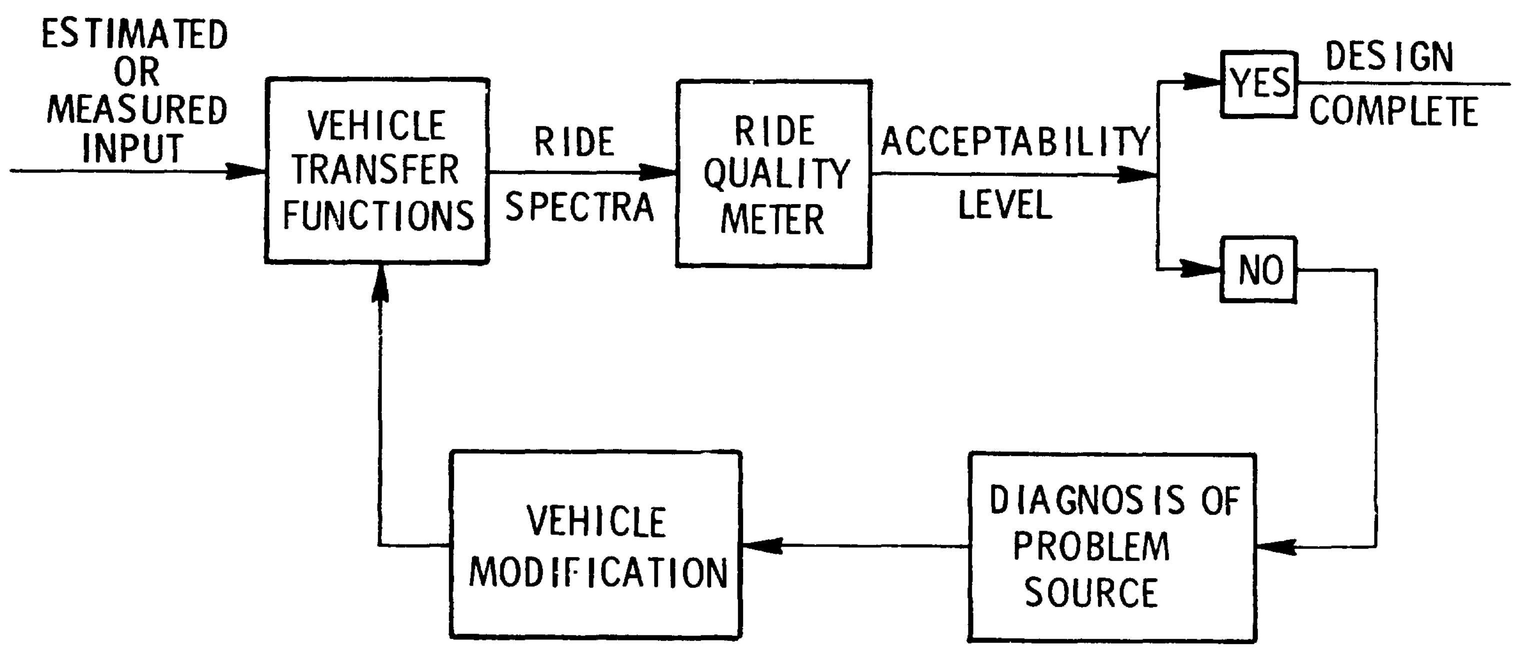


Figure 3

COMPARISONS OF INTENSITY AND DISCOMFORT RESPONSES

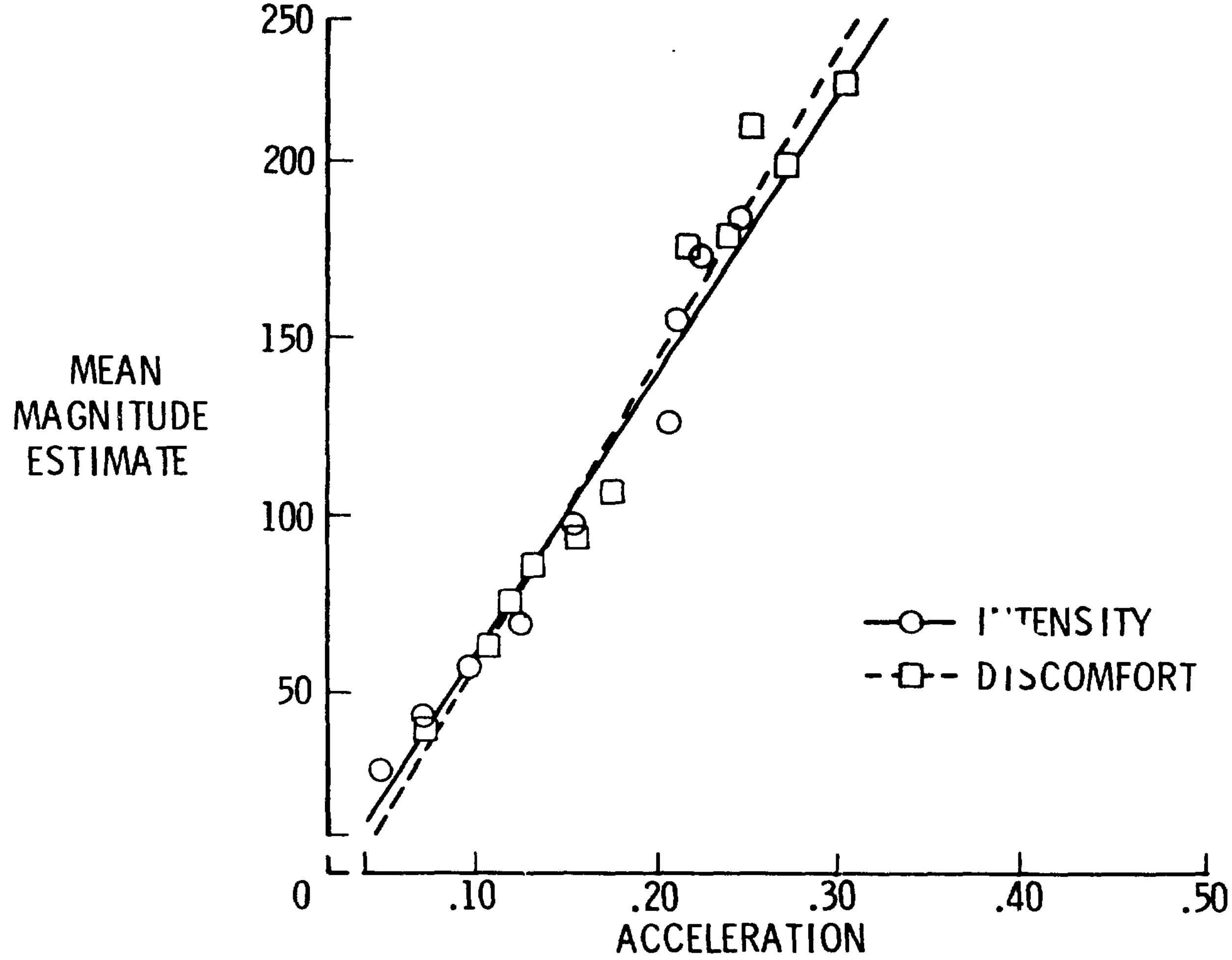


Figure 4

EFFECT OF SEAT ACCELERATION AND FREQUENCY ON DISCOMFORT

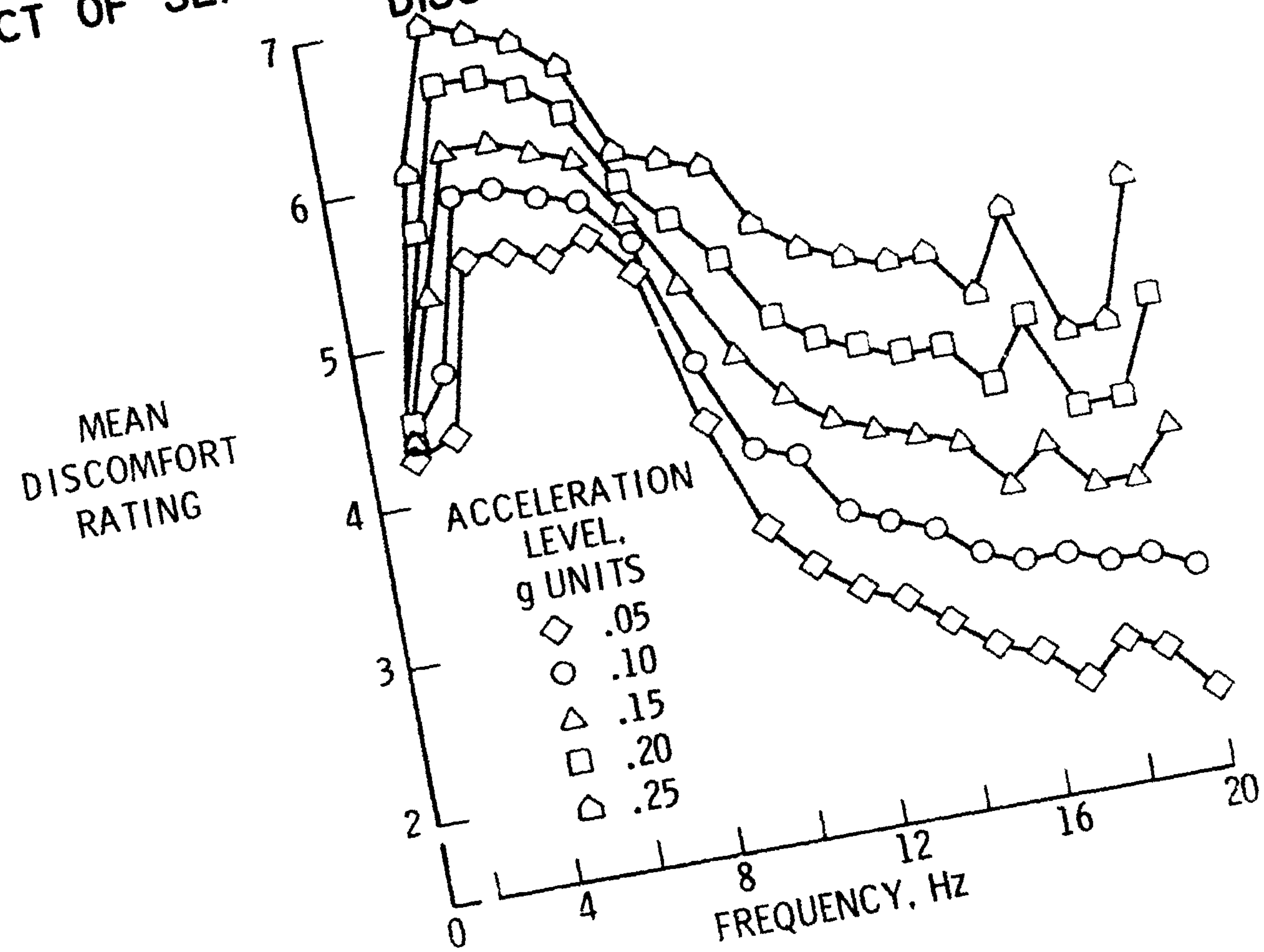


Figure 5

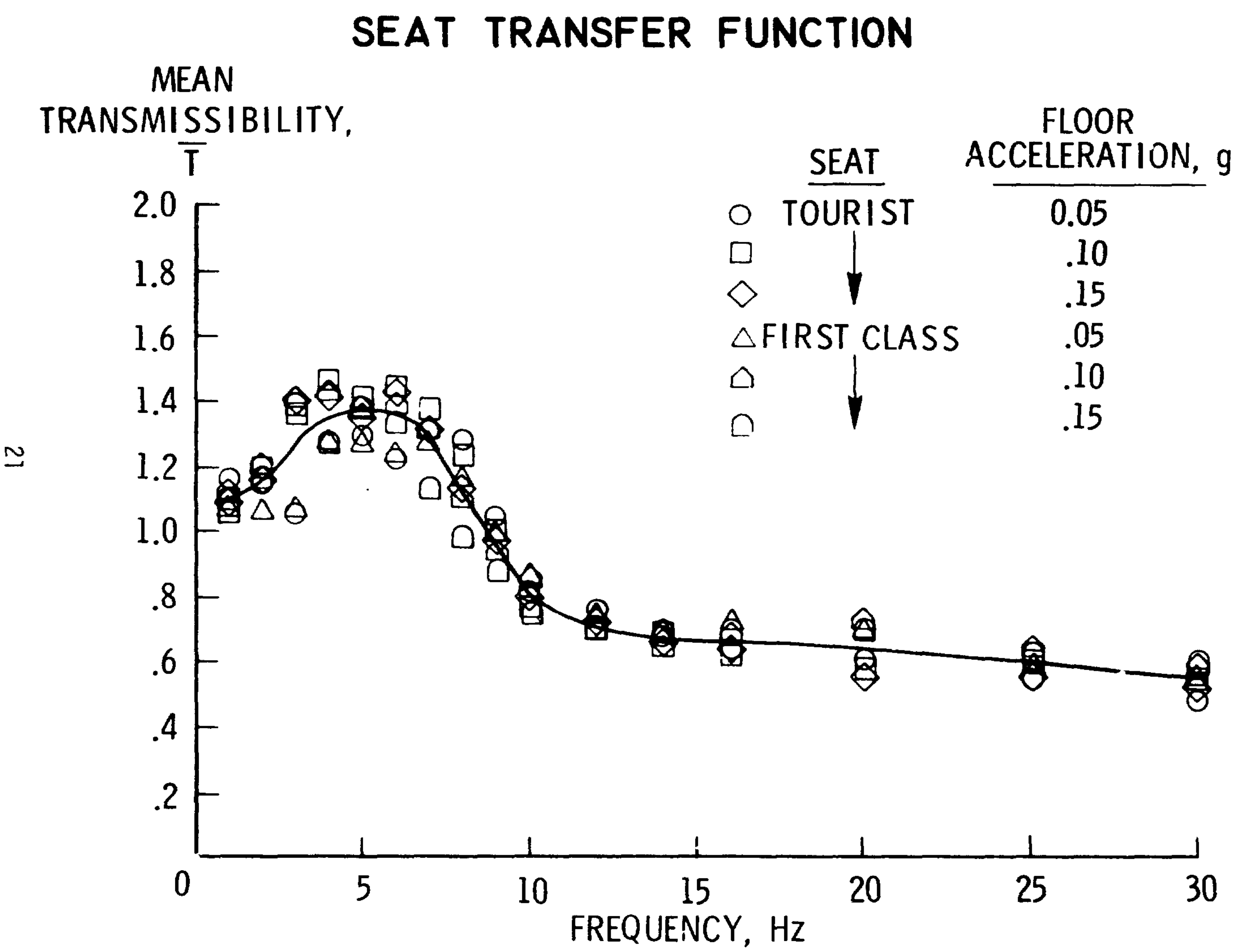

SEAT TRANSFER FUNCTION
MEAN TRANSMISSIBILITY, $\overline{T}$
2.0
1.8
1.6
1.4
1.2
1.0
.8
.6
.4
.2
0
5
10
15
20
25
30
FREQUENCY, Hz
SEAT
FLOOR ACCELERATION, g
TOURIST
0.05
.10
.15
FIRST CLASS
.05
.10
.15

Figure 6

DISCOMFORT AS A FUNCTION OF FLOOR AND SEAT ACCELERATION

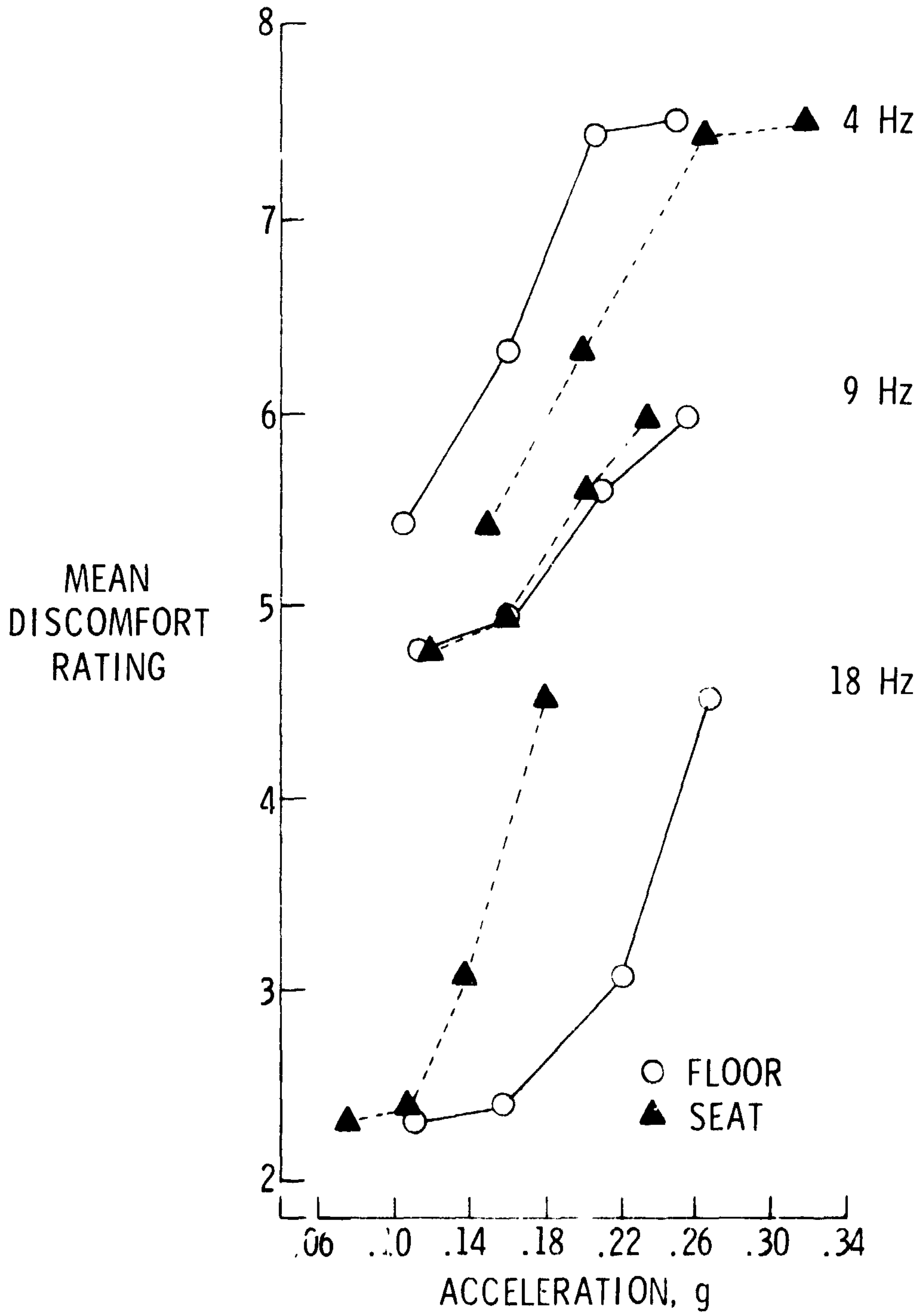
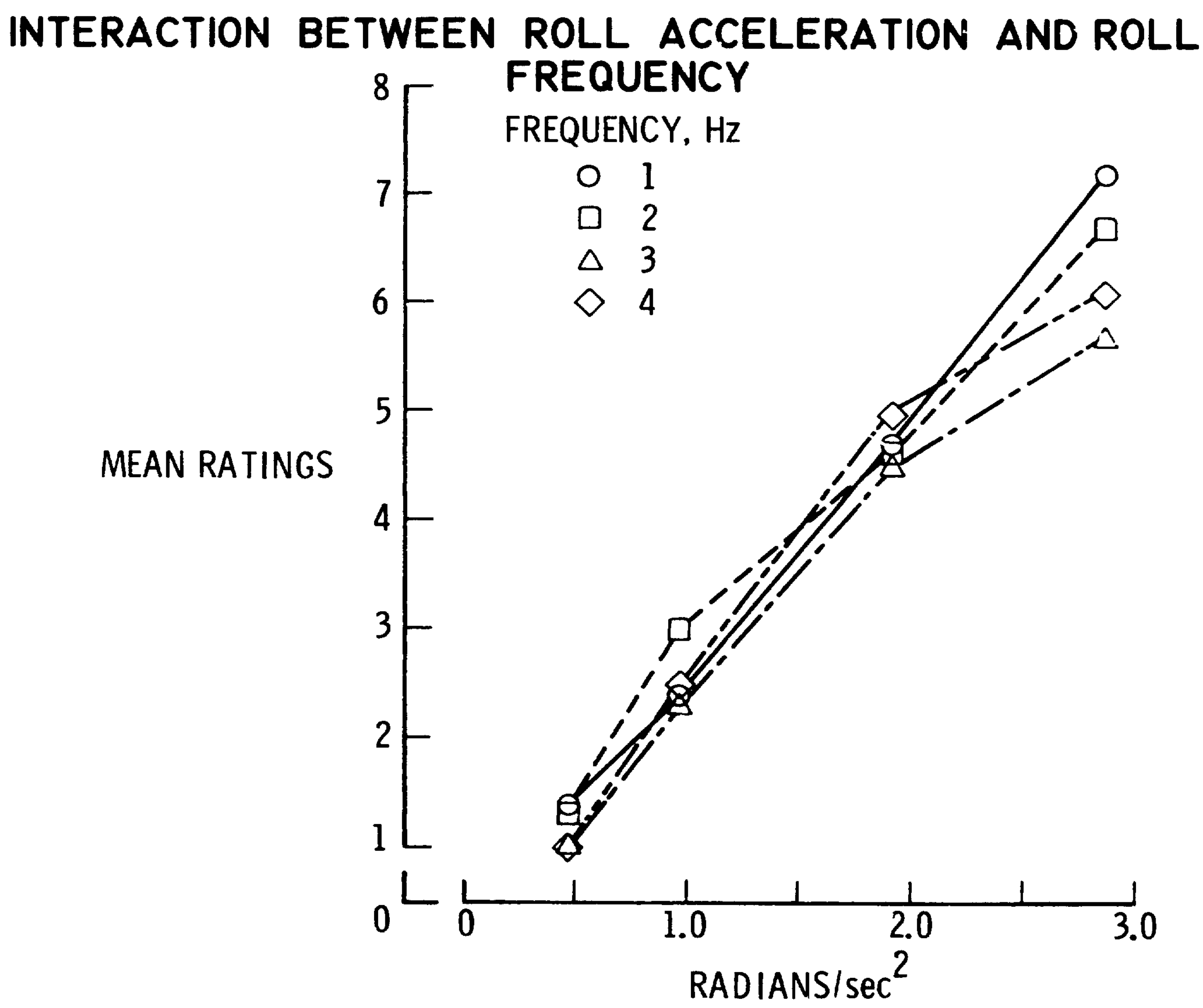


Figure 7



INTERACTION BETWEEN ROLL ACCELERATION AND ROLL FREQUENCY
FREQUENCY, Hz
1
2
3
4
MEAN RATINGS
0
1
2
3
4
5
6
7
8
0
1.0
2.0
3.0
RADIANS/sec²

Figure 8

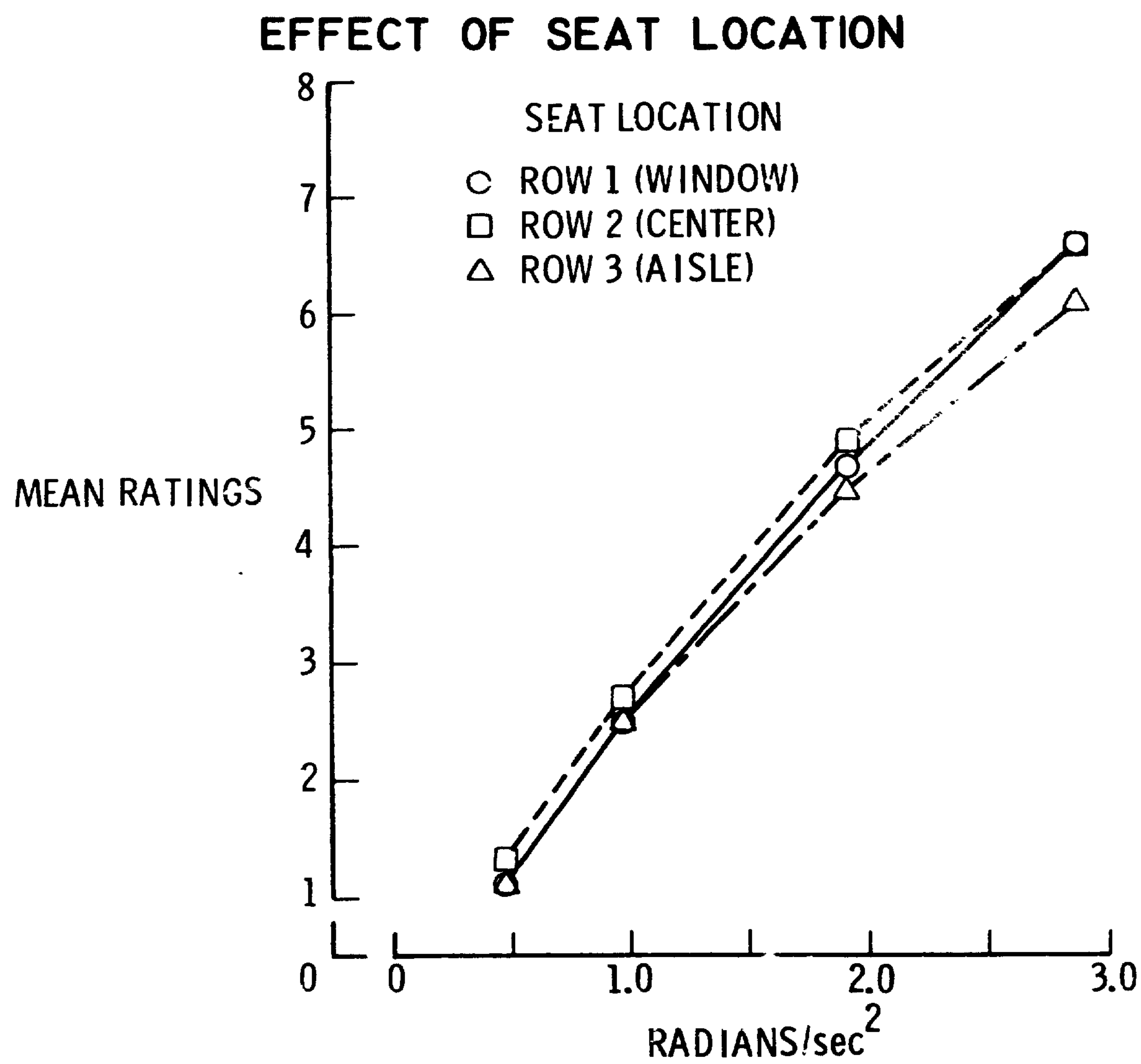

EFFECT OF SEAT LOCATION
SEAT LOCATION
○ ROW 1 (WINDOW)
□ ROW 2 (CENTER)
△ ROW 3 (AISLE)
MEAN RATINGS
8
7
6
5
4
3
2
1
0
0
1.0
2.0
3.0
RADIANS/sec²

Figure 9

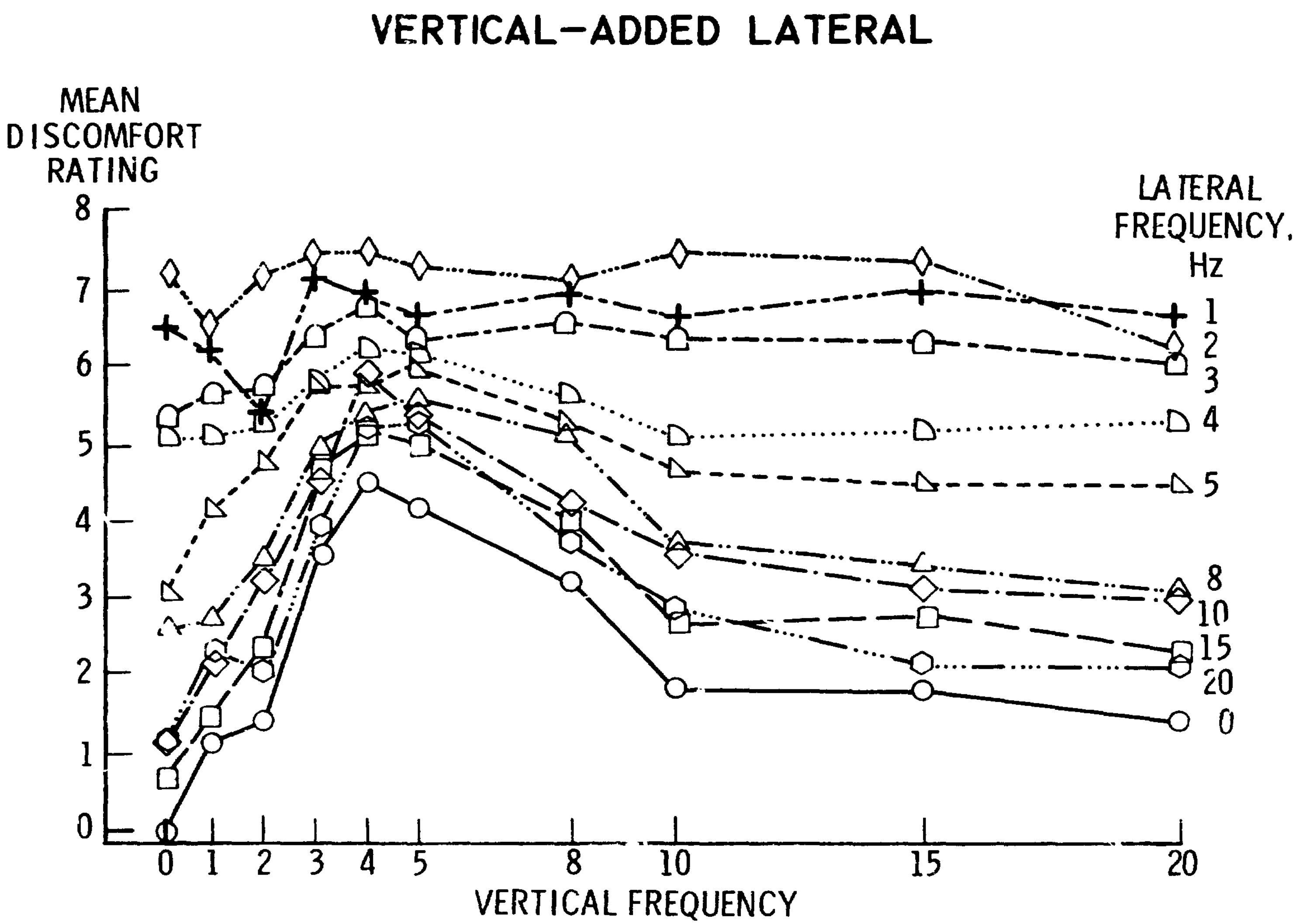

VERTICAL–ADDED LATERAL
MEAN DISCOMFORT RATING
0
1
2
3
4
5
6
7
8
VERTICAL FREQUENCY
0
1
2
3
4
5
8
10
15
20
LATERAL FREQUENCY, Hz
1
2
3
4
5
8
10
15
20
0

Figure 10

LATERAL-ADDED VERTICAL

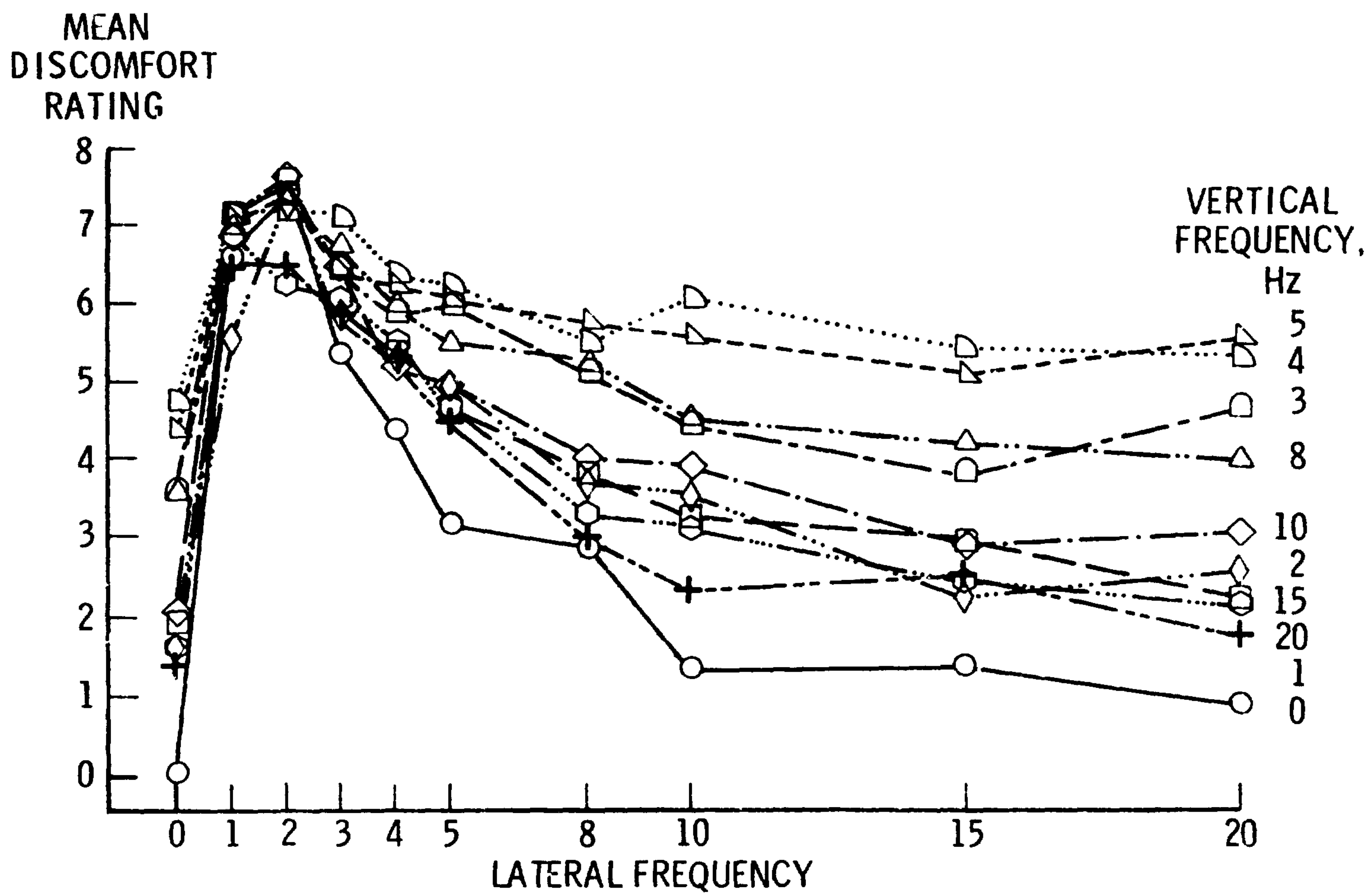


Figure 11

STUDY A — FREQUENCY METHOD RESULTS

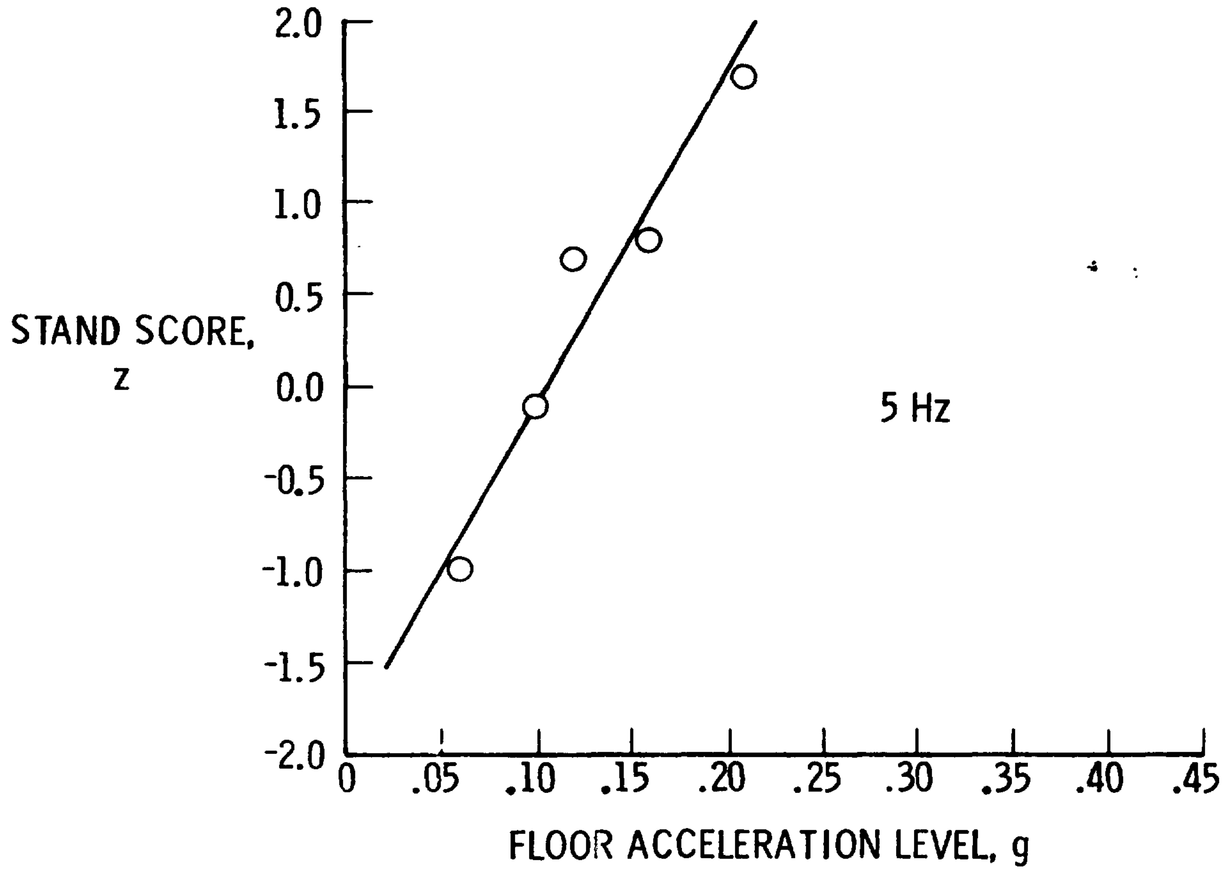


Figure 12

STUDY A — CONSTANT DISCOMFORT CURVE

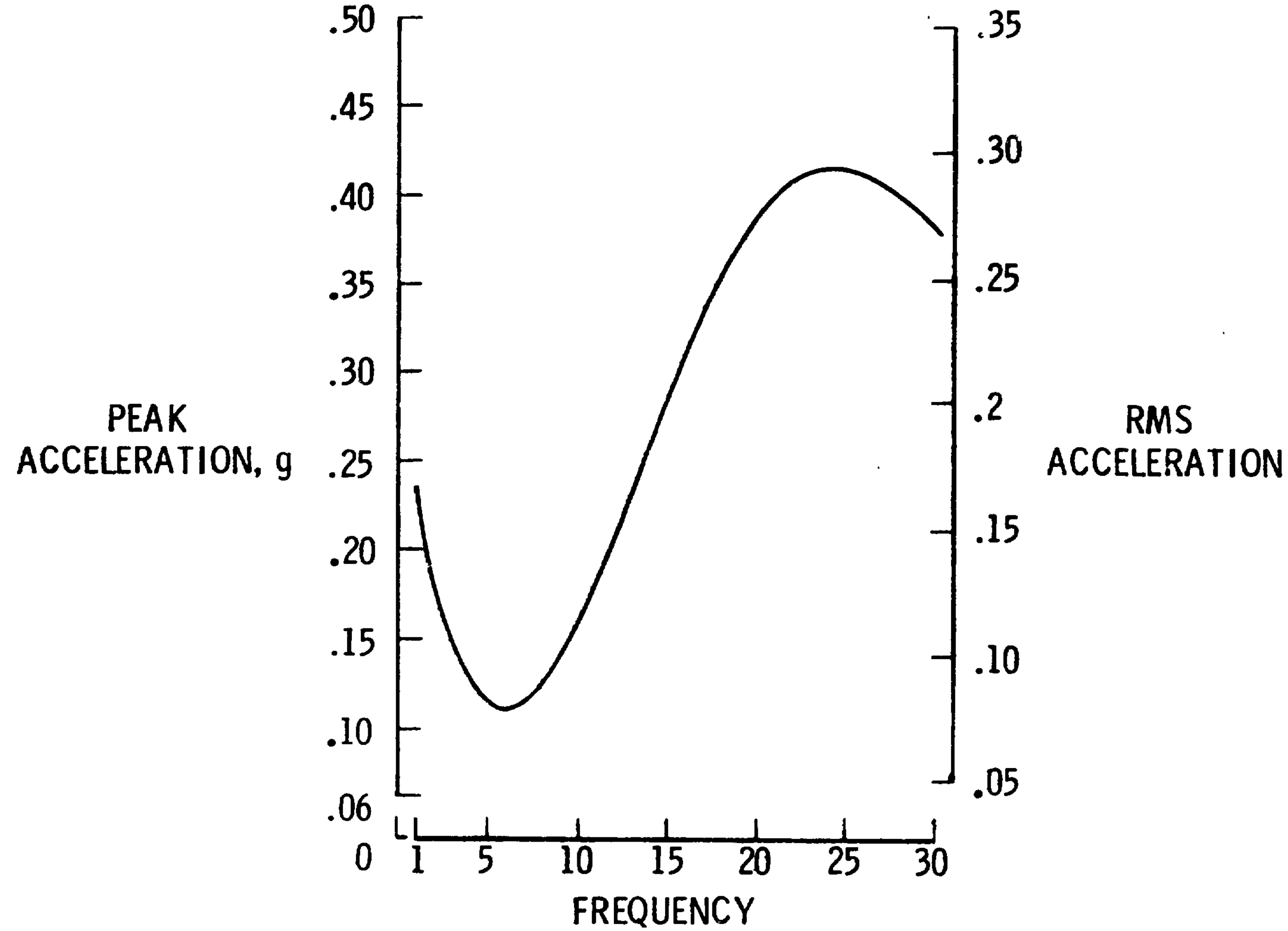


Figure 13

STUDY B – MAGNITUDE ESTIMATION RESULTS

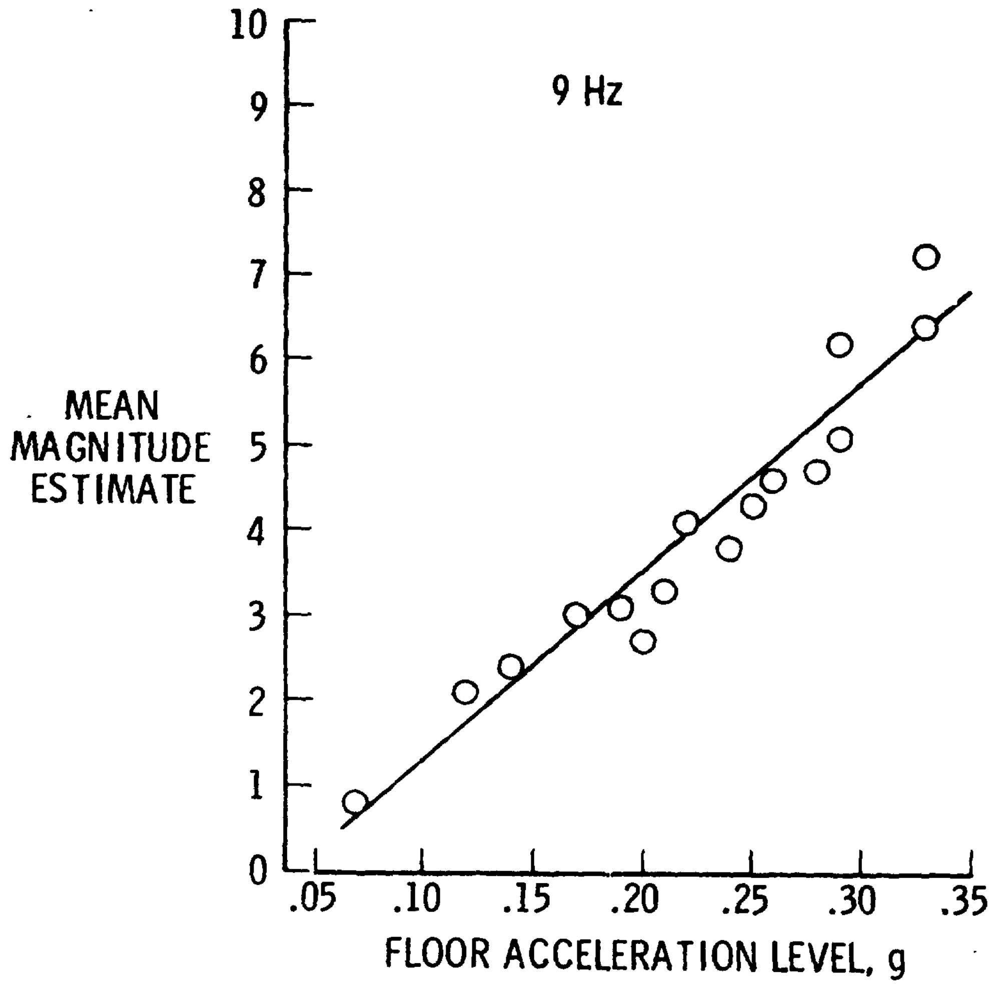


Figure 14

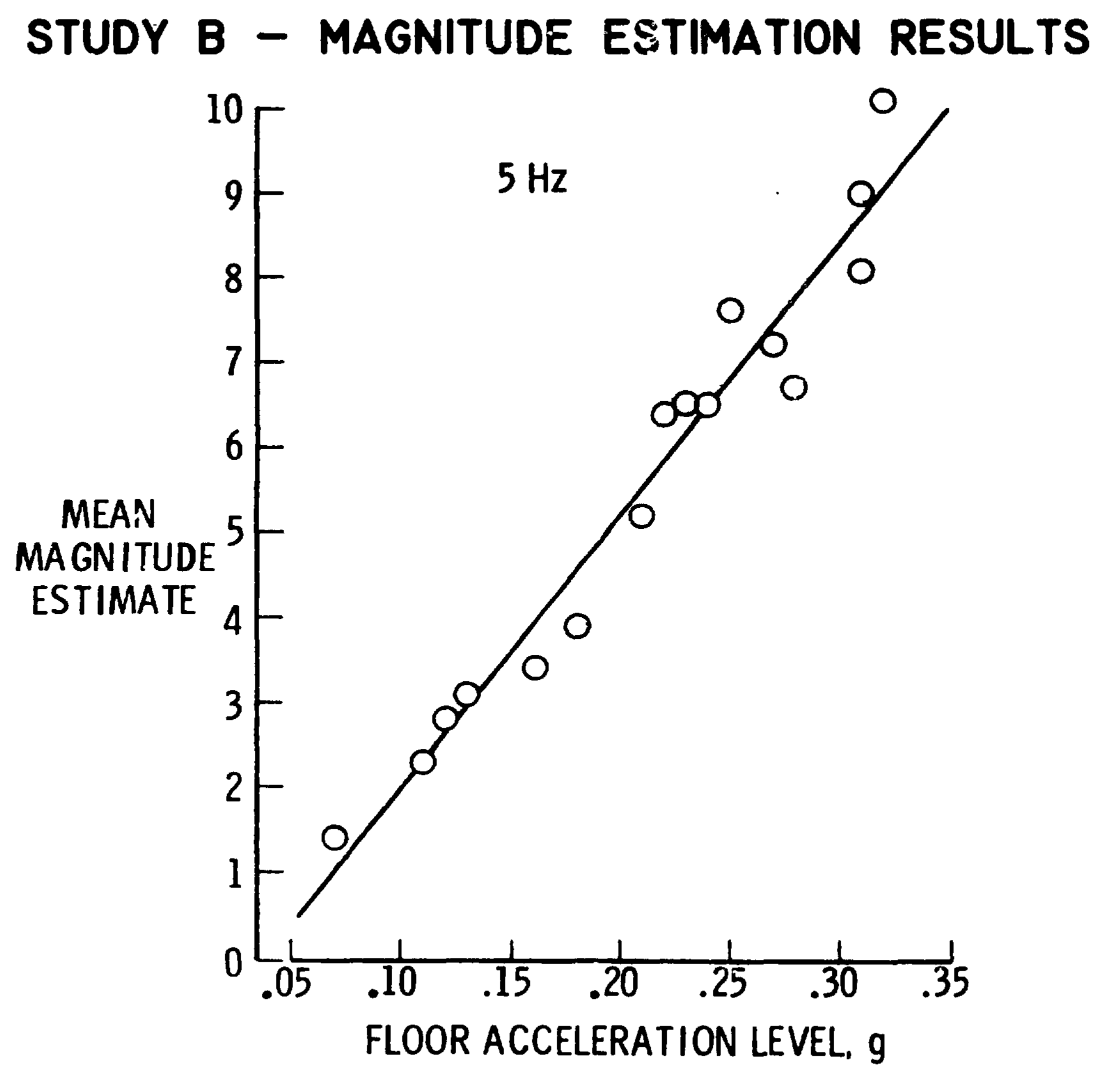

STUDY B — MAGNITUDE ESTIMATION RESULTS
5 Hz
MEAN MAGNITUDE ESTIMATE
10
9
8
7
6
5
4
3
2
1
0
.05
.10
.15
.20
.25
.30
.35
FLOOR ACCELERATION LEVEL, g

Figure 15

EQUAL DISCOMFORT CURVES

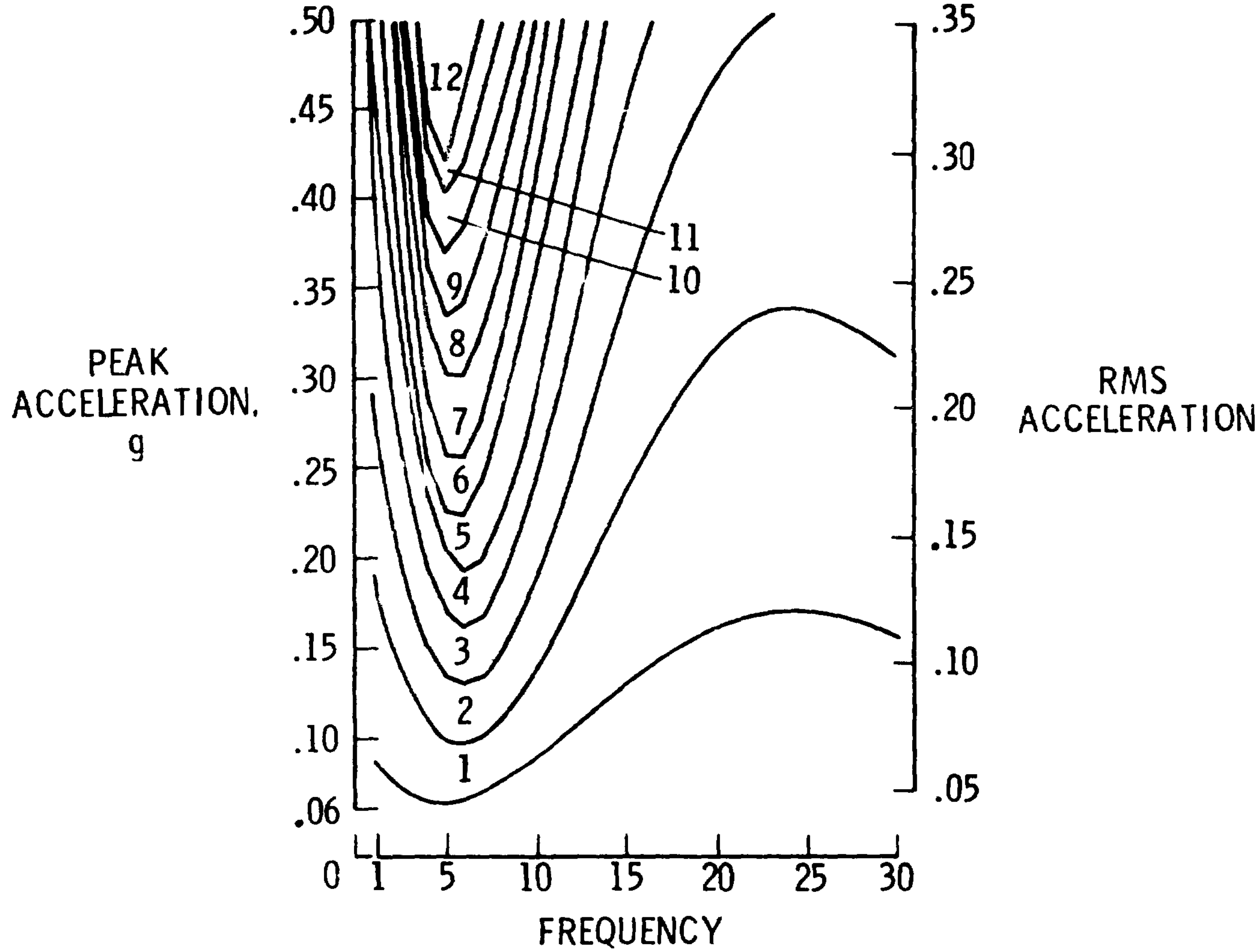


Figure 16