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EFFECT OF VIBRATION IN COMBINED AXES ON SUBJECTIVE EVALUATION OF RIDE QUALITY

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INTRODUCTION

The first study of subjective evaluations of ride quality produced by simultaneous vibrations occurring in more than one axis was reported by Jacklin and Liddell (ref. 1). The results of that study showed that introduction of various combinations of amplitudes and frequencies in the horizontal axis lowered the thresholds for ratings of Disturbing and Uncomfortable in the vertical axis, for frequencies below 7 Hz. The experimental design of the study, however, did not permit detection of interactions between the effects of vertical and horizontal vibrations on subjective ratings.

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Holloway and Brumaghim (ref. 2) have studied the effects of narrow-band, random-frequency vibrations with center frequencies between 0.20 and 7 Hz applied simultaneously to the vertical and lateral axes. That study showed that increasing the amplitude of vibrations in the lateral axis led to lower levels of amplitude in the vertical axis being rated as Objectionable. As with the Jacklin and Liddell study, it was beyond the scope of the research to study possible interactions between the effects of vibrations in the two axes.

The studies herein reported investigated the effects of simultaneous sinusoidal vibration in the vertical and lateral axes on ratings of discomfort. The first experiment concentrated on the effects of variation of frequency in the two axes, and the second study concentrated on the effects of amplitude variation in the two axes.

EXPERIMENT I - VARIATION OF FREQUENCY

Subjects

The subjects for this research were 11 males and 13 females recruited from the undergraduate student body of Old Dominion University. The 24 subjects used were recruited from a larger list of volunteers who had been medically screened and approved by Langley Research Center. The mean age of the subjects was 23.7 years and the standard deviation of the ages was 8.2 years.

Apparatus

The apparatus used in this experiment was the Langley passenger ride quality apparatus (PRQA). This apparatus, designed as a simulated passenger aircraft, can present subjects with whole-body vibration of various frequencies, amplitudes, and waveforms in the vertical, lateral (side-to-side), longitudinal (fore-and-aft), pitch, and roll axes. For this experiment the PRQA was equipped with six tourist-class seats. Additional details about the PRQA can be obtained from Clevenson and Leatherwood (ref. 3) and Stephens and Clevenson (ref. 4).

Design

The experimental design used was treatments by treatments by sessions with subjects nested under sessions (Winer, ref. 5). The first treatment variable was the frequency of vibration input in the vertical axis; the 10 levels of vertical frequency employed were 0, 1, 2, 3, 4, 5, 8, 10, 15, and 20 Hz. The second treatment variable was frequency of vibration input in the lateral axis; the same 10 levels of frequency were used in the lateral axis as were used in the vertical. Groups of six subjects were tested simultaneously on the PRQA, and there were four groups, or sessions. For each group of subjects the apparatus was set at one level of vertical frequency, and all levels of lateral frequency were presented in random order with that vertical frequency. Then the next level of vertical frequency was presented. A different random order of lateral frequencies was used for each level of vertical frequency and a different random order of vertical frequencies was used for each of the four sessions. The amplitude of all stimuli was 0.15g (peak).

Rating Scale

The rating scale employed was a 9-point, unipolar scale. For each stimulus the subject was provided with a separate scale consisting of a line with 9 divisions, numbered from 0 to 8. Above the 0 was the anchor Comfortable or zero discomfort and above the 8 was Maximum discomfort. The subjects were instructed to use the scale as an equal-interval scale, rating stimuli between the numbered divisions as well as on them. The subjects were also instructed to rate the discomfort produced by the stimuli. Before beginning each new level of vertical frequency, the subjects were presented with two anchor stimuli. The first had no vertical input and a lateral input of 10 Hz and was described as "One that many people might give a low number rating". The second had a vertical input of 4 Hz and a lateral input of 5 Hz, and was described as "One that many people would probably assign a high number rating".

Procedure

The subjects were transported to the Langley Research Center from Old Dominion University, a distance of approximately 40 km (25 miles), in a late-model, nine-passenger station wagon. Upon arriving at the

Langley Research Center the subjects were taken to a conference room adjacent to the room housing the PRQA. Here the subjects were given their instructions regarding the experiment and appropriate safety procedures. The subjects were then seated in the PRQA and asked to fasten their seat belts.

Throughout the testing, two-way audio communication was maintained with the subjects and the subjects were also continually observed through a one-way mirror as part of the safety procedures.

Instructions regarding the anchor stimuli and the test stimuli were recorded on audiotape. At the beginning of each test stimulus the subjects were told "Begin" and at the end of the stimulus presentation the subjects were told "Rate". Each trial consisted of 5 seconds for the stimulus to reach the appropriate level, 15 seconds of stimulus, 5 seconds for the offset of the stimulus, and 10 seconds between trials. The subjects were given a 1-minute rest between each series of 10 stimuli and a 15-minute intermission halfway through the testing, i.e., after 50 stimuli.

Results

Table 1 shows the results of analysis of variance with repeated measures on two variables. Clearly, the most significant variable affecting the ratings of the subjects was the frequency of lateral vibrations. The effect of frequency in the vertical axis was also significant, as was the interaction between these two variables. The interaction appears to be due to each axis masking the effects of the other axis at frequencies rated as being of maximum discomfort, with the lateral axis masking the effects of the vertical more than in the reverse direction.

Figure 1 shows the mean ratings of the subjects as a function of the frequency of vertical input with frequency of lateral input as a parameter. Figure 2 shows the same data but with the ratings as a function of lateral frequency with vertical frequency as a parameter. The lateral axis appears to have a dominant effect at lower frequencies, whereas at higher frequencies the relative significance of the vertical axis is much greater than it is at lower frequencies. The significant interaction appears to be due to each axis masking the effects of the other axis at frequencies rated at maximum discomfort in the former axis, with the lateral axis masking the effects of the vertical more than in the reverse direction.

A multiple-regression analysis was subsequently computed using the physical measures of vertical and lateral frequency and various nonlinear transformations of these measures to predict the subjective responses of discomfort. The resulting predictive equation was used to generate the response surface presented in figure 3; it should be noted that the multiple correlation coefficient associated with the criterion variable and the predictor variables was 0.685, accounting for 47 percent of the variability in the individual subjective responses.

EXPERIMENT II - VARIATION OF AMPLITUDE AND FREQUENCY

Whereas the first experiment was primarily concerned with the effects of variation in frequency of vibrations simultaneously presented in the two axes, this experiment was concerned with the effects of variation of amplitude in the two axes on ratings of discomfort, and with interactions between the effects of amplitude and the effects of frequencies.

Subjects

The subjects for this research were 72 undergraduate students recruited from the student body of Old Dominion University in a manner similar to that used in recruiting subjects for Experiment I.

Apparatus

As in Experiment I the apparatus used was the Langley passenger ride quality apparatus (PRQA).

Design

The experimental design used was a 4 × 4 × 4 × 4 factorial design with 12 subjects nested in each of the vertical frequencies and with repeated measures over the vertical amplitudes, the lateral frequencies, and the lateral amplitudes. Thus, each subject was exposed to only one of the four vertical frequencies but experienced that frequency at each of its four amplitudes combined with 16 (or 4 × 4) lateral frequency and amplitude conditions. The four levels of vertical frequency were 2, 5, 9, and 15 Hz. The four levels of vertical amplitude planned were 0.05g, 0.10g, 0.15g, and 0.25g (peak). The four levels of lateral frequency were 2, 4, 8, and 16 Hz, and the four levels of lateral amplitudes planned were, like the vertical amplitudes, 0.05g, 0.10g, 0.15g, and 0.25g (peak). In addition, as a control condition, 12 other subjects experienced each of the vertical frequencies at each of the four amplitudes in the absence of lateral input. As a final control, another group of 12 subjects experienced each of the lateral frequencies at each of the four amplitudes in the absence of vertical input.

Groups of 6 subjects were tested on the PRQA simultaneously; 12 such groups were tested. For each of the 10 experimental groups plus 2 control groups that experienced lateral vibration, the apparatus was set at a level of lateral frequency and all combinations of vertical amplitude and lateral amplitude were presented with that level of lateral frequency before going on to another level of lateral frequency. For the control group that received only vertical input, the apparatus was set at a level of vertical frequency and all levels of vertical amplitude were presented with that before going on to another level of vertical frequency. To the extent possible, the order of presentation of levels of amplitude was counterbalanced.

Procedure

The rating scale and procedure used were the same as in Experiment I, except that the anchor stimuli and a 1-minute rest were given after each 8 trials rather than after each 10 trials.

RESULTS AND DISCUSSION

Before considering the analyses of the subjective ratings, a comparison was made between the amplitudes that were planned, the input amplitudes, and the amplitudes that were recorded from the PRQA during the testing, the output amplitudes. Although the magnitudes of the output amplitudes differed slightly from the input amplitudes, there appeared to be no major systematic variations between the planned inputs and the outputs across the experimental conditions. As noted above, the amplitudes that were planned were 0.05g, 0.10g, 0.15g, and 0.25g (peak); the means of the amplitude outputs were 0.06g, 0.10g, 0.15g, and 0.26g (peak).

The results of the analysis of variance of the ratings of discomfort, excluding the control conditions, are shown in table 2. All four main effects (vertical frequency, vertical amplitude, lateral frequency, and lateral amplitude) were significant, as were all six of the simple interactions between these four parameters of vibration. Two of the triple interactions were significant, as was the four-way interaction.

Figures 4 to 7 show the mean ratings of the subjects as a function of each of the parameters of vibration. These figures were obtained by averaging across all the remaining experimental conditions not shown in each figure. The first two of the figures, figures 4 and 5, show that the main effects found in Experiment I, regarding the effects of frequency on ratings of discomfort, were replicated in the second experiment. Figures 6 and 7 show that the effect of increasing amplitude of vibration in either axis is to increase ratings of discomfort, an expected finding.

The more interesting and important findings of the experiment are shown in figures 8 to 13, which show the simple interactions between the six pairs of vibration parameters. In each of these figures the discomfort ratings were averaged across both of the vibration parameters not shown in each figure, thus revealing the form of the interaction between the two variables that are shown. The interaction shown in figure 8, between vertical frequency and lateral frequency, is a replication of the interaction found in Experiment I, and shown in figure 1.

Figure 9 shows the interaction between the effects of the vertical amplitude and the lateral amplitude. It appears that the form of this interaction is terminative, since high amplitudes in either axis tend to mask the effects of variation in amplitude in the other axis.

The interactions between frequency and amplitude within each axis are shown in figure 10 for the vertical axis and figure 11 for the lateral axis. In both figures the effect of variation in amplitude is greatest at those frequencies rated as being of most discomfort while amplitude variation had less effect at frequencies rated as being of less discomfort.

The interactions between frequency in one axis and amplitude in the other are shown in figures 12 and 13. First, the interaction between vertical frequency and lateral amplitude is shown in figure 12; the other interaction, between lateral frequency and vertical amplitude, is shown in figure 13. In contrast to the form of the interaction shown in figures 10 and 11, these interactions are in the opposite direction, with amplitude variation having the greatest effect at frequencies rated as being of least discomfort. Perhaps a more appropriate conclusion, however, is that at frequencies rated as being of most discomfort, there is some masking of amplitude effects from the other axes while the effects of amplitude from the same axis are enhanced

Regarding the simple interactions, note should be taken that the three smallest interactions as reflected by the statistical values were found for interactions involving vertical frequency, suggesting that perhaps interactio with vertical frequency is the least important among those found. Regarding the other interactions, no pattern is apparent beyond that obvious from table 2. Although a significant four-way interaction was found, no explanation of it is readily apparent.

To summarize the results of Experiment II, it appears that the four major parameters of vibration not only affect ratings of discomfort, but they also interact with each other in their effects. Interactions between frequencies in the two axes and between amplitudes in the two axes were expected as was, to some extent, the interaction between frequency and amplitude withi one axis. However, the interaction between frequency in one axis and amplitu in the other was not expected.

Taken together, the results of these two experiments strongly suggest th there are effects on discomfort that occur when subjects are vibrated in several axes at once that cannot be assessed with research using vibration in on one axis. Although the interactions between the four parameters of vibration used in these experiments may be of less importance in accounting for discomf than are the main effects of these four major parameters, an understanding of these interactions may very well affect the precision with which standards ca be set to govern the acceptable limits for exposure of humans to vibration. I conclusion, these results also suggest the wisdom of further research on the effects of vibration in combined axes directed toward appropriate revision of the standard established by ISO in reference 6 regarding vibrations occurring in more than one axis simultaneously.

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TABLE 1. - THREE-WAY ANALYSIS OF VARIANCE WITH REPEATED MEASURES ON TWO VARIABLES

Source of variation	Sum of squares	Degrees of freedom	Mean square	F
Se	321.69	3	107.23	2.50
VF	1751.37	9	194.60	50.71**
LF	5680.88	9	631.21	327.56**
Se × S w. groups	858.31	20	42.92	
SE × V	200.27	27	7.42	1.93**
Se × L	146.89	27	5.44	2.82**
V × L	722.35	81	8.92	8.33**
V × S w. groups	690.80	180	3.84	
L × S w. groups	346.86	180	1.93	
Se × VF × LF	551.64	243	2.27	2.12**
VF × LF × S w. groups	1734.26	1620	1.07	

** $p < 0.01$

Notation:

F	mean-square ratio
LF	lateral frequency
p	probability
S	subjects
Se	sessions
VF	vertical frequency
w.	within

TABLE 2. - FOUR-WAY ANALYSIS OF VARIANCE WITH REPEATED MEASURES ON THREE VARIABLES

Source of variation	Sum of squares	Degrees of freedom	Mean square	F
VF	951.56	3	317.19	13.39**
LF	1178.82	3	392.94	105.73**
VA	1851.90	3	617.30	273.32**
LA	2160.80	3	720.21	260.80**
S w. VF	1042.38	44	23.69	
VF × LF	103.33	9	11.48	3.09**
VF × VA	173.37	9	19.26	8.53**
LF × VA	222.99	9	24.78	18.73**
VF × LA	103.65	9	11.52	4.17**
LF × LA	469.01	9	52.11	58.59**
VA × LA	249.03	9	27.67	39.92**
LF × S w. VF	490.58	132	3.72	
VA × S w. VF	298.13	132	2.26	
LA × S w. VF	364.52	132	2.76	
VF × LF × VA	39.26	27	1.45	1.10
VF × LF × LA	42.75	27	1.58	1.78*
VF × VA × LA	15.67	27	.58	0.84
LF × VA × LA	65.04	27	2.41	4.30**
LF × VA × S w. VF	523.86	396	1.32	
LF × LA × S w. VF	352.22	396	.89	
VA × LA × S w. VF	274.48	396	.69	
VF × LF × VA × LA	80.21	81	.99	1.77**
LF × VA × LA × S w. VF	665.45	1188	.56	

* $p < 0.05$
** $p < 0.01$

Notation:

F	mean-square ratio	S	subjects
LA	lateral amplitude	VA	vertical amplitude
LF	lateral frequency	VF	vertical frequency
p	probability	w.	within

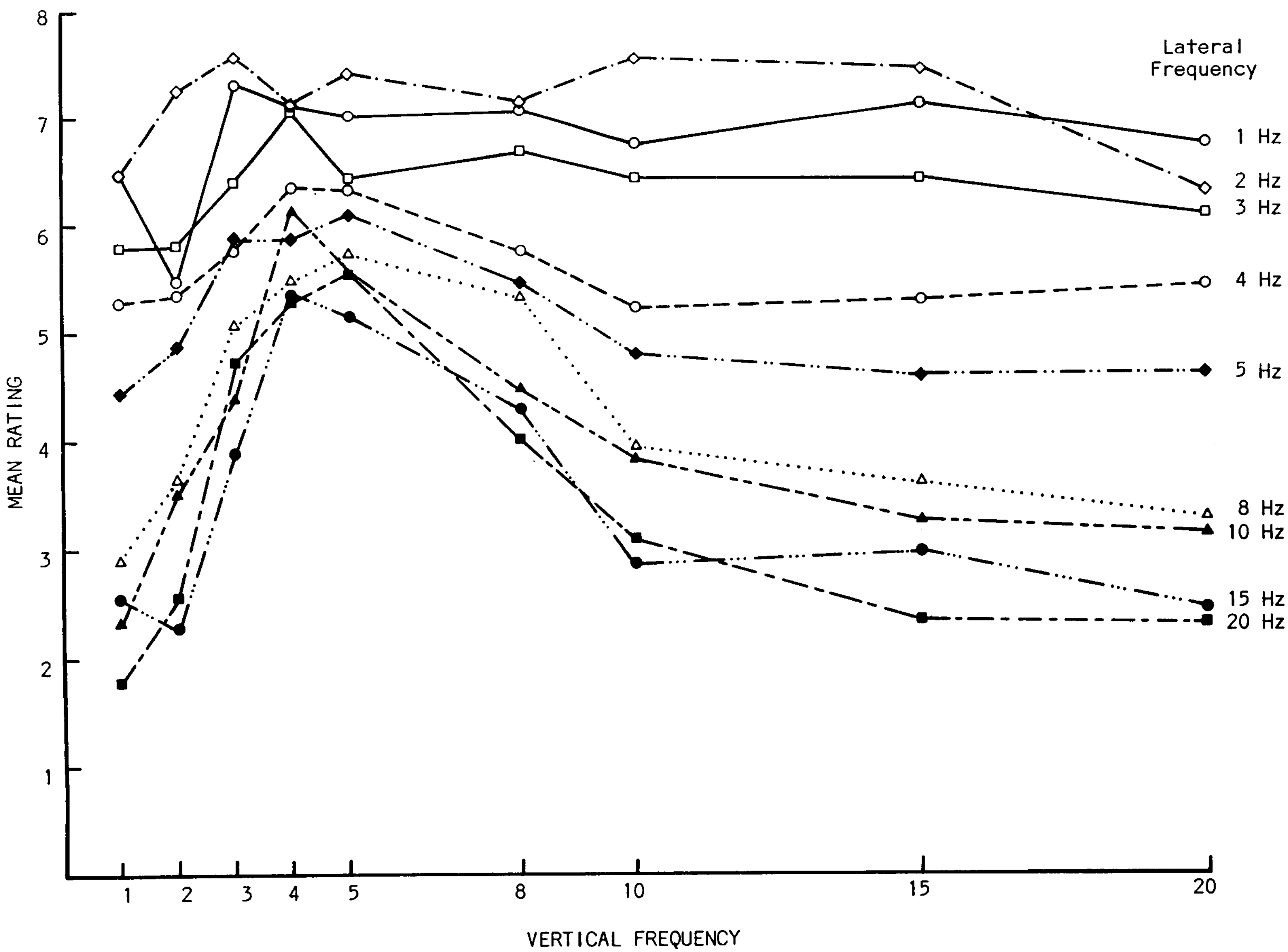

Figure 1.- Mean rating as a function of vertical frequency with lateral frequency as a parameter.

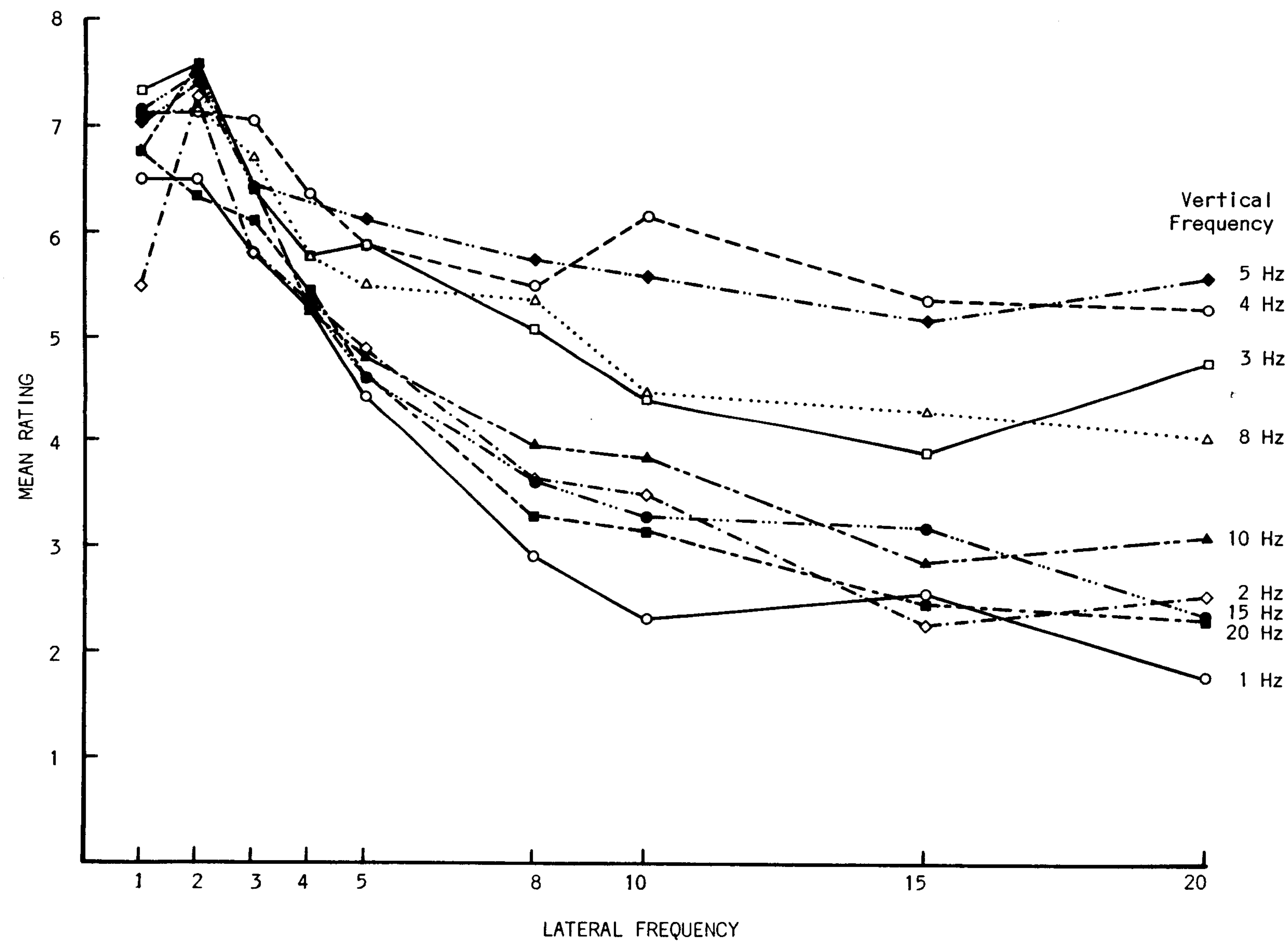

Figure 2.- Mean rating as a function of lateral frequency with vertical frequency as a parameter.

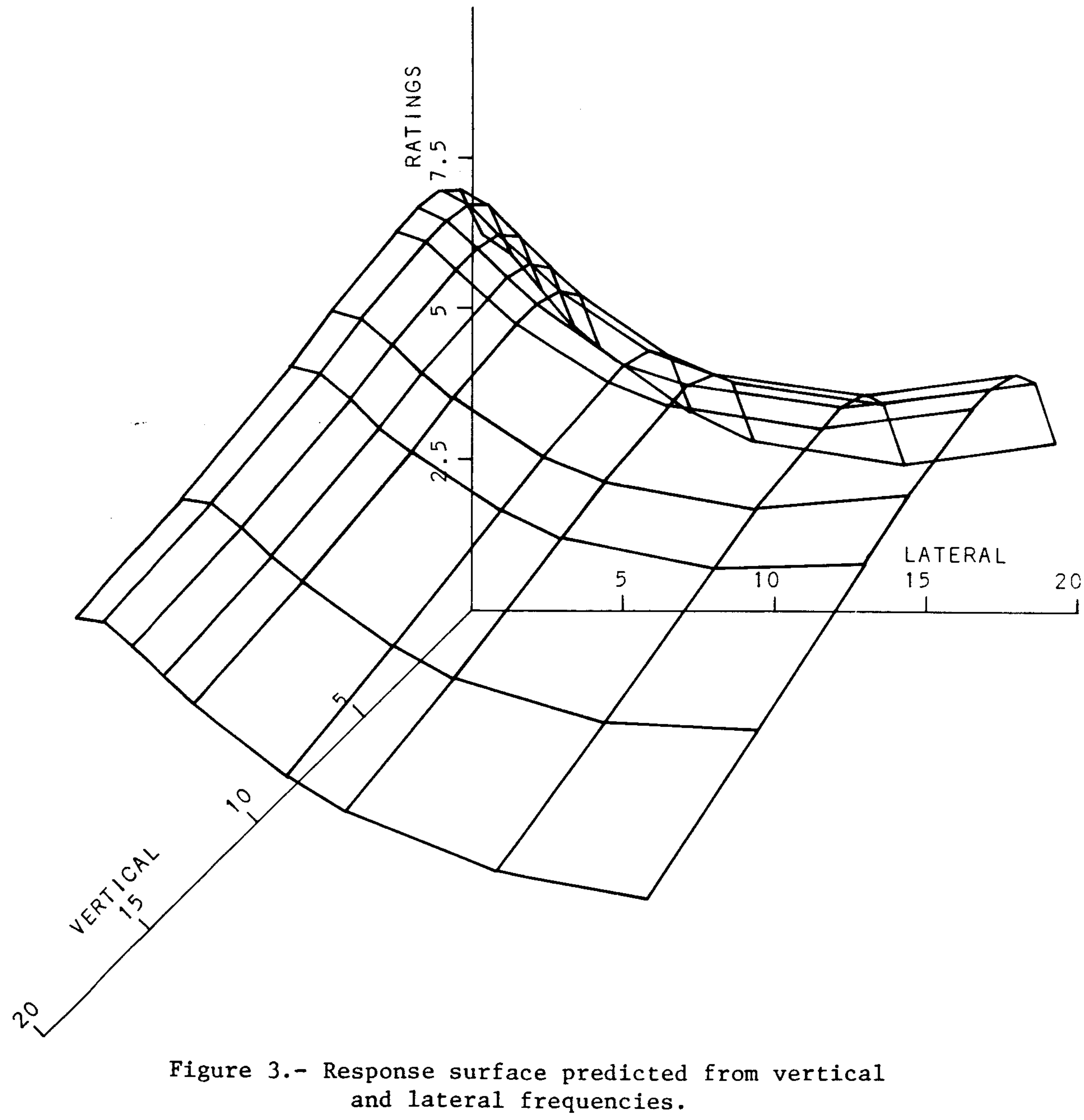

Figure 3.- Response surface predicted from vertical and lateral frequencies.

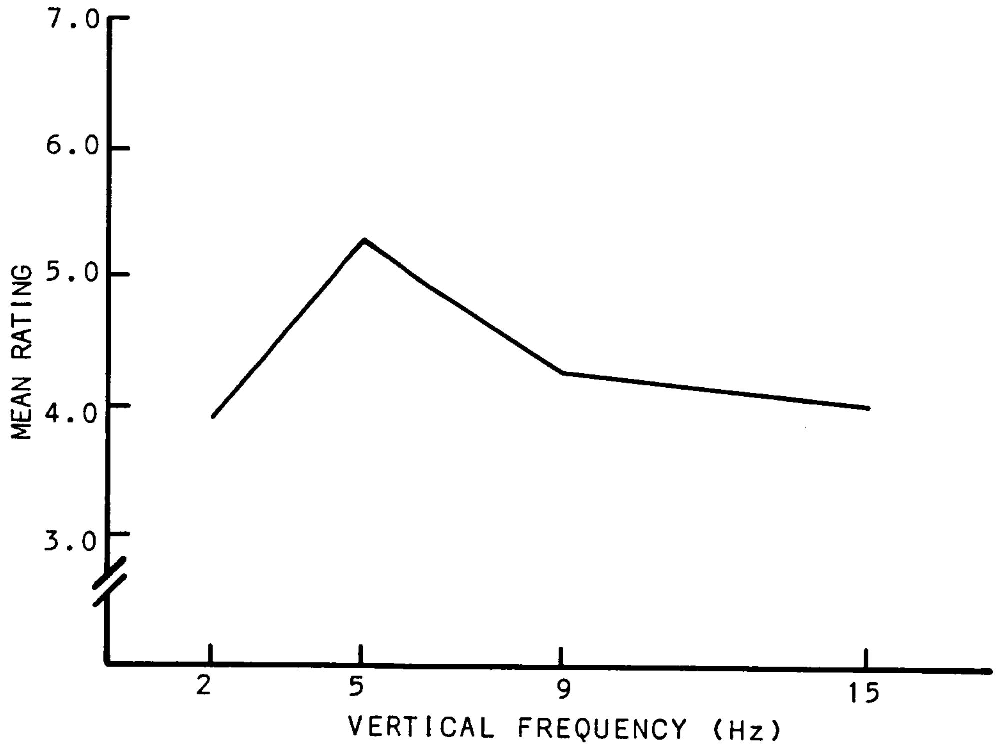

Figure 4.- Subjective rating as a function of vertical frequency.

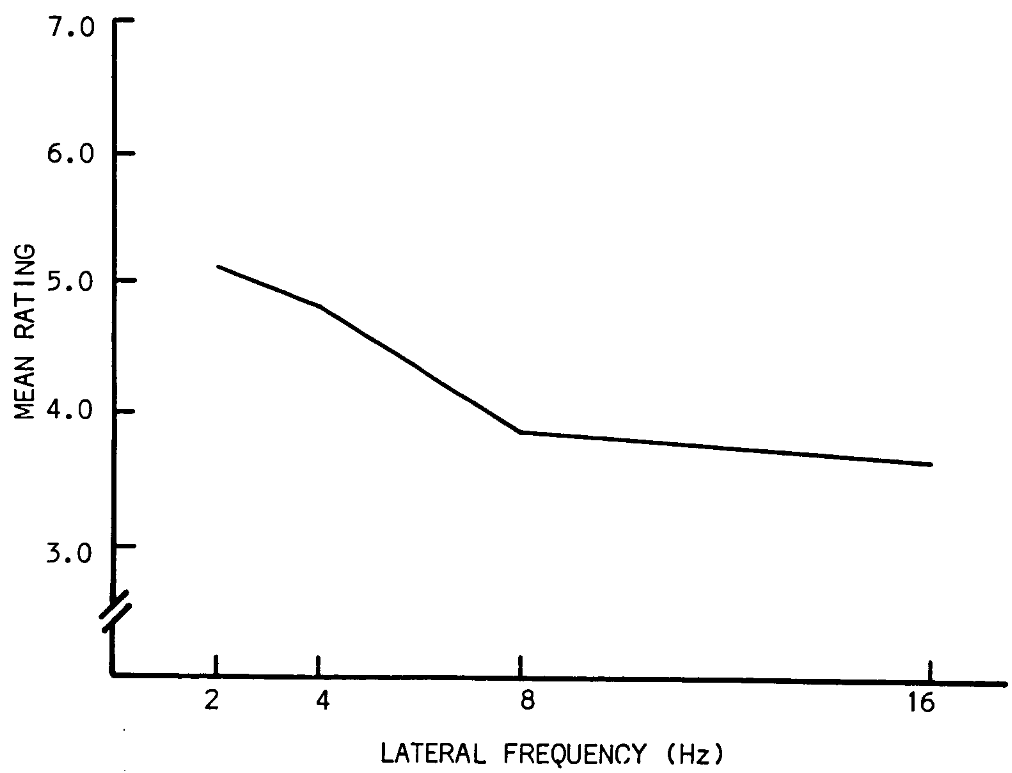

Figure 5.- Subjective rating as a function of lateral frequency.

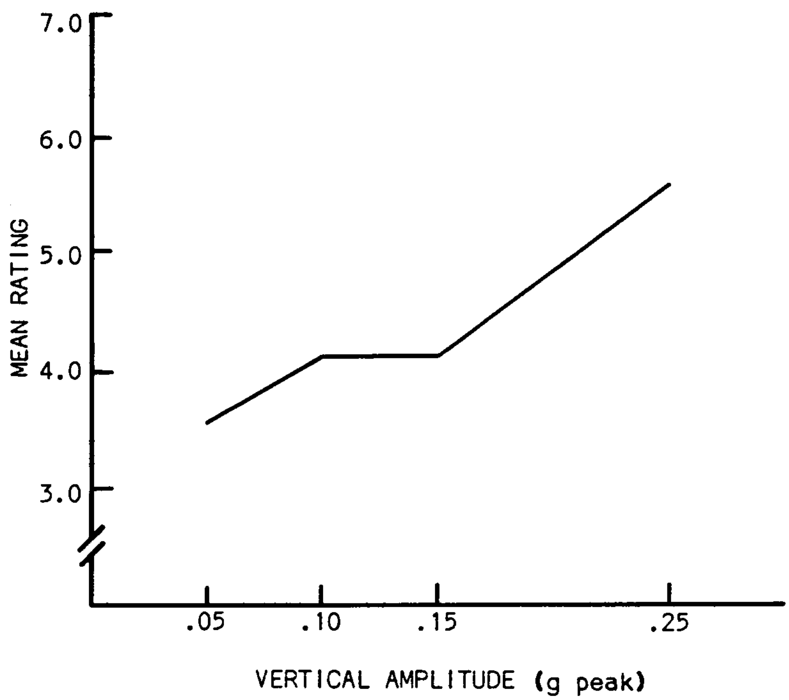

Figure 6.- Subjective rating as a function of vertical amplitude.

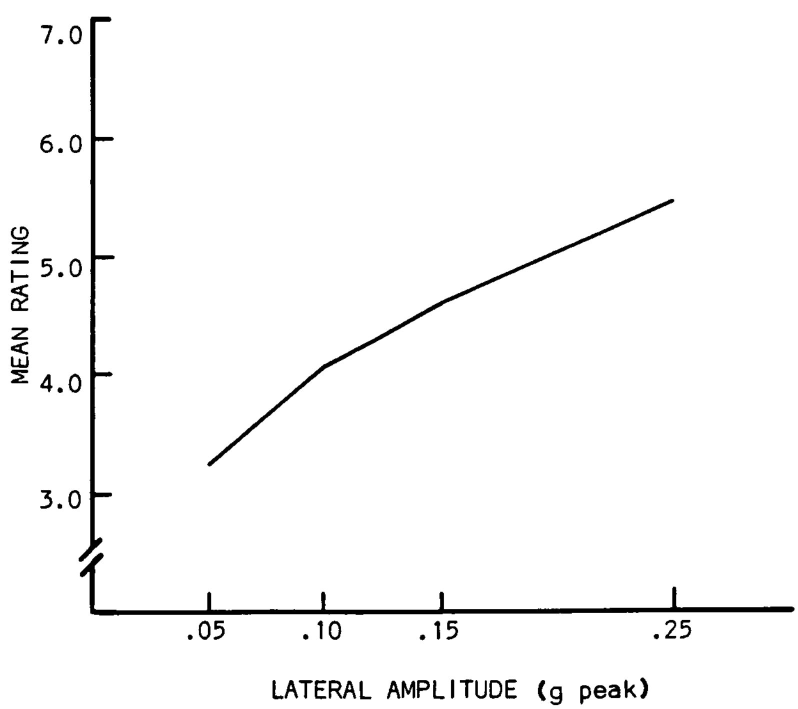

Figure 7.- Subjective rating as a function of lateral amplitude.

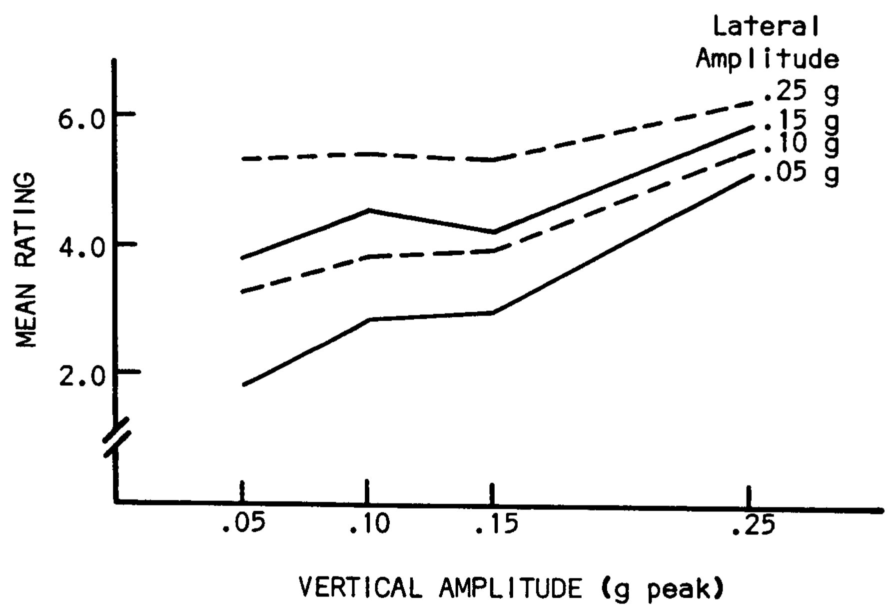

Figure 8.- Subjective rating as a function of the interaction between vertical frequency and lateral frequency.

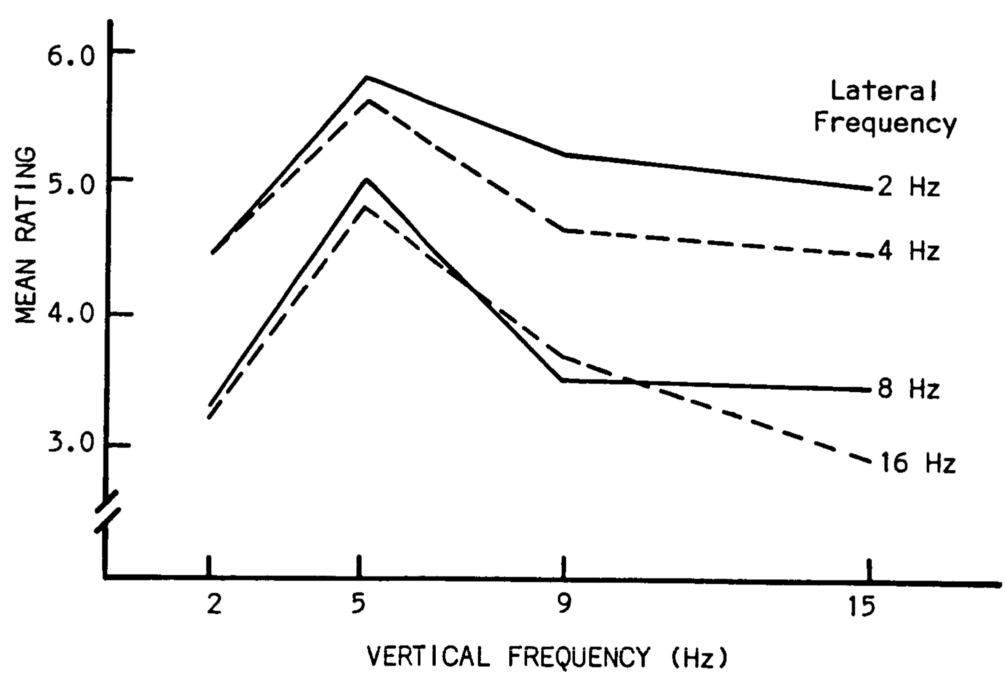

Figure 9.- Subjective rating as a function of the interaction between vertical amplitude and lateral amplitude.

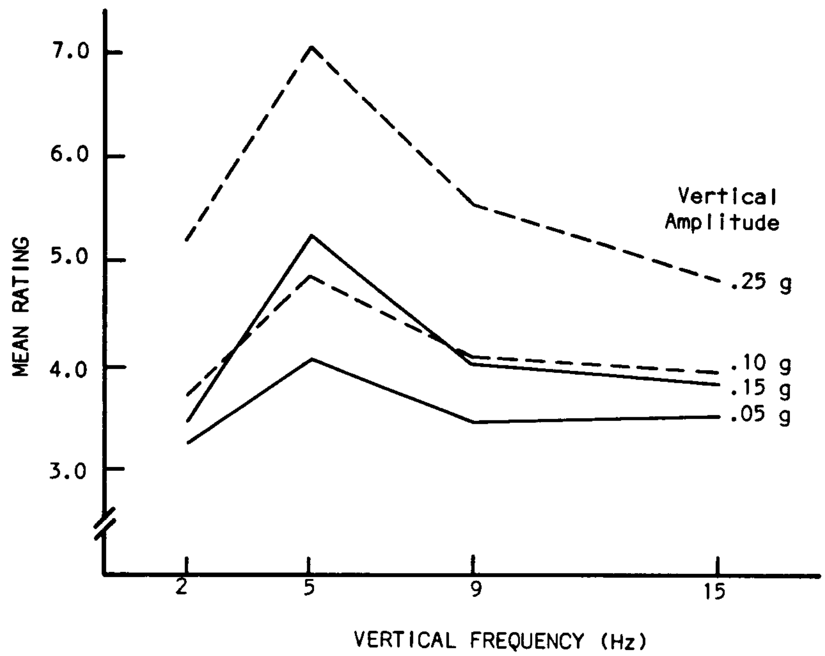

Figure 10.- Subjective rating as a function of the interaction between vertical frequency and vertical amplitude.

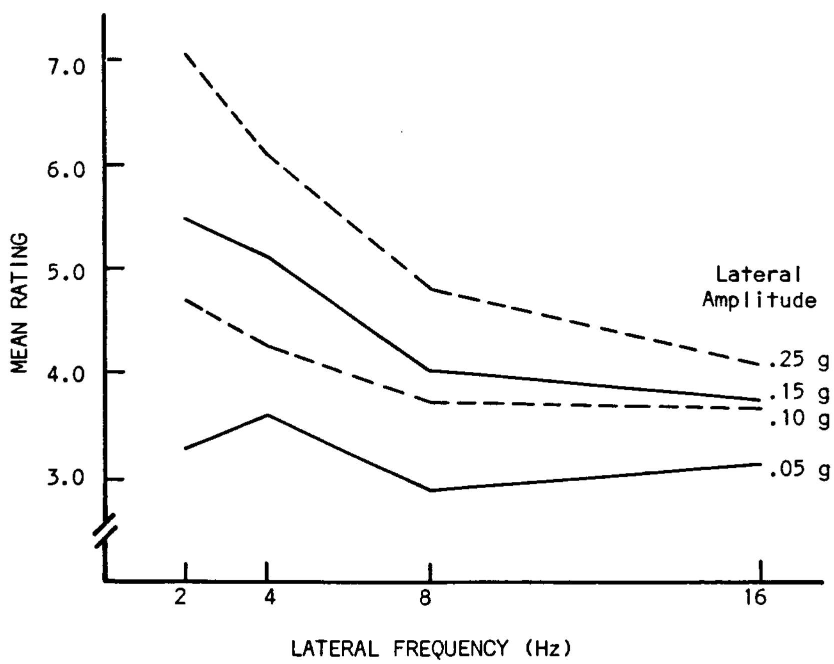

Figure 11.- Subjective rating as a function of the interaction between lateral frequency and lateral amplitude.

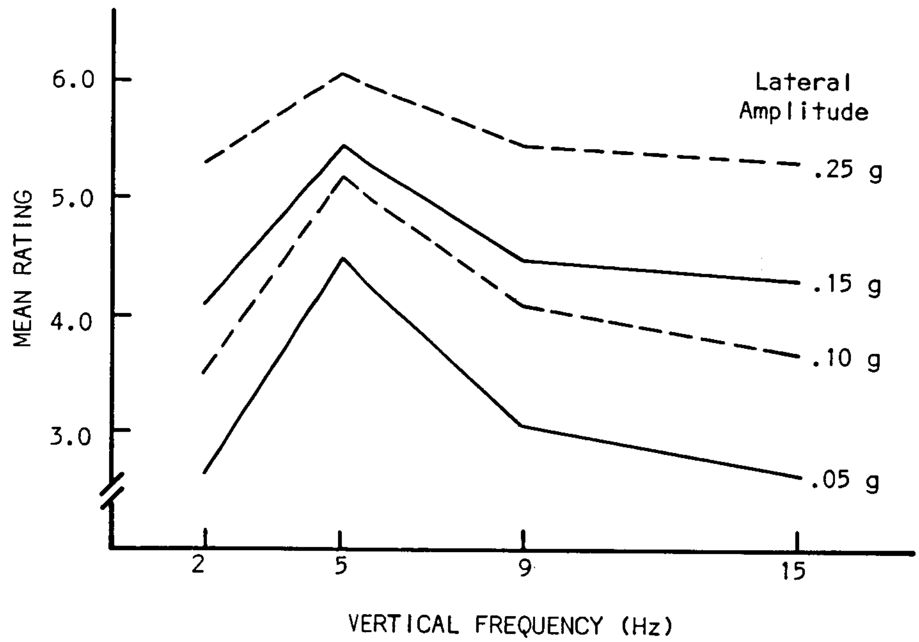

Figure 12.- Subjective rating as a function of the interaction between vertical frequency and lateral amplitude.

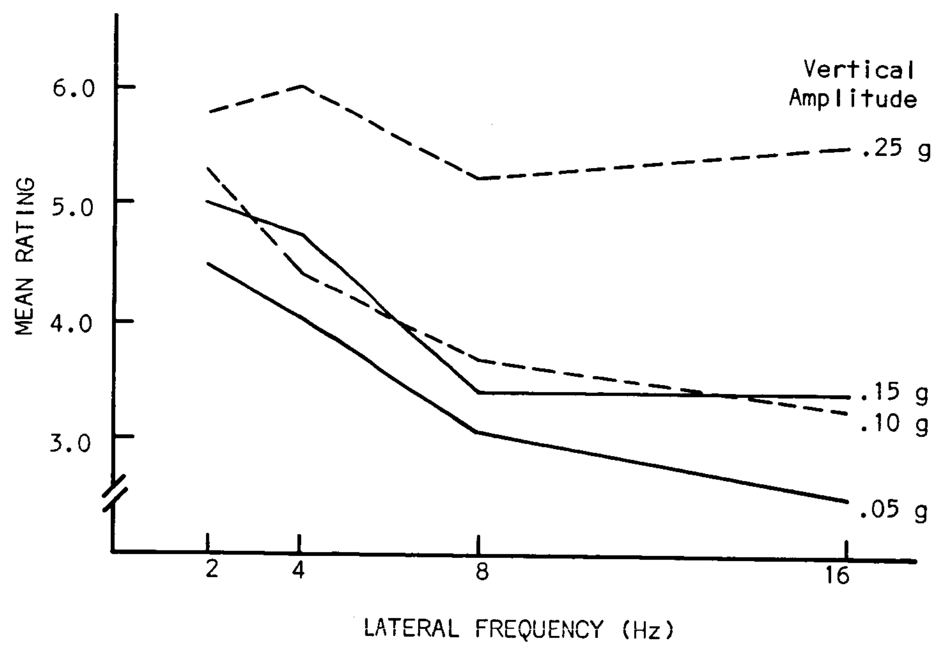

Figure 13.- Subjective rating as a function of the interaction between lateral frequency and vertical amplitude.