A Review of Available Information on the Acoustical and Vibrational Aspects of Manned Space Flight

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THIS PAPER is a review of the problem of noise and vibration with respect to manned space flight. For the purposes of this discussion, noise will be defined as the energy transmitted to a man through the air at all frequencies up to 15,000 cps. Vibration will be defined as all of the energy transmitted to a man through the structural components for all frequencies above 0.5 cps. The separation of noise and vibration with respect to space vehicle problems in this report is entirely a matter of convenience. The sources of the vibration and noise impinging upon a man in a vehicle are ultimately one and the same. Fluctuating pressure levels from several sources cause the capsule structure to vibrate, which results in the transmission of this energy through the air as noise, and through the seat structure as vibration.

NOISE ENVIRONMENT CONNECTED WITH SPACE VEHICLE OPERATIONS

Powered Flight.—A general analysis of the powered flight acoustic environment external to the capsule for a theoretical space vehicle mission has been made by Hoeft and Leech.[7] As they pointed out, there are two primary sources of noise in the region of the missile, the rocket engine jet and the boundary layer turbulence or aerodynamic noise. Both produce a wideband random noise with essentially no pure tones. The noise problem changes throughout the mission as the relative contribution from these sources change. Hoeft and Leech make the following assumptions for their analyses: 1. The vehicle will contain two or more stages, with an initial thrust/drag ratio of 1.5, following a hyperbolic curve until burnout. First stage will terminate at 100,000 to 300,000 feet with a burnout velocity of 10,000 ft./sec., 2. The space vehicle will have a diameter of from 7 to 15 feet, length from 70 to 125 feet, and 3. The occupant will be located in the nose cone portion of the vehicle.

The over-all acoustic power from the rocket engines was predicted on the basis of Figure 1, taken from a study by Cole, Von Gierke, et al.[3] This prediction scheme tends to give a high acoustic power figure because of the assumption that the mechanical to acoustical efficiency increases with thrust. Certain aerodynamic arguments indicate that the efficiency will level off at 1 per cent. Nevertheless, the approximation is close enough for the purpose. Figure 2 shows the predicted acoustic power level spectrum for three large rockets.

A characteristic of rocket noise is

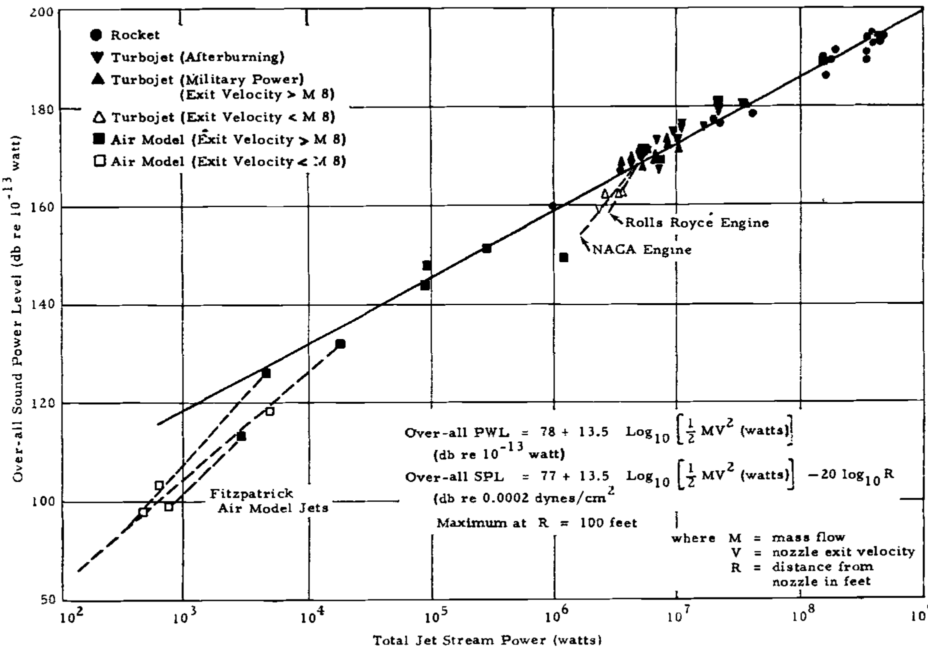

Fig. 1. The over-all acoustic power of engines.

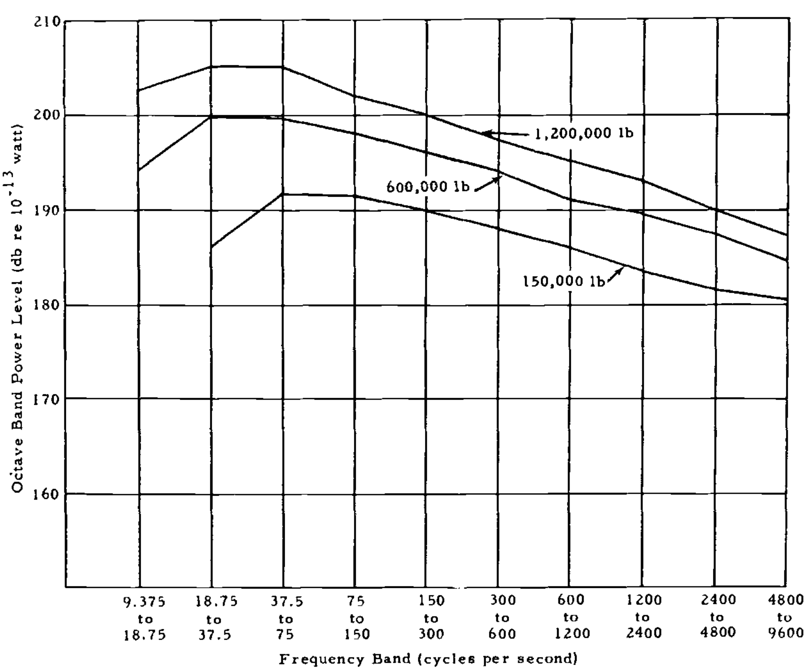

Fig. 2. Predicted acoustic power level spectrum for three large rockets.

its directivity. Directivity indices, for 0° and 90° from the nose of the vehicle (Table I), were used in calculating the sound pressure level for each octave band at the outside of the nose cone by the following formula:

TABLE I. DIRECTIVITY INDICES AT ONE HUNDRED FEET

Position	Frequency Band										
	O/A	9.375/ 18.75	18.75/ 37.5	37.5/ 75	75/ 150	150/ 300	300/ 600	600/ 1200	1200/ 2400	2400/ 4800	4800/ 9600
0° (nose)	−12	−14*	−14*	−14	−15	−12	−12	−16	−14	−12	−10
90°	−2.5	−3*	−3*	−5	−2	−2	−2	0	+1.5	+1	+2

*Not based on measured data.

OB SPL=OB PWL—10 log A DI where

OB SPL=octave band sound pressure level in db,
re: 0.0002 dynes/cm²

OB PWL=octave band acoustic power level in db,
re: 10^{-13} watts

DI=directivity index in db

$A=4\pi R^2$ when the source is radiating into free space (i.e., considerably above the ground).

The sound pressure levels thus calculated for a space craft with engines of 150,000 pounds thrust under static firing conditions are shown in Figure 3. The sound pressure levels are shown as bands rather than points because the geometry of the launch stand configuration introduces uncertainties as to the amount of energy reflected from the ground (probably no more than 3 db). The effect of launching on the acoustic environment is also shown in Figure 3. The difference between static firing and launch condition is 10 lb in the low frequency bands and 15 db in the high frequency bands.

The second major source of noise in space vehicles is aerodynamic noise or boundary layer turbulence. Recent measurements on sleds and aircraft have validated the correlation between aerodynamic noise and indicated air speeds up to at least Mach 1.8, with some erratic behavior around Mach 1.

TABLE II. PREDICTION SCHEME FOR AERODYNAMIC NOISE OUTSIDE OF A NOSE CONE

Bands	Formulae
300/ 600 cps	$SPL=55 \log_{10} IAS-33\pm4$
600/1200 cps	$SPL=55 \log_{10} IAS-25\pm4$
1200/2400 cps	$SPL=55 \log_{10} IAS-21\pm4$
2400/4800 cps	$SPL=55 \log_{10} IAS-22\pm4$
4800/9600 cps	$SPL=55 \log_{10} IAS-25\pm4$

SPL=octave band sound pressure level in db re 0.0002 dyne/cm² at outside skin of nose cone.
IAS=indicated air speed in ft/sec.

Although a good prediction scheme is not available at the present time, the present measurements allow an approximation of the noise generated by the boundary layer turbulence. Aerodynamic noise is predominantly high frequency noise. Table II gives Hoeft and Leech's prediction scheme for sound pressure levels at the outside surface of the nose cone. This scheme was derived by subtracting 5 db from the levels predicted by Rogers[9] whose calculations are for a noise source relatively closer to the man. The prediction scheme is based on the premise that the aerodynamic noise will increase with the 2.75 power of velocity. Various measurements indicate that the sound pressure level varies as the

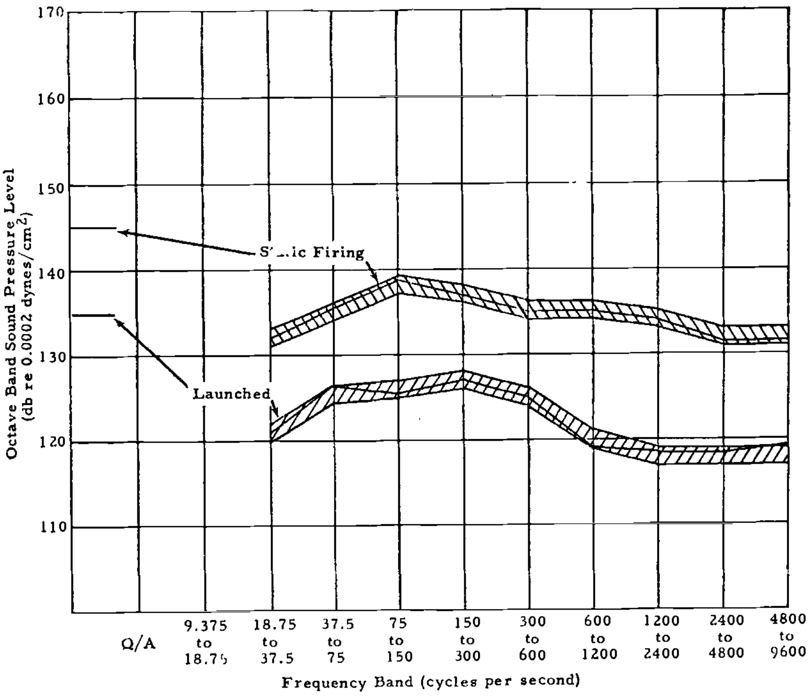

Fig. 3. Predicted sound pressure levels at nose cone for static firing and launched conditions (150,000 lb. thrust rocket).

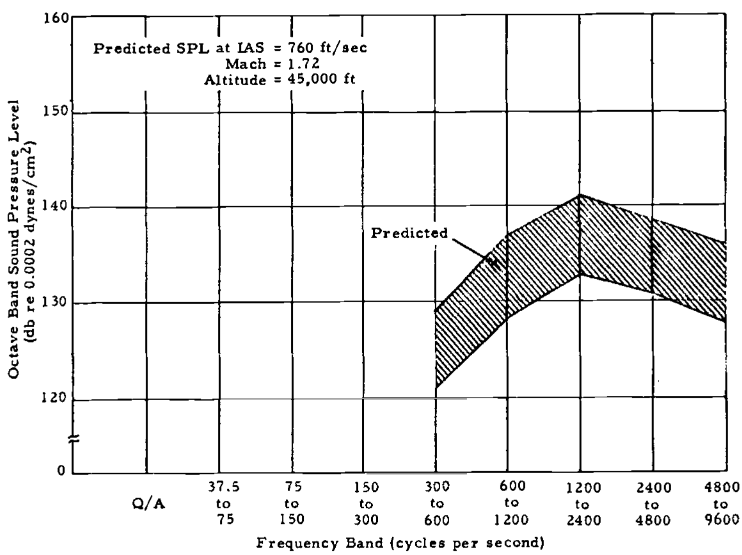

Fig. 4. Predicted sound pressure levels outside of nose cone.

second or third power of the velocity and $v^{2.75}$ is a good approximation.

In the range of Mach 0.9 to 1.1, the sound pressure levels toward the rear of the missile may increase up to 20 db because of shock wave formation; however, this is generally not true near the nose.

Figure 4 shows the calculated maximum sound pressure level for Hoeft and Leech's hypothetical mission which occurred at an altitude of 45,000 feet, a true air speed of 1650 ft./sec., an indicated air speed of 760 ft./sec., a Mach of 1.72 and an elapsed time of 65 seconds after launch. When the vehicle reaches speeds above 10,000 ft./sec. it is out of the atmosphere and the major sources of noise are not in operation. Another source of noise inside the capsule results from vibrational energy transmitted from the rocket engine through the structural elements of the vehicle to the capsule. The effect of this "internal noise source" is relatively minor.

Re-entry Noise.—In the presentation by Hoeft and Leech, no predictions of re-entry aerodynamic noise were made. Callaghan[2] reported some theoretical calculations of the sound pressure levels expected inside the capsule during the re-entry of a blunt noise ballistic vehicle of 3000 pounds from an orbit of 150 nautical miles. He stated that the maximum sound pressure level would be 146 db and would remain above 130 db for approximately fifty seconds during the re-entry. Recently he revised his figures downward to a maximum of 130 to 135 db.

Summary of Predicted Data.—We may consider the following conditions as representative of the probable acoustic environment for space capsules.

Condition
(1) Launch
(2) Ascent
(3) Re-entry

Duration
5 to 10 sec.
2 min.
30 to 50 sec.

Peak Over-all Pressure Level
150 db external—135 internal
140 db external—125 internal
140 db external—125 internal
135 db external—120 internal

The nature of the capsule construction will, by the best available estimates, afford 15 to 20 db attenuation of the external acoustic environment.

The type of analyses presented above is applicable to the types of space vehicles and missions that are predicted in the foreseeable future. The degree of accuracy has been experimentally shown to be sufficient for human factors analyses and will permit the engineer to set up adequate acoustic design criteria in the development of manned space vehicles.

Human Tolerance to Noise, Permanent Effects.—The effect of noise on the human ear involves three major parameters; intensity, duration of exposure, and frequency characteristics. "Damage-risk criteria" defining minimum noise levels, above which permanent hearing is impaired, have been proposed by Rosenblith and Stevens,[10] for random noise such as produced by jets and rockets (Fig. 5). These criteria only apply to "lifetime" exposures, that is, eight-hours per day over months and years. They are included in this report because of their possible usefulness to ground test personnel at missile bases and test stand facilities. Eldred, Gannon, and Von Gierke[5] have proposed "short-time exposure criteria" more applicable to the problem of manned space vehicles. Their data pertain to turbojet engines which also produce wide band noise. Figure 6 presents their criteria in terms of maximum permissible continuous over-all sound pressure level in db, re: 0.0002 dynes/cm.,[2] for exposure to jet noise ranging from a few seconds to eight hours.

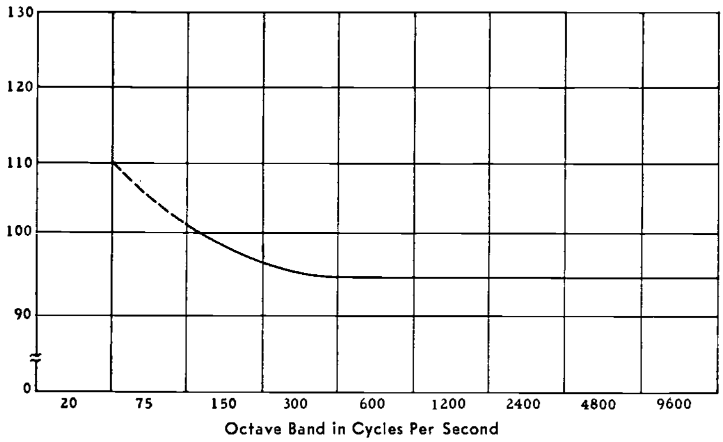

Fig. 5. Damage-risk criteria: Lifetime exposure to wide band noise eight hours per day.

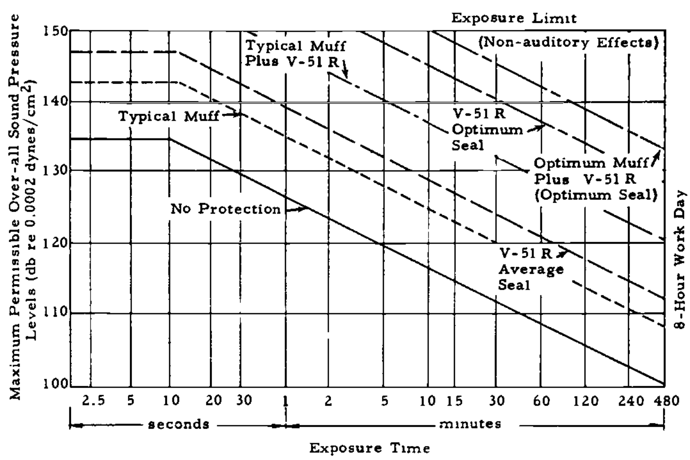

Fig. 6. Short-time exposure criteria for jet type noise. Note: The maximum permissible over-all sound pressure level of jet exhaust noise is given as a function of the average daily exposure time for the protected and unprotected ear.

The "no-protection" curve considers 135 db as the maximum allowable over-all sound pressure level for exposures up to ten seconds. The curve then decrements to allow a constant noise energy exposure with increasing time up to eight-hours duration. Consequently, the maximum permissible cause of the extra-auditory effects encountered.

Human Tolerance to Noise, Temporary Effects.—Exposure to loud noise considerably below the previously de-

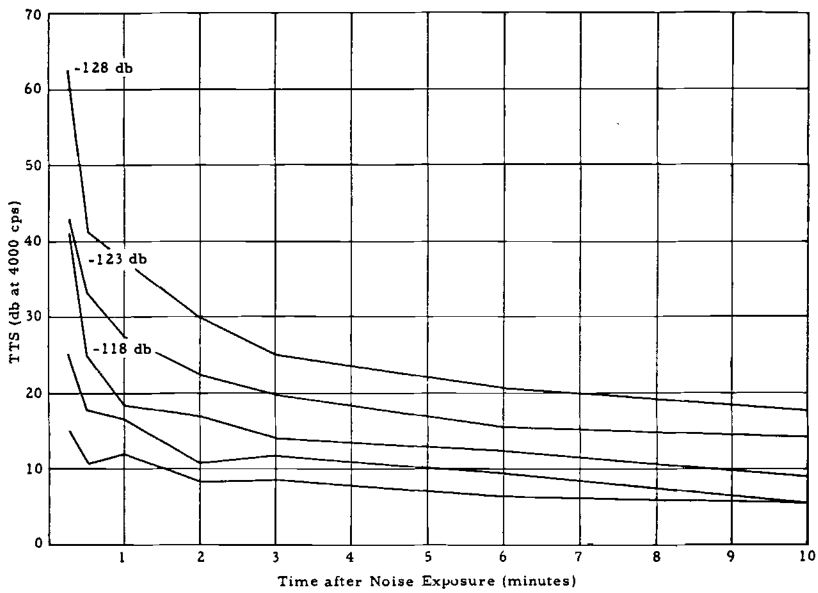

Fig. 7. The effects of three-minute exposure to wide band random noise.

over-all sound pressure level is reduced by 3 db for each doubling of the exposure time after the ten-second point. The noise level allowed for eight-hour exposure corresponds to the over-all sound pressure level given by the "damage-risk criteria" of Rosenblith and Stevens for jet noise spectra. The curves representing greater degrees of protection allow the same noise energy to reach the ear as is allowed by the "no-protection" curve.

All curves were terminated at 150 db as it is considered unwise to expose personnel to higher levels regardless of the type of ear protection worn, be-

scribed "short-time exposure criteria levels" will cause significant temporary reductions in man's auditory threshold. Two studies have been done which are pertinent to the acoustic environment in space flight.

Trittipoe[11] studied the effects of three-minute exposures to wide band noise on the auditory threshold of young men. Intensity levels ranging from 108 db to 128 db were studied in 5 db steps. Each subject was followed for ten minutes after the exposure by means of a Bekesky-type audiometer at 4000 and 6000 cps. Figure 7 illustrates the type of data obtained. In general, the degree of upward shift in the auditory threshold (temporary threshold shift—TTS) increases with the intensity of the noise exposure over the tested range. These threshold shifts are transitory. However, the changes to 128 db exposures are quite significant. For example, at fifteen seconds after the exposure the TTS is 68 db above normal and at one minute it is still 38 db above normal.

Davis, et al[4] did an extensive study of the effects of exposure to pure tones of 500, 1000, 2000, and 4000 cps and to a wide-band random noise, at intensities of 110 to 130 db, for periods of from one to sixty-four minutes. The auditory function tests used were (1) threshold sensitivity for pure tones (audiometery), (2) perception of loudness, (3) perception of pitch, and (4) ability to understand speech (Fig. 8).

The aspect of this work which is most pertinent to manned space vehicle problems is the observation that when the threshold sensitivity of the human ear is depressed markedly (60 db) by exposure to high intensity noise, the loss is only 25 db for the level of average speech (70 db) and for loud speech (100 db) the perception of speech is nearly normal. The conclusion of Davis' group is that the TTS is a "nerve" type of deafness, which varies with the loudness-level, that is, the higher the input signal, the less the reduction in sensitivity.

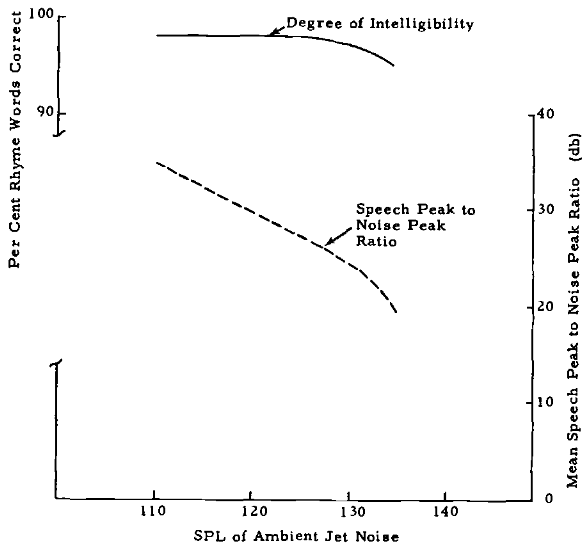

Fig. 8. The effect of noise on speech.

A comparison of the predicted acoustic environment for space vehicles and the available data on human tolerance to noise indicates that noise will not present a health hazard if attention will be given to the design of the manned capsule with respect to its resonance characteristics. However, the operational problem of voice communications should be considered.

Communications in High Noise Fields.—The work of Klemp and Webster[8] indicate that adequate radio communications systems can be developed for voice communication in 135 db random noise fields. Their particular system was designed to operate on the flight decks of aircraft carriers. The pertinent design criteria for a successful system are as follows: 1. Bandwidth as wide as possible—(200 to 6100 cps desirable), 2. Side tones less than 10 db over the preferred level noise actuated (zero side tone is acceptable), 3. Automatic noise actuated volume control to conform with preferred listening levels, 4. Peak clipping of 12 db of maximum power to earphones, 5. Flat frequency response and minimum distortion in the audio circuity, 6. Pilot and talker training for a minimum of four hours.

Figure 8 indicates the degree of intelligibility obtainable with a system incorporating the above design criteria. The lower curve in this figure indicates the speech-peak-to-noise-peak ratio.

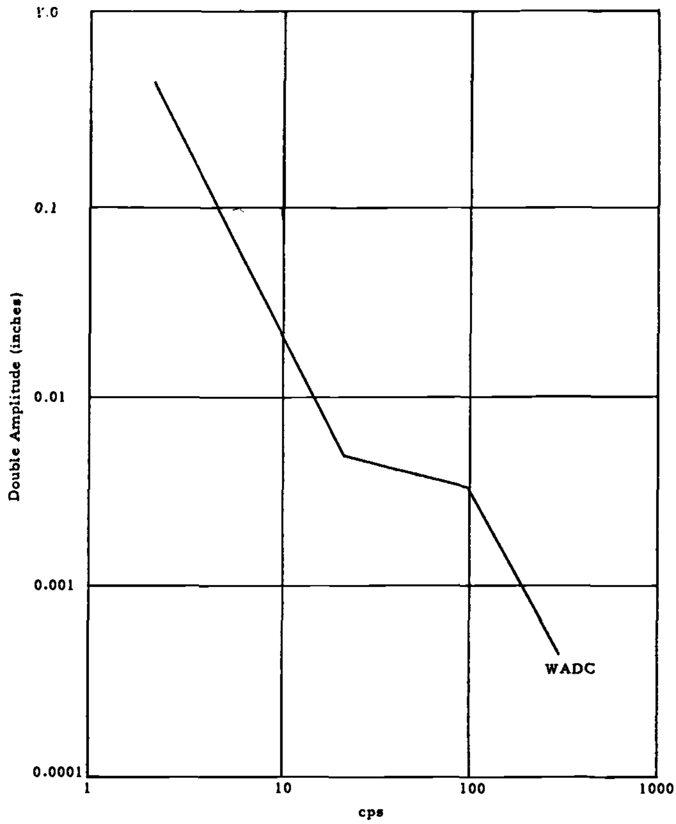

Fig. 9. Human vibration tolerance.

VIBRATIONAL ENVIRONMENT IN A FUTURE SPACE VEHICLE

The principal sources of vibration in space vehicles are the same as for noise, that is, the propulsion system and the aerodynamic gust loads. Of these, the propulsion system is the most important. The fluctuating pressure levels generated from the rocket engine jet and combustion chamber are transmitted by air to the nose cone and by the structure acting as a filter. Vibrational energy is transmitted for the most part at the structure's resonant frequencies. These resonant frequencies depend on the missile's length, mass, and stiffness, and will usually be below 50 cps. In flight, the mass and length change as fuel is used and booster stages are discarded. Therefore, the principal vibration frequencies will also change. Accurate prediction of the vibrational characteristics of a future vehicle is nearly impossible at the present state of the art.

Human Tolerance to Vibration.—Figure 9 presents the data obtained by Getline[6] for human tolerance to several hours exposure to vibration levels 10 times as high as shown in Figure 9.

The body organs will vibrate at resonant frequencies of 5 and 10 cps. This resonance is a function of mass and dimensions.

SUMMARY

Acoustic environment can be predicted for future space vehicles with sufficient accuracy for human factor analyses.

The noise environment should not create a barrier to manned space travel.

Vibration, as limited by the structural requirements of current space vehicle design, is within human tolerance limits.

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