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Three psychophysical matching experiments were conducted to compare the perceived intensity of angular vibrations, in roll, pitch or yaw, with the perceived intensity of Z-axis translational vibrations. Seated subjects matched their perceptions of the intensity of Z-axis stimulus vibrations - at six frequencies from 2.5-8 Hz, at each of three intensity levels - by adjusting the intensity of angular response vibrations at the same frequencies. The results showed that the acceleration of the angular matching responses increased significantly as a function of both the frequency and the intensity of the stimulus vibrations.

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Since the stimuli were chosen from existing Z-acis equal intensity contours, the mean matching responses define equivalent contours for angular vibrations. Determination of relationships between translational and angular vibration is essential for the development of improved vibration exposure criteria applicable to complex vibration environments.

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Psychophysical comparison of vertical and angular vibrations

RICHARD W. SHOENBERGER

Air Force Aerospace Medical Research Laboratory, Wright-Patterson Air Force Base, Ohio 45433

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Three psychophysical matching experiments were conducted to compare the perceived intensity of angular vibrations, in roll, pitch or yaw, with the perceived intensity of Z-axis translational vibrations. Seated subjects matched their perceptions of the intensity of Z-axis stimulus vibrations—at six frequencies from 2.5-8 Hz, at each of three intensity levels—by adjusting the intensity of angular response vibrations at the same frequencies. The results showed that the acceleration of the angular matching responses increased significantly as a function of both the frequency and the intensity of the stimulus vibrations. Since the stimuli were chosen from existing Z-axis equal intensity contours, the mean matching responses define equivalent contours for angular vibrations. Determination of relationships between translational and angular vibration is essential for the development of improved vibration exposure criteria applicable to complex vibration environments.

EXISTING CRITERIA for human exposure to whole-body vibration (1,3,9) are limited to translational vibrations along the X, Y, and Z axes. However, operational environments also have angular vibration components around each of these axes in roll, pitch, and yaw. In order to be applicable to all vibration environments, vibration standards must provide criteria for all six of these directions of motion. Little information is available concerning human response to angular vibration. Even if a significant amount of data existed on angular vibration effects, specific information on the comparability of angular and translational vibrations would be needed.

One factor that complicates comparisons between linear and angular vibrations is that intensity is measured in different physical units for the two types of vibration—m/s^2 (or G) for translational vibration, and rad/s^2 for angular vibration. Although these are both units of acceleration, there is no physical way to equate them. However, linear and angular vibrations can be equated psychophysically using an intensity-matching technique. Through a procedure known as cross modality matching, widely differing perceptual qualities, such as the loudness of a sound, the brightness of a light, or the severity of an electric shock have been equated with the force exerted on a hand dynamometer (8). A similar psychophysical matching technique has also been used successfully to compare the subjective intensities of vibrations with different frequencies (5), different translational axes (6), and different spectral compositions (7).

The purpose of the research reported here was to obtain data comparing the subjective intensities of translational and angular vibrations, needed for the incorporation of angular oscillations into human vibration exposure criteria. Three experiments were conducted, one for each direction of angular vibration. In each experiment the subjects matched their perceptions of the intensity of translational stimulus vibrations in the vertical direction (Z axis), by adjusting the physical intensity of angular response vibrations in roll, pitch, or yaw. Vertical vibrations were used as the stimuli in all three experiments, for two reasons: first, because existing data and knowledge are most extensive for Z-axis vibration; and second, to provide a common reference for comparison of all three angular modes.

MATERIALS AND METHODS

Subjects: Male Air Force military personnel served as subjects. They were physically qualified volunteer members of a vibration panel, and received incentive pay for participation in vibration experiments. There were 11 subjects in the roll experiment, 14 in the pitch experiment, and 10 in the yaw experiment.

Apparatus: Whole-body vibration was produced by the AFAMRL six-degree-of-freedom motion device (SIXMODE). The SIXMODE is a multiaxis electrohydraulic vibrator, capable of motion in all six degrees-of-freedom. The vibration seat was rigidly constructed of alu-

This research was conducted by personnel of the Air Force Aerospace Medical Research Laboratory. Reprints are identified as AFAMRL-TR-80-46. The voluntary informed consent of the subjects was obtained as required by Air Force Regulation 169-3.

Instrumentation and operation of the vibration machine, and production, analysis, and calibration of the vibration stimuli were by personnel of the University of Dayton Research Institute, under Contract F33615-79-C-0509.

minum and bolted directly to the vibration platform. The subject was seated on a standard F-105 seat insert made up of a parachute container and seat pad. Previous research (2) had shown that this setup provided a stiff but comfortable coupling between the seat and subject with a negligible effect on vibration transmission to the subject over the frequency range from 2-10 Hz. The subject was secured to the seat by a lap belt and shoulder harness. He was also provided with a hand-held potentiometer to control the intensity of the angular matching vibration, and a headset and microphone connected to an intercom system between the subject, experimenter, and SIXMODE operator. The overall experimental setup is shown in Fig. 1.

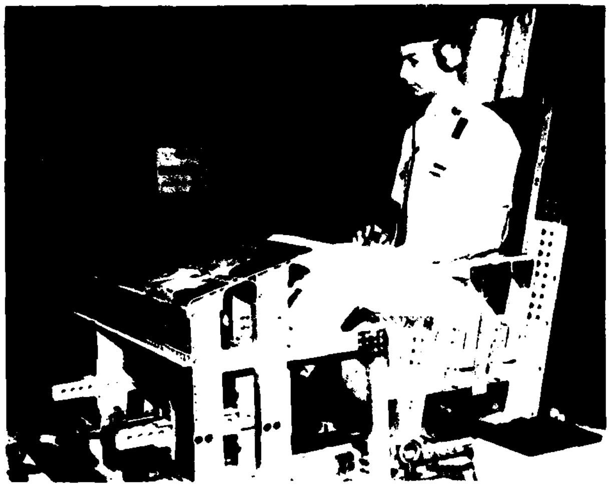

Fig. 1. View of experimental setup.

The vibration table was instrumented with accelerometers which measured the acceleration of the table in all six degrees-of-freedom. These acceleration signals were recorded on six channels of a strip chart recorder. In addition, the signals for the vertical direction and for the appropriate angular direction for each experiment were fed to true R.M.S. meters, providing a digital readout for the Z-axis input accelerations, in R.M.S. G, and the angular response accelerations, in R.M.S. rad/s^2.

Vibration: In all three experiments, the Z-axis stimulus vibrations were administered at each of six frequencies—2.5, 3.15, 4.0, 5.0, 6.3 and 8.0 Hz. For the roll and pitch experiments, each Z-axis frequency was presented at three intensity levels: the 2.5-h Fatigue-Decreased Proficiency (FDP) level (3), the 1-h FDP level, and the 25-min FDP level. The Z-axis acceleration values of the 18 vibration stimuli used in the roll and pitch experiments are shown in Table I. In view of the relatively small contribution of yaw-axis vibration to flight vehicle motion environments, and its even smaller contribution in land and sea vehicles, the yaw experiment was abbreviated and only the 1-h FDP level stimuli were used. In all three experiments, the angular response vibrations were presented at the same frequencies as the stimulus vibrations and were adjusted in intensity by the subjects.

Procedure: Each subject was required to match his

TABLE I. VIBRATION STIMULI.

Frequency	Acceleration (R.M.S. G_z)		
(Hz)	2.5-h FDP	1-h FDP	25-min FDP
2.5	0.092	0.153	0.228
3.15	0.082	0.135	0.204
4.0	0.072	0.120	0.183
5.0	0.072	0.120	0.183
6.3	0.072	0.120	0.183
8.0	0.072	0.120	0.183

perception of the intensity of each of the Z-axis stimulus vibrations listed in Table I by adjusting the intensity of angular vibration in either the roll, pitch, or yaw axis until he felt that its subjective intensity was the same as the stimulus vibration he had just experienced. For each match, the frequency of the angular response vibration was the same as that of the particular stimulus vibration being matched. Each match involved a 30-s exposure to the Z-axis stimulus vibration and a subsequent exposure to the matching angular vibration that lasted approximately 20-45 s, depending on how quickly the subject achieved a match.

When each subject arrived at the test facility, he was given a set of written instructions which explained the nature of the experiment and the intensity-matching procedure. He was then seated in the vibration chair and given a short practice session to familiarize him with the operation of the equipment and the matching technique. The subject then experienced a series of matching runs (pairs of stimulus and matching vibrations) consisting of two matches at each of the six frequencies at one of the three intensity levels (Table I). In the roll and pitch experiments, testing was carried out during three test sessions, with a different intensity level in each session. Sessions were scheduled at approximately 1-week intervals. The order of intensity levels across sessions and the order of frequencies within a session were randomized for each subject. The yaw experiment involved only one intensity level and, therefore, required only one test session.

RESULTS AND DISCUSSION

Results of the roll experiment are summarized in Table II. The table gives the mean accelerations of the roll-axis matching responses (two matches per subject per stimulus) for each of the 18 vibration stimuli listed in Table I. Examination of Table II reveals that the mean roll response increased across intensity levels, and that

TABLE II. MEAN ROLL RESPONSE (R.M.S. rad/s^2) FOR EACH STIMULUS CONDITION.

Frequency	Stimulus Level		
(Hz)	2.5-h FDP	1-h FDP	25-min FDP
2.5	0.63	1.09	1.48
3.15	0.68	1.33	1.93
4.0	0.91	1.55	2.79
5.0	1.05	2.11	3.86
6.3	1.64	2.92	4.94
8.0	2.06	3.74	5.74

within each intensity level roll response also increased with frequency. These data are also presented in Fig. 2,

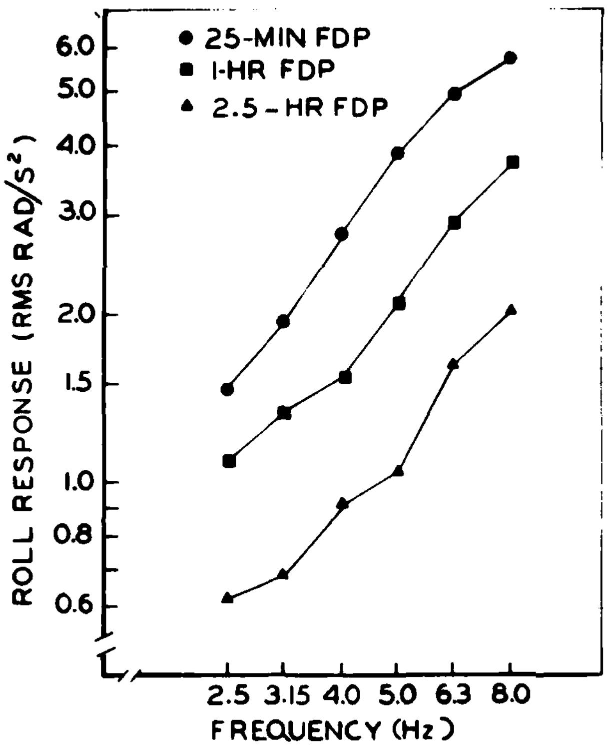

Fig. 2. Mean acceleration of roll response as a function of frequency for each level of stimulus intensity.

which shows roll response as a function of frequency, with stimulus intensity (FDP level) as a parameter. The figure clearly indicates that the mean acceleration of the roll-axis matching response increased as a function of frequency and as a function of the intensity level of the Z-axis stimulus vibrations. An analysis of variance showed that both of these effects were statistically significant ($p<0.001$).

The pitch experiment results are presented in a parallel manner. Table III lists the means of the pitch-axis

TABLE III. MEAN PITCH RESPONSE (R.M.S. rad/s²) FOR EACH STIMULUS CONDITION.

Frequency	Stimulus Level		
(Hz)	2.5-h FDP	1-h FDP	25-min FDP
2.5	0.72	1.10	1.60
3.15	0.67	1.10	1.62
4.0	0.64	1.05	1.63
5.0	0.72	1.40	2.07
6.3	0.84	1.38	2.01
8.0	0.97	1.74	2.78

matching responses, and Fig. 3 depicts pitch response as a function of frequency and stimulus intensity. Although the results shown in Fig. 3 are not quite so orderly as those in Fig. 2, similar overall effects are apparent. The mean acceleration of the pitch-axis matching response also increased with frequency and with the intensity of the Z-axis stimuli. An analysis of variance again

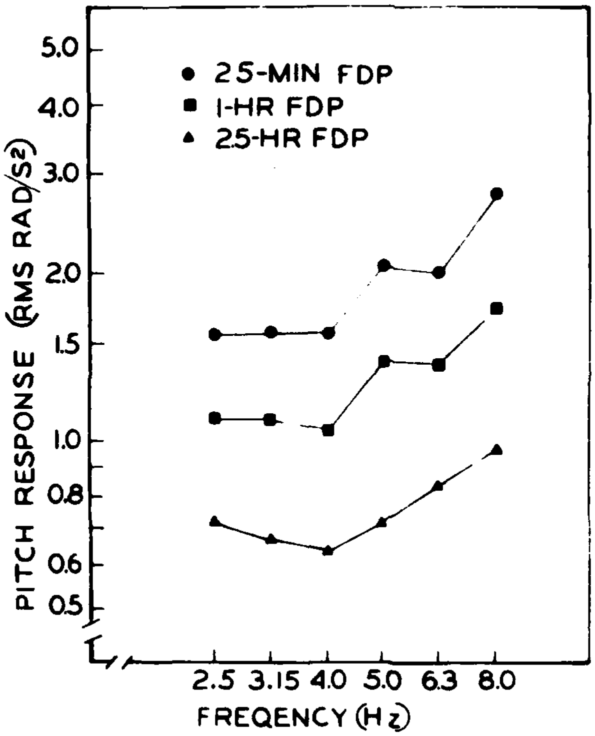

Fig. 3. Mean acceleration of pitch response as a function of frequency for each level of stimulus intensity.

demonstrated that these effects were significant ($p<0.001$).

Table IV gives the mean acceleration of the yaw-axis matching responses for the 1-h FDP stimuli. The same results are also presented graphically in the upper curve of Fig. 4. Once again, response acceleration increased as a function of frequency, and the significance of this effect was verified by an analysis of variance ($p<0.001$).

To facilitate comparisons across all three experiments, Fig. 4 also shows the roll and pitch results for the 1-h FDP level. Except for the 2.5-Hz point, the yaw results parallel the roll results, but a higher angular acceleration in yaw was required to match the subjective intensity of the Z-axis stimulus vibrations. The configuration of the SIXMODE table plus the height of the seat resulted in the subject being seated approximately 81.3 cm (32 in) above the axis of rotation for roll and pitch, but for yaw the axis passed vertically through the seat. Thus, the translational acceleration components produced by a given angular acceleration were greater for vibrations in roll and pitch than in yaw, and this difference undoubtedly contributed to the elevation of the yaw responses.

TABLE IV. MEAN YAW RESPONSE (R.M.S. rad/s²) FOR EACH STIMULUS CONDITION.

Frequency	Stimulus Level
(Hz)	1-h FDP
2.5	1.86
3.15	1.78
4.0	2.50
5.0	3.32
6.3	4.26
8.0	5.20

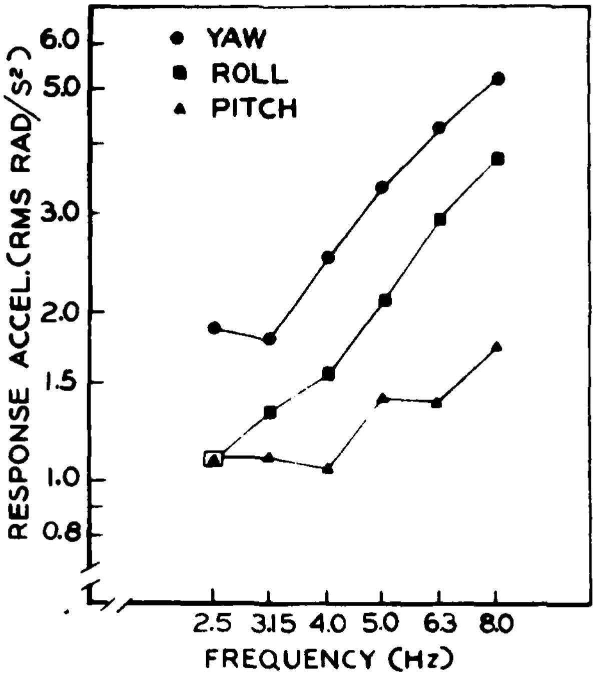

Fig. 4. Mean response acceleration as a function of frequency for each direction of angular response (1-h FDP stimuli).

The roll and pitch responses are at similar levels at 2.5 Hz but, as frequency increases, roll response increases almost linearly (on log-log coordinates) while pitch response is essentially flat up to about 4 Hz and then increases, but at a much lower rate. Other investigators (4) have found subjective response functions for roll and pitch that show more similarity; however, their subjects were seated unrestrained on a flat seat with no backrest. The greater sensitivity to pitch motions shown in the present study is most likely related to the subjects being restrained in a seat with a backrest. In pitch, the motions of the backrest are an additional source of vibration input to the subject; but in roll, backrest motions are tangential to the subject and provide little additional input.

The results of these experiments demonstrate that perception of the subjective intensity of angular vibrations, as indicated by the acceleration of the angular matching responses, is significantly related to both the frequency and intensity of the Z-axis stimulus vibrations. These results provide information on relationships between Z-axis vibrations, measured in translational acceleration units of G, and angular vibrations in roll, pitch, and yaw, measured in angular acceleration units of rad/s^2. Such information is essential for the development of improved and expanded vibration exposure criteria applicable to complex vibration environments consisting of both angular and translational motions. Since the stimuli for all three experiments were chosen from existing Z-axis equal intensity contours, the mean matching responses define equivalent contours for angular vibrations, for the conditions under which the experiments were conducted. However, the need for further research, to systematically evaluate the subjective effects of seating configuration parameters, is indicated by the apparent influence of seating variables on some of the results of the present study, and on differences between the results and those of other investigators. Factors deserving additional attention include: distance of the subject from the axis of rotation, type of seat (with or without backrest, etc.), and type of restraint system.

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