TRANSPORTATION

A SURVEY OF SHOCK AND VIBRATION ENVIRONMENTS IN THE FOUR MAJOR MODES OF TRANSPORTATION*

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An investigation has been conducted, the purpose of which was a review of all available information and test data describing shock and vibration environments in the four major modes of transportation. This information has been collated, analyzed, and combined, to provide a unified reference source of transportation environments for use by the packaging and/or design engineer. A portion of the results of this investigation are presented in this paper.

INTRODUCTION

Over three hundred reports were reviewed and contacts were made with fifty-five agencies and organizations active in the transportation field. Based on the data collected, acceleration versus frequency envelopes were constructed for each of the four major transportation modes. These envelopes facilitate the comparison of transportation environments in the different modes. Where applicable, the information and data are also presented to show the effect of various operating parameters on the transportation environment.

Although many programs have been conducted to collect transportation shock and vibration data, only a portion of the collected data is applicable for use in a general transportation criteria. The lack of applicability is summarized as follows:

1. Few programs dealt solely with cargo environments.

2. The data are not segregated and include measurements from locations such as vehicle appendages, aircraft wing tips, etc.

3. Many studies have been conducted on military vehicles operating under the most severe conditions, which, although setting an upper limit, are not representative of normal commercial carrier environments.

4. Many programs, although providing meaningful information for the purpose for which they were conducted, have no general application.

5. Measurements were made on vehicles that are obsolete or of limited interest.

6. Measurements were made over unknown or restricted frequency ranges, or other factors of importance to general criteria were not recorded.

7. The original data existed in a variety of forms.

In order to correlate the data, a requirement of the review was to edit all reports and include only response measurements of the cargo floor (i.e., input to the cargo). No attempt has been made to define transfer functions or cargo response relationships. In addition to

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the constraint that data be included which are descriptive only of the cargo floor, unless otherwise noted, the data have been further restricted to standard commercial vehicles traveling normal routes. Data obtained from (a) military vehicles, (b) cross-country terrain operations, (c) special road course operations, and (d) special transporters, have been omitted from the study. Exceptions to the above are (a) data for ships which describe the environment at the aft perpendicular (the area of severest vibrational environment), and (b) results of tests with the 377PG (Pregnant Guppy Aircraft), a special transporter.

In the subsequent figures defining the environments, instrumentation and/or interest limits define the frequency ranges from which the data were taken. A lack of definition in some frequency ranges should not be construed as a lack of environment, but merely a lack of available data to define that environment.

DATA PRESENTATION

The data used to develop the graphs summarizing the shock and vibration environments were extracted from numerous reports. The original data existed in a variety of forms. Some data were in the form of peak acceleration versus frequency, other data were given in peak acceleration versus duration. For the latter, unless otherwise specified, a half sinusoidal shape was assumed and a frequency computed.

An acceleration versus frequency format was chosen for the graph to utilize as much of the available data as possible. The selection of the format was based on two principal factors: (a) it is the only one which will accept all useful data, and (b) it permits data originally presented in terms of power spectral density to be transformed to its original form by merely noting the bandwidth used in the original analysis. G (rms) versus frequency is used for the format when the original data were reduced by a Spectrum Analyzer. G zero-to-peak versus frequency is used for the format when original data were recorded with oscillographs and visually analyzed.

Vibrations which occur in the cargo area have dominant frequencies for particular vehicles, loads, locations, and speeds. Even though conditions and circumstances vary, the graphs show that the vibration levels are fairly constant over wide frequency ranges. In some instances, particularly with aircraft, a noticeable lack of significant levels may occur in certain frequency bands.

Aircraft

Extensive shock and vibration measurements on aircraft have been performed by the Wright Air Development Division (WADD). Their most recent test programs cover the following aircraft:

1. (C-123), Medium assault cargo airplane, high wing, twin engine (reciprocating), three-bladed propellers.

2. (C-130), Medium range cargo airplane, high wing, four engine (turboprop), three-bladed propellers.

3. (C-133), Long range cargo airplane, high wing, four engine (turboprop), three-bladed propellers.

4. (H-37), Cargo helicopter, single main rotor plus torque compensating tail rotor, twin engine (reciprocating), five main rotor blades and four tail rotor blades.

The measurements were taken during all of the normal service conditions, such as taxi, ground run-up, take-off, straight and level flight (at various altitudes and speeds, and power settings), turns, descents, landing, and landing roll. The effects of cargo load, speed brakes, and other control surfaces were also investigated on some of the aircraft.

These aircraft were instrumented with velocity pickups, and the vibration data were recorded on magnetic tape. Data reduction was performed with a Davies Automatic Analyzer employing a variable-frequency, narrow-band (10 cps) filter.

Vibration data from the Pregnant Guppy (377PG), a low wing, four-engine (reciprocating), four-bladed propeller cargo airplane, were also reviewed. This aircraft is used in transporting space rockets and their allied equipment. A considerable number of vibration measurements have been taken on the cargo floor during transportation of this special cargo.

The environment in these tests was monitored with accelerometers, and the data were recorded on magnetic tape. A variable frequency, one-half cycle, bandwidth filter was used in the analysis of the data. Frequency bands having relatively high vibration levels were analyzed further. A distribution of the accelerations was determined at these frequencies. Data are available for a number of locations, for a number of flight conditions, and for various loads. These data represent one of the most complete descriptions of the shock and vibration environment for any transport vehicle.

Vibration data for the KC-135, a military version of the Boeing 707 jet aircraft, has been obtained from tests by Boeing. The data cover ground run-up, taxi, take-off and cruise conditions. The original report presents the vibration data in power spectral density (g^2/cps versus frequency). The data were converted to g (rms) versus frequency for presentation in this paper. The vibrations were monitored with accelerometers and recorded on magnetic tape. Analyses were performed with a Davies analyzer with the following filters being used for different frequency ranges:

Frequency Range (cps)	Filter Bandwidth (cps)
0-30	0.80
30-50	1.33
50-100	2.64
100-200	5.41
200-400	10.1
400-800	18.7
800-1000	35.3
1000-2000	43.5

Figure 1 is composed of acceleration envelopes depicting the environment for propeller, helicopter, and jet aircraft. These envelopes were obtained by encompassing the maximum vibration levels for the respective classification. Data for the C-123, C-130, C-133, and 377PG were used in developing the plot for propeller aircraft, while the H-37 and KC-135 were used to describe the environment for the helicopter and jet, respectively. The plots show that the vibration levels are highest for the helicopter, and lowest for the jet.

Figure 2 shows the maximum acceleration envelopes for several individual aircraft. These plots were constructed by encompassing the highest recorded vibration levels for all flight conditions. The plots are presented in terms of g (rms) versus frequency.

Railroad

Data descriptive of the railroad shock and vibration environment have been categorized into two major classifications: (a) over-the-road operation, and (b) coupling. The over-the-road environment includes all data except the shock motions associated with coupling or humping operations.

Acceleration versus frequency envelopes of the shock and vibration environment of railroad cars have been compiled from many sources. Because of the high amplitude transient vibrations which occur during starts, stops, slack run-outs, and run-ins, these data have been segregated, when specified, from the vibration data describing normal running conditions. These high amplitude vibrations in Fig. 3 are labeled "transient," whereas the normal running conditions are labeled "continuous." Both of these plots have been constructed by enveloping all reliable data for all types of trucks, rail conditions, directions, and speeds. Therefore, the transient and continuous plots in Fig. 3 represent the highest vibration levels which would be encountered during over-the-road operations.

The two plots appearing in the lower half of Fig. 3 show the effect that soft ride equipment has on the over-the-road vibration environment. These plots were formed by enveloping the maximum accelerations recorded on the floor of a Minuteman transporter railroad car during cross-country operation. The data were reduced by averaging the 4-6 maximum acceleration values within each frequency bandwidth. The truck suspension system for this missile car consisted of a combination air and coil spring system in the vertical direction, and a pendulum system with snubbers in the lateral direction. Damping is provided in both directions of motion. In the longitudinal direction isolation is provided by a sliding center sill and a hydraulic cushioning device.

The effect of train speed on vibration levels is shown in Fig. 4 for a number of train speeds (20, 40, 73, 80 mph). The curves depicting the environment at 40, 73, and 80 mph are a result of tests conducted by the U.S. Army Signal Corps. The data were taken with different types of trucks. The vibrations on the cargo floor were monitored with barium-titanate accelerometers and recorded on magnetic tape. The frequency range of interest in these tests was 20-10,000 cps. The recorded data were analyzed by passing them through a series of octal band pass filters. The results of the

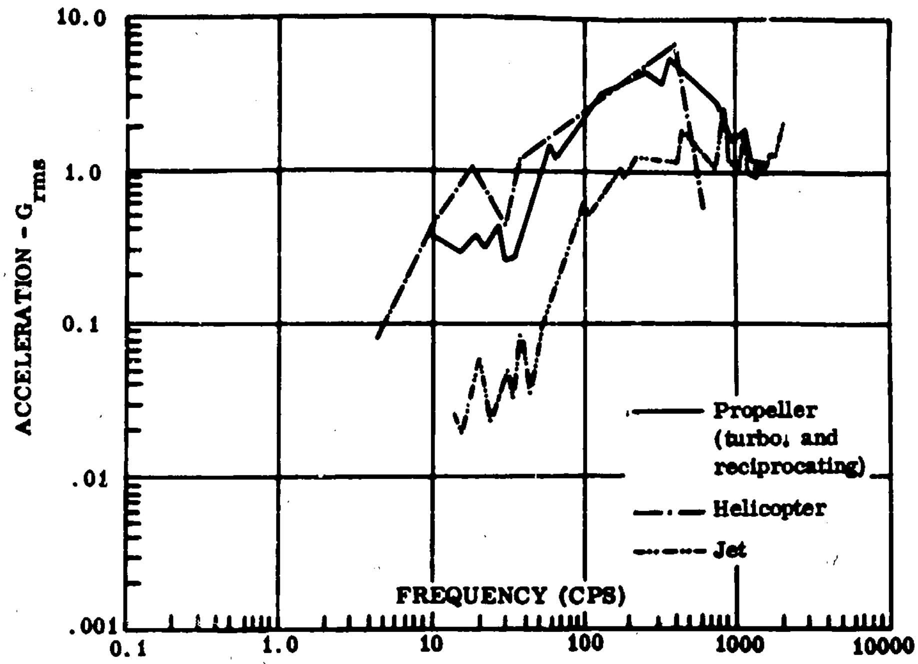

Fig. 1. Aircraft acceleration envelopes (overall composites)

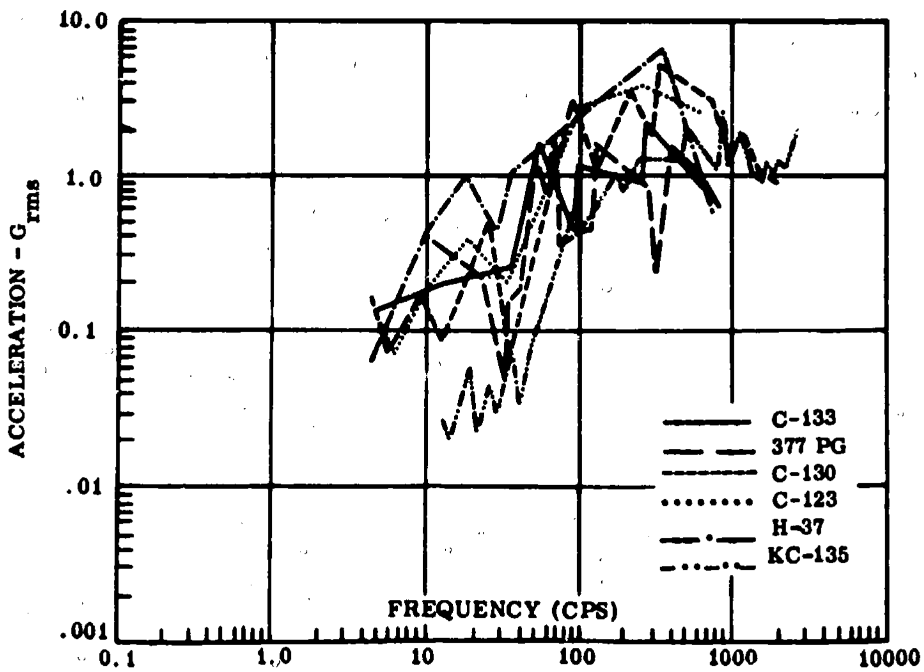

Fig. 2. Aircraft acceleration envelopes (individual composites)

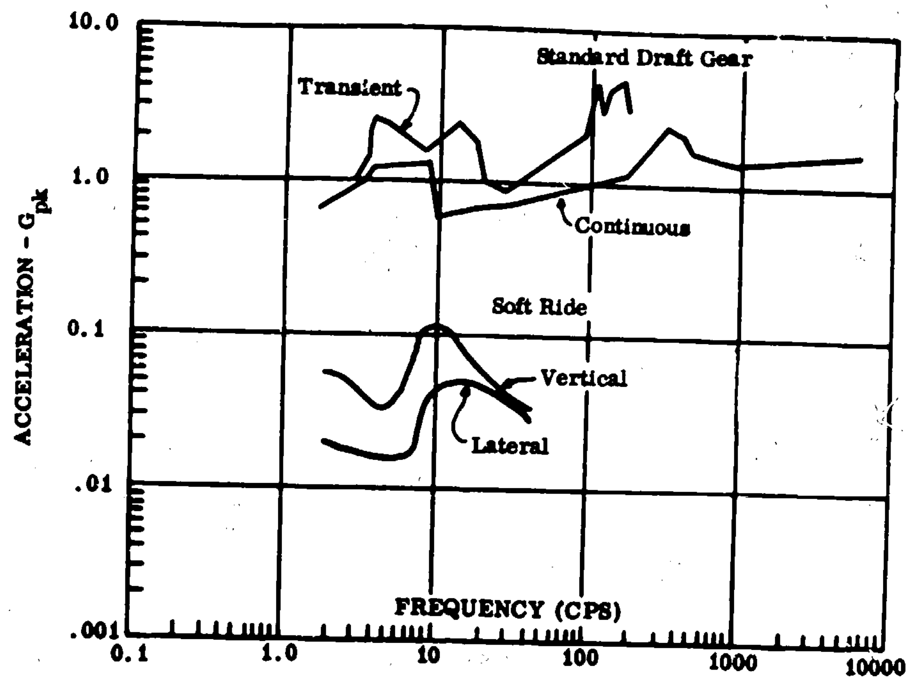

Fig. 3. Railroad acceleration envelopes (over-the-road)

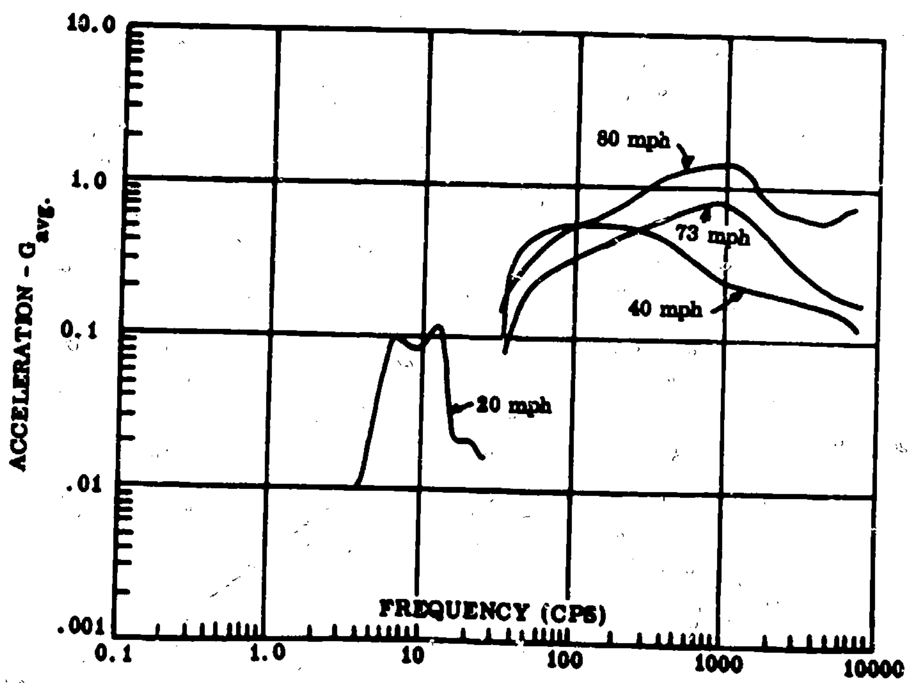

Fig. 4. Railroad acceleration envelopes (over-the-road)

analysis are presented in terms of average acceleration versus frequency (cps).

The data presented for 20 mph speed may be misleading because of the different frequency range. These data are a result of a separate program in which frequencies greater than 25 cps were not of interest. The data were analyzed with a frequency analyzer having a continuous band-scan device, with a frequency resolution less than one-half cycle. These data were also presented in terms of average acceleration versus frequency.

Figure 5 consists of plots that show the effect of orientation (direction). These plots are restricted to include only the data descriptive of the continuous vibration environment (i.e., data for transient vibration have been omitted). The plot shows that the vertical is the most severe environment over wide frequency ranges.

Railroad Coupling

Curves describing the shock and vibration environment for railroad coupling and/or humping operations are presented as shock spectra. A shock spectrum is defined as the maximum acceleration of a series of single degree-of-freedom systems resulting from a specific shock excitation. This method of data presentation has been chosen because it provides information on all frequency components.

Data are presented for both standard and shock-absorbing draft gears. These shock spectra were constructed by enveloping the peaks of shock spectra given in the original report. Figures 6-14 show shock spectra for standard draft gear at coupling speeds of 3.4, 6.0, 8.0, and 10 mph. The data used in Figs. 6-14 were obtained from tests conducted by Sandia Corporation. The tests were conducted by impacting a lightly loaded test car with a hammer car.

Figures 15-18 present additional shock spectra for a Miner draft gear at various impact speeds. The Miner draft gear is a high capacity shock absorbing draft gear.

Railroad Distribution of Coupling Speeds

Figure 19 shows the distribution of coupling speeds based on 3369 measured impacts. This plot has been constructed by averaging the results of a number of independent investigations. Data are presented in terms of percent of total impacts versus coupling speed (mph).

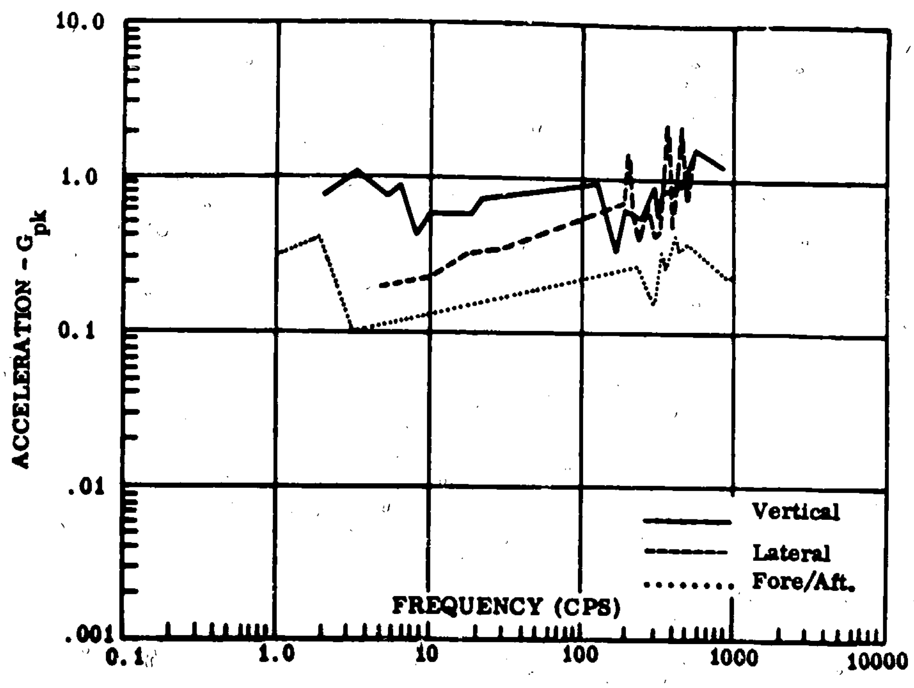

Fig. 5. Railroad acceleration envelopes (directional composites)

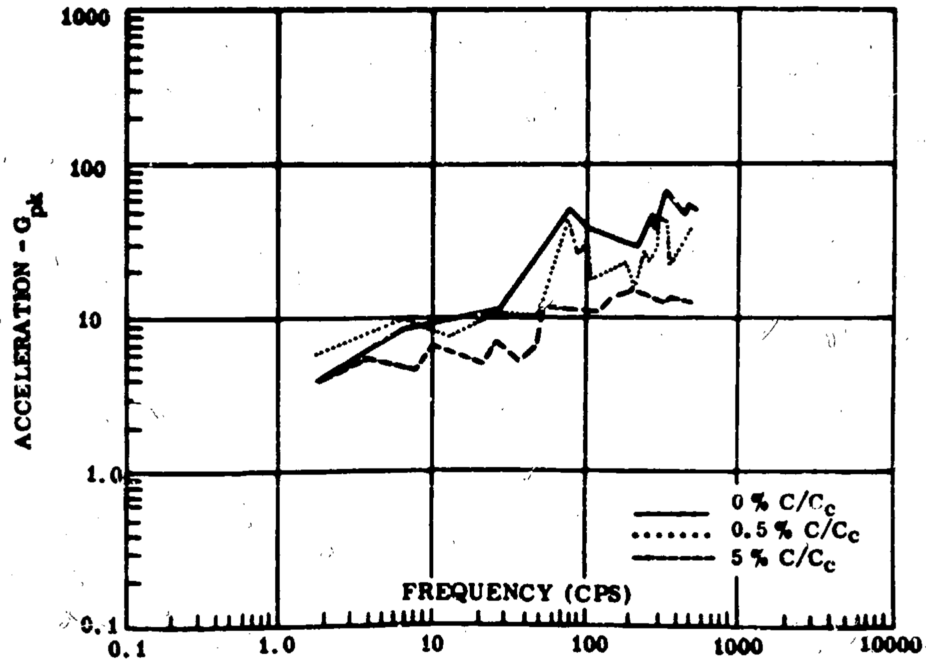

Fig. 6. Railroad coupling shock spectrum (3.4 mph, fore/aft) standard draft gear

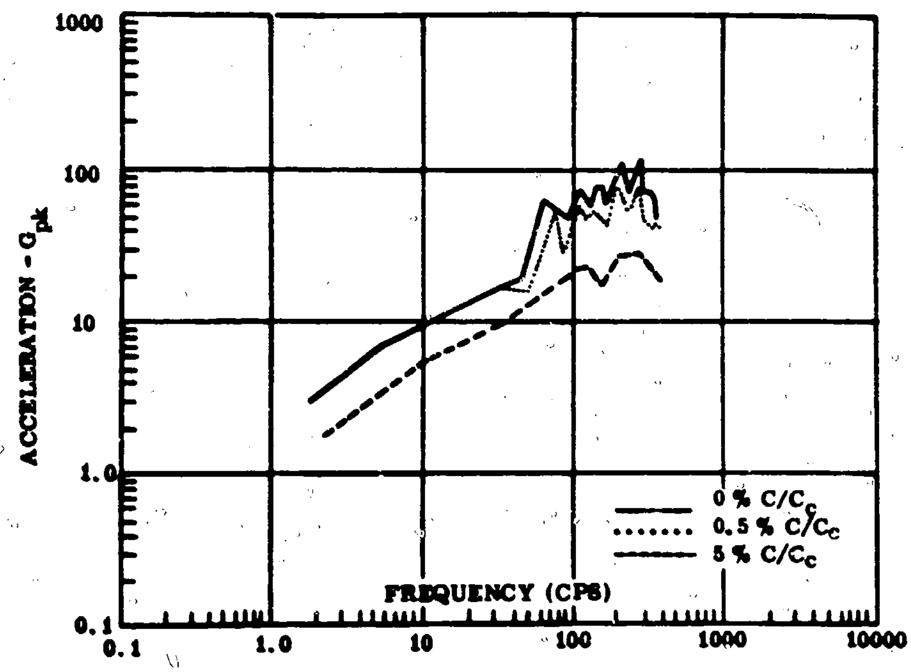

Fig. 7. Railroad coupling shock spectrum (3.4 mph, vertical) standard draft gear

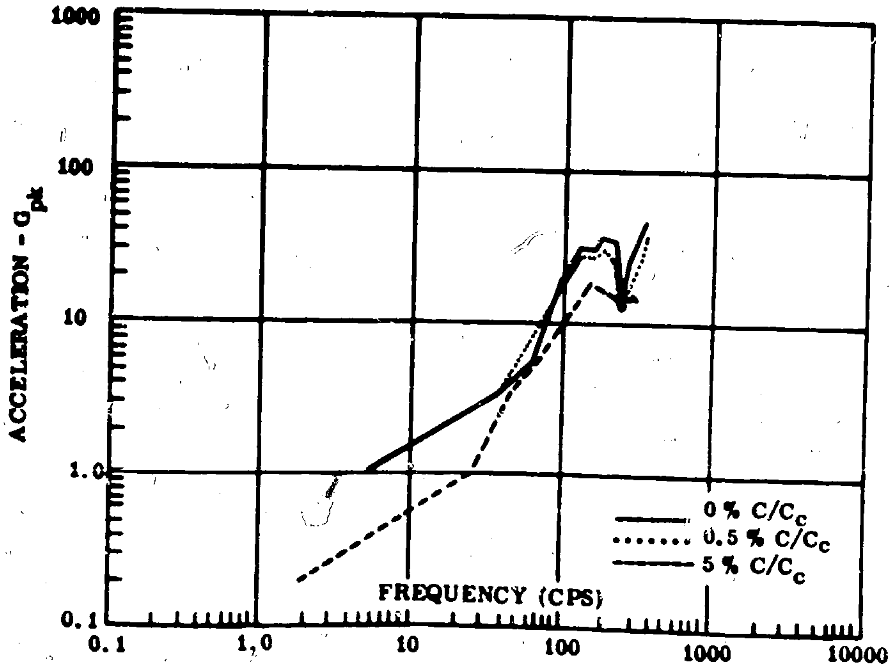

Fig. 8. Railroad coupling shock spectrum (3.4 mph, lateral) standard draft gear

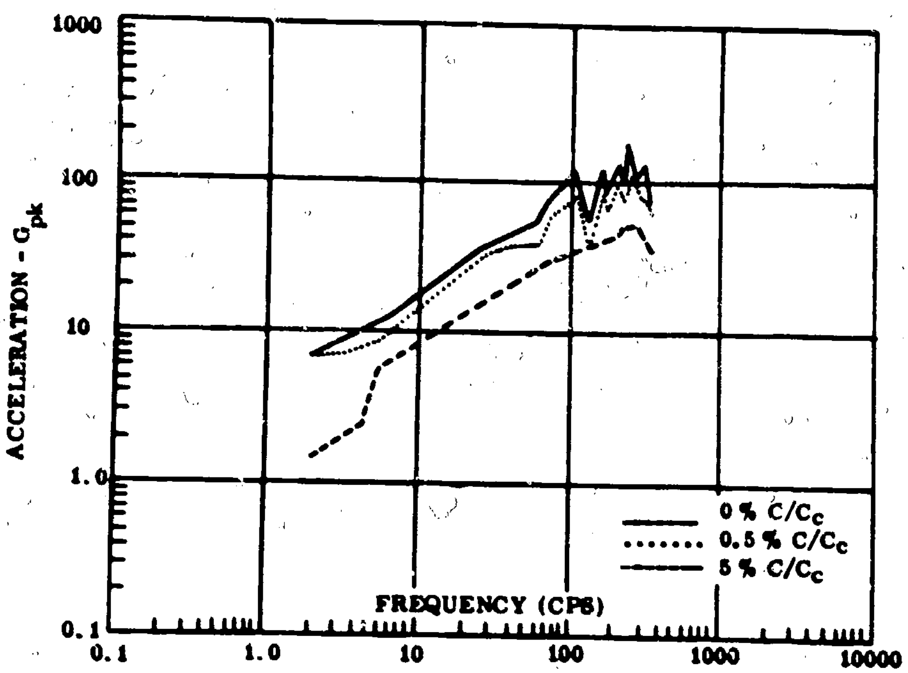

Fig. 9. Railroad coupling shock spectrum (6.0 mph, fore/aft) standard draft gear

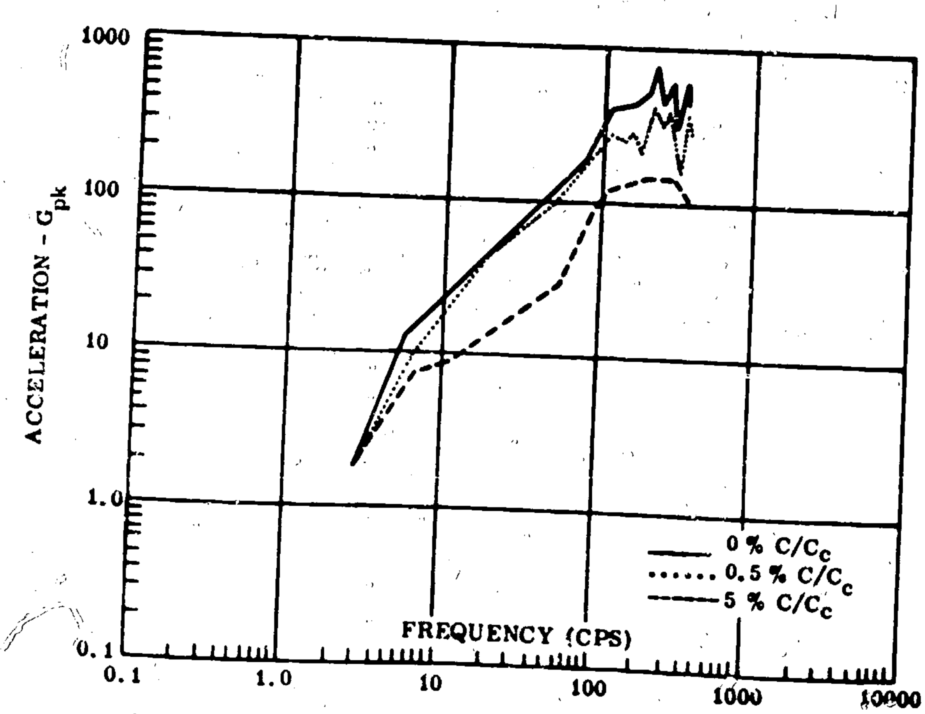

Fig. 10. Railroad coupling shock spectrum (6.0 mph, vertical) standard draft gear

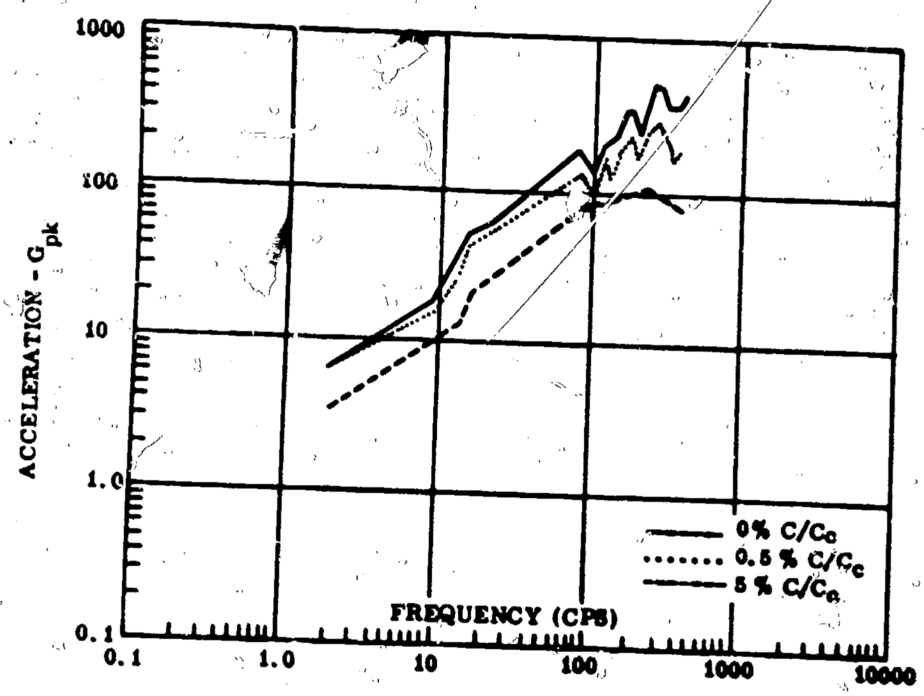

Fig. 11. Railroad coupling shock spectrum (8.0 mph, vertical) standard draft gear

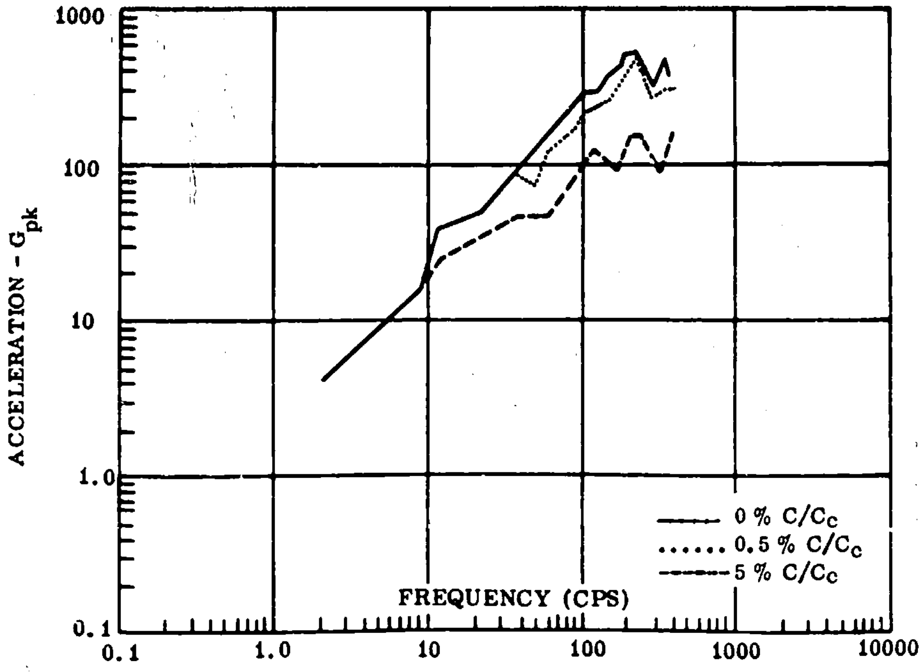

Fig. 12. Railroad coupling shock spectrum (10.0 mph, vertical) standard draft gear

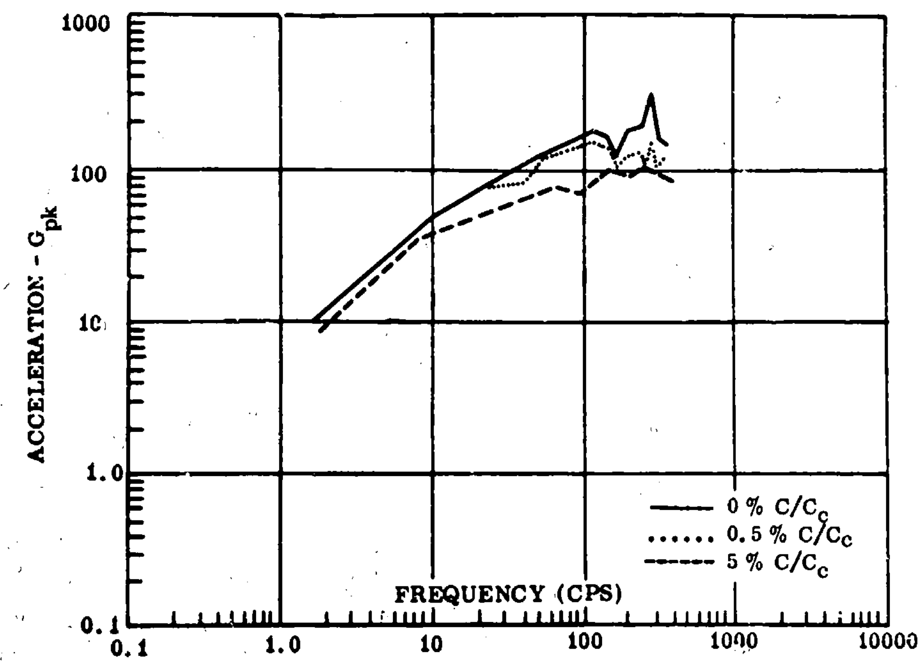

Fig. 13. Railroad coupling shock spectrum (10.0 mph, fore/aft) standard draft gear

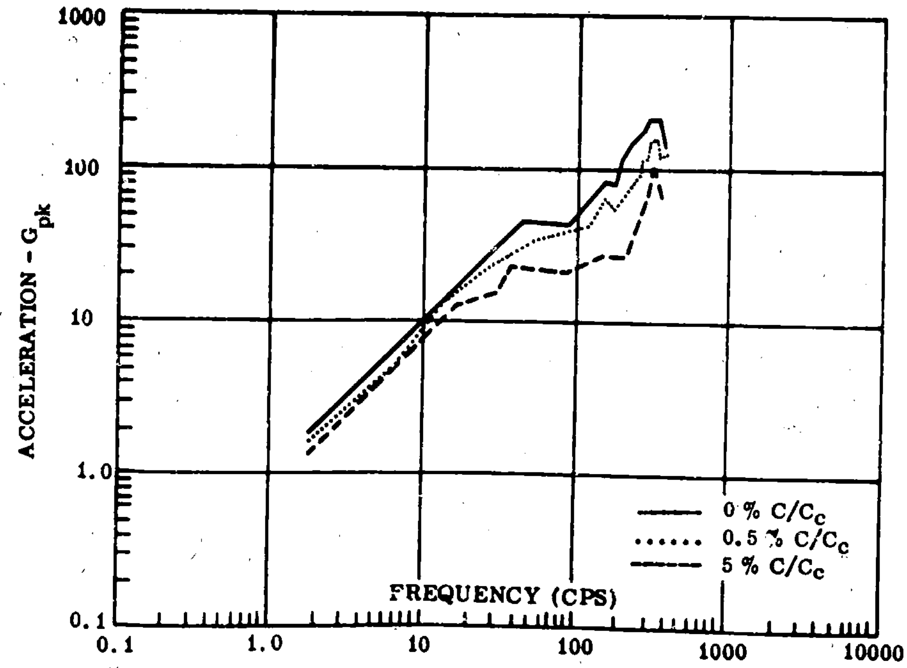

Fig. 14. Railroad coupling shock spectrum (10.0 mph, lateral) standard draft gear

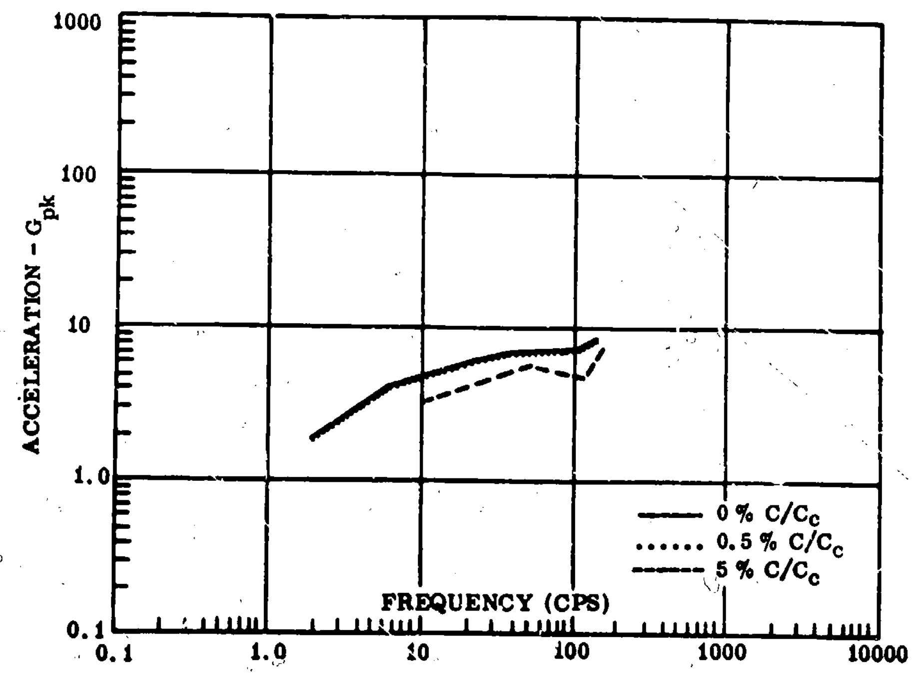

Fig. 15. Railroad coupling shock spectrum (3.7 mph, fore/aft) cushioned draft gear

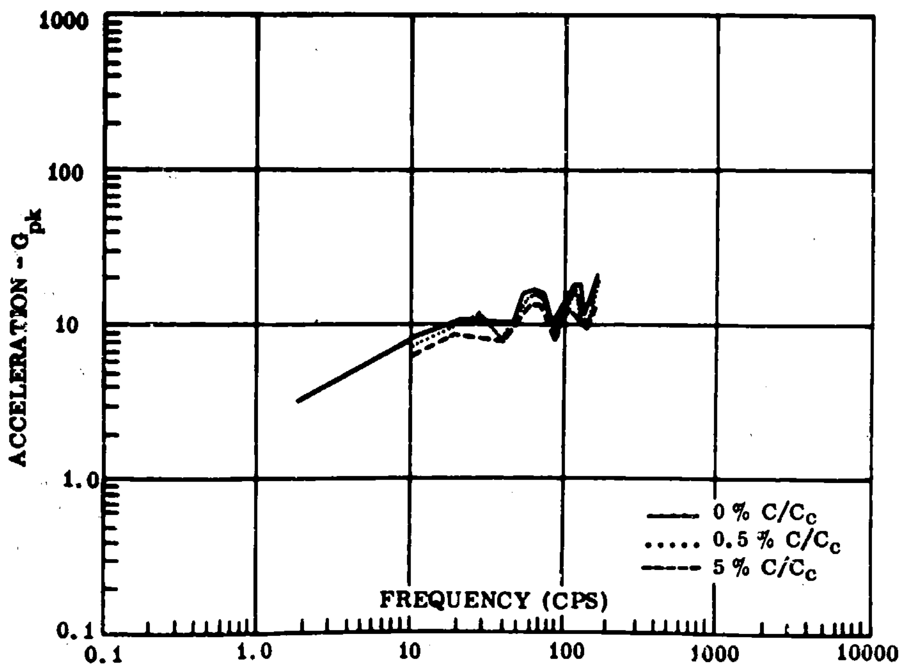

Fig. 16. Railroad coupling shock spectrum (6.8 mph, fore/aft) cushioned draft gear

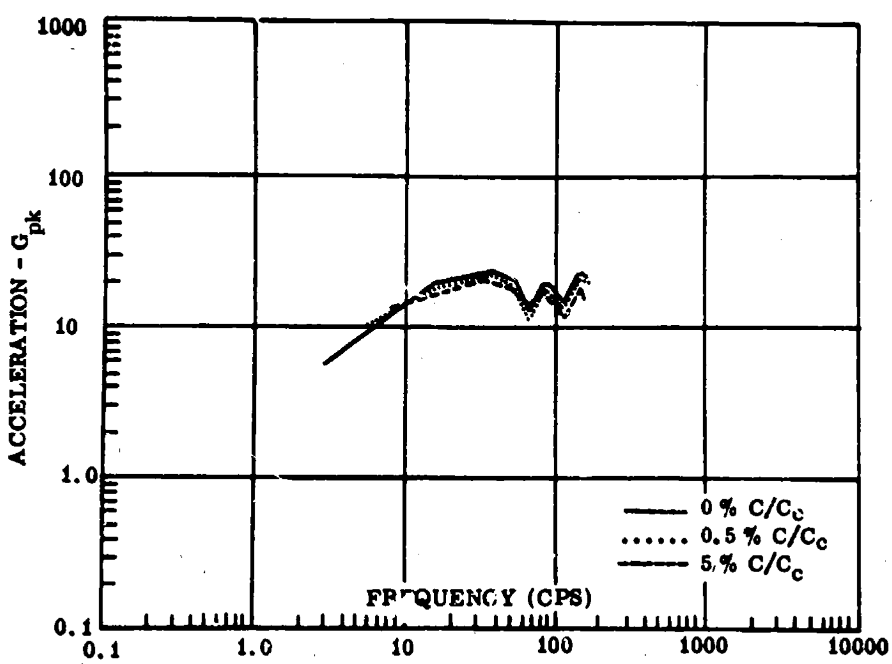

Fig. 17. Railroad coupling shock spectrum (9.8 mph, fore/aft) cushioned draft gear

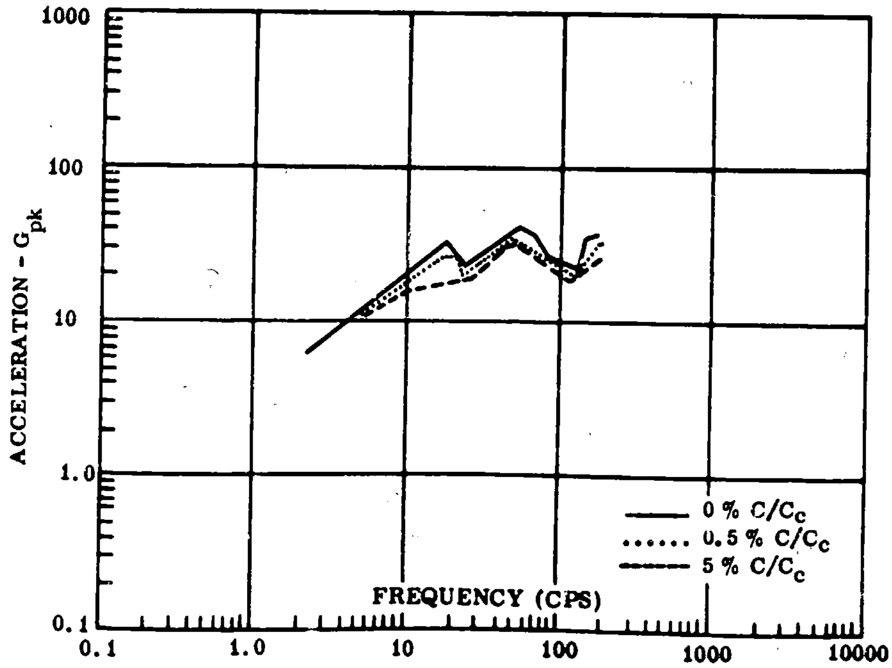

Fig. 18. Railroad coupling shock spectrum (12.0 mph, fore/aft) cushioned draft gear

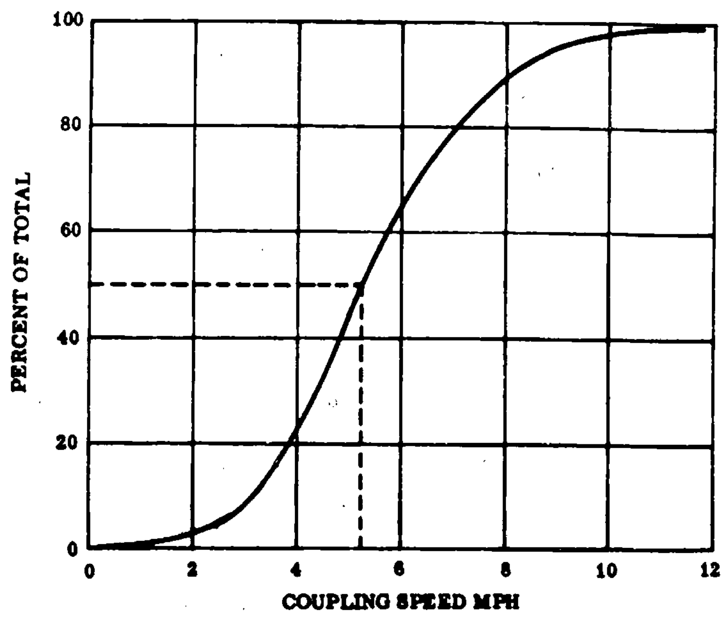

Fig. 19. Railroad distribution of coupling speeds

Ship

The data used in plotting the overall composite curves for ships have been separated into continuous and transient vibrations. Transient vibrations are defined as those which occur during emergency maneuvers and slamming (the impacting of the ship with water after the bow has left the water). This separation of data is made because transient vibrations can usually be eliminated from the environment. Slamming, for example, can be avoided if the ship avoids storm areas. Continuous vibrations are defined as those which occur during normal operations, including operations in rough seas.

Most of the data for the shipboard shock and vibration environment were collected by the David Taylor Model Basin. The major portion of their data, however, have been recorded near the aft perpendicular (a line perpendicular to the water line at the stern). This area experiences the highest vibrational levels on a ship. The levels of vibration for the cargo area will always be lower. However, since meager information is available for the cargo area, data for the stern location can serve as an upper bound of the environment.

The upper two curves in Fig. 20 have been constructed by enveloping all data applying to continuous vibration on one diagram, and all data referring to slamming and emergency on another. The continuous vibration composite envelope includes data recorded under extremely rough sea conditions.

The third and lowest plot in Fig. 20 is constructed from data taken on a 572-ft, single screw ship. Measurements were taken with velocity pick-ups mounted at the main thrust bearing foundation and to an angle welded to the deck over the main transverse member at the aft perpendicular. The data were recorded on straight runs and maneuvers during operations in calm seas, and at various propeller speeds.

Figure 21 shows the effect of orientation (i.e., the effect of direction). The data used to construct this figure were obtained from the tests conducted on the 572-ft single screw ship mentioned above. The curves show that the vertical vibration environment is the highest, followed by the lateral and fore-and-aft directions.

Figures 22 and 23 show the effect of sea state for two different ship lengths (L = 820 ft and L = 380 ft). The curves show that the acceleration levels increase with increasing frequency from 4 to 10 cps, and are constant at higher frequencies. The accelerations for the small ship (L = 380 ft) are almost twice as large as those for the larger ship (L = 820 ft). For each ship class, the acceleration increases by a factor of two, when the ship operates in a rough rather than in a smooth sea.

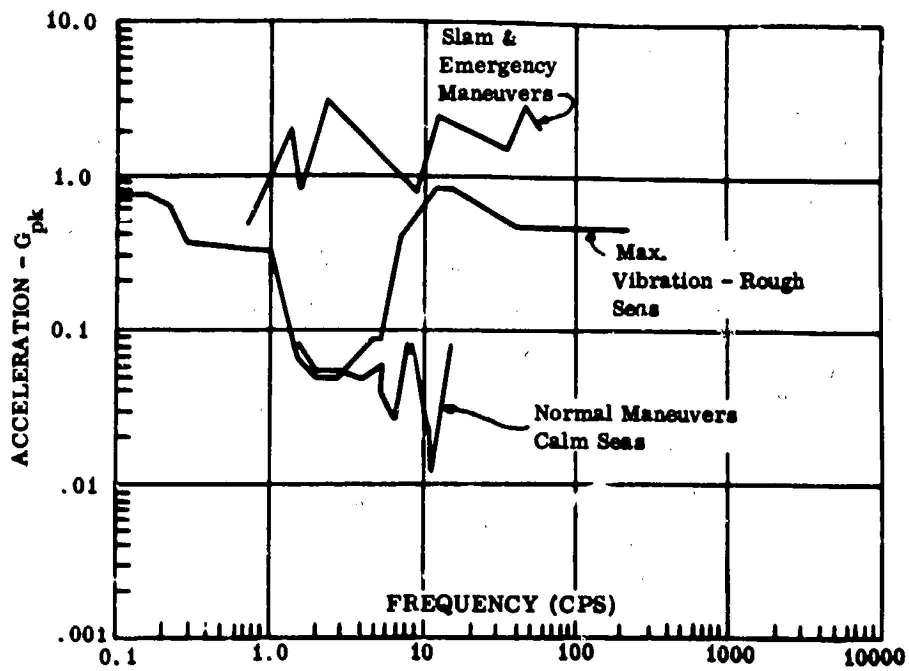

Fig. 20. Ship acceleration envelopes

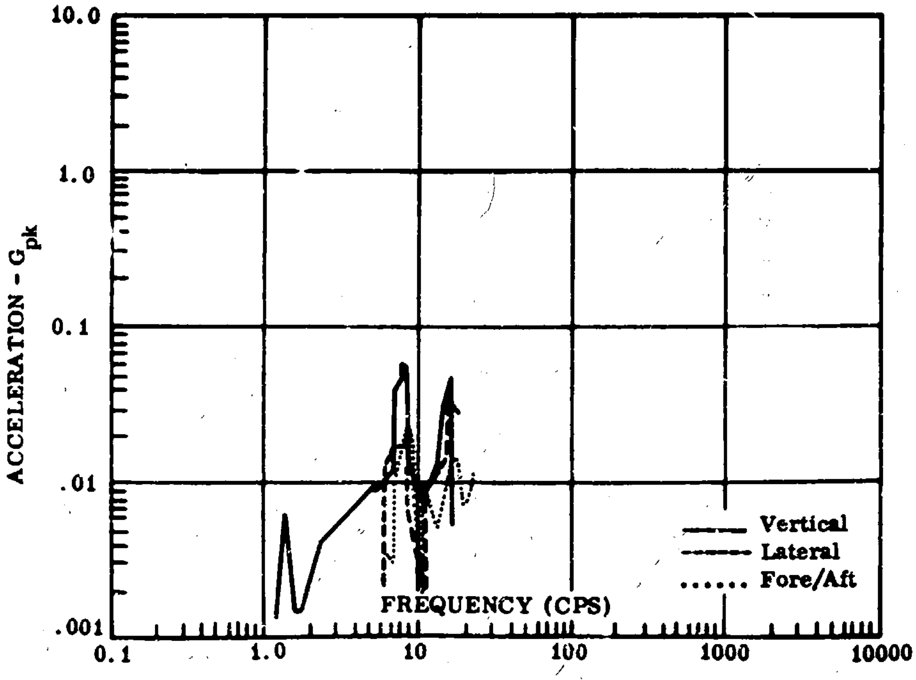

Fig. 21. Ship acceleration envelopes (straight runs)

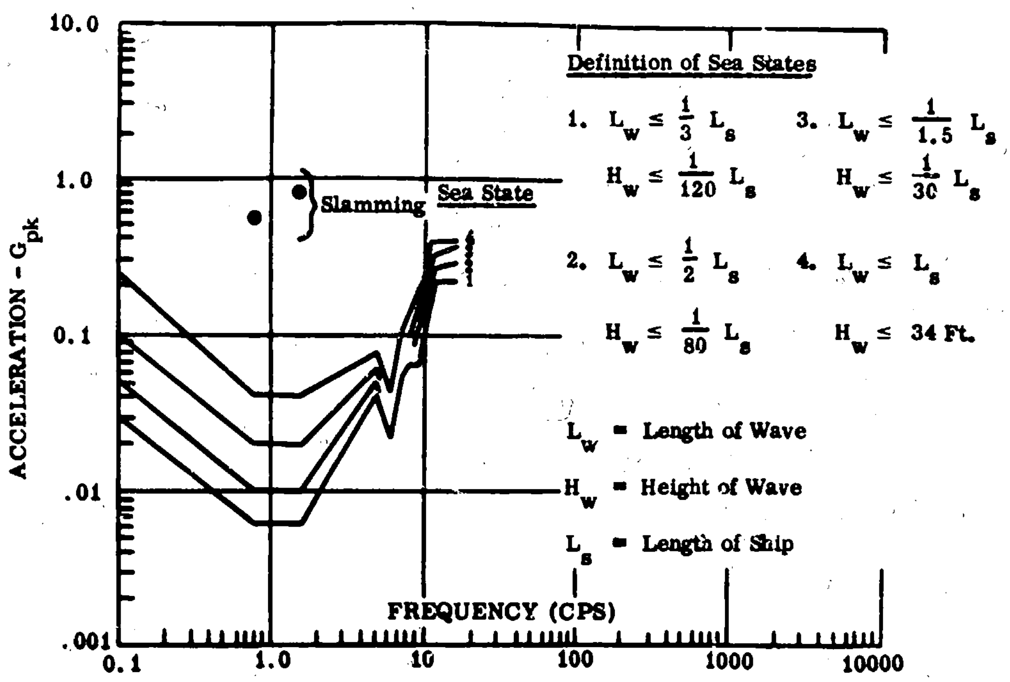

Fig. 22. Ship acceleration envelopes (L_s = 820 ft)

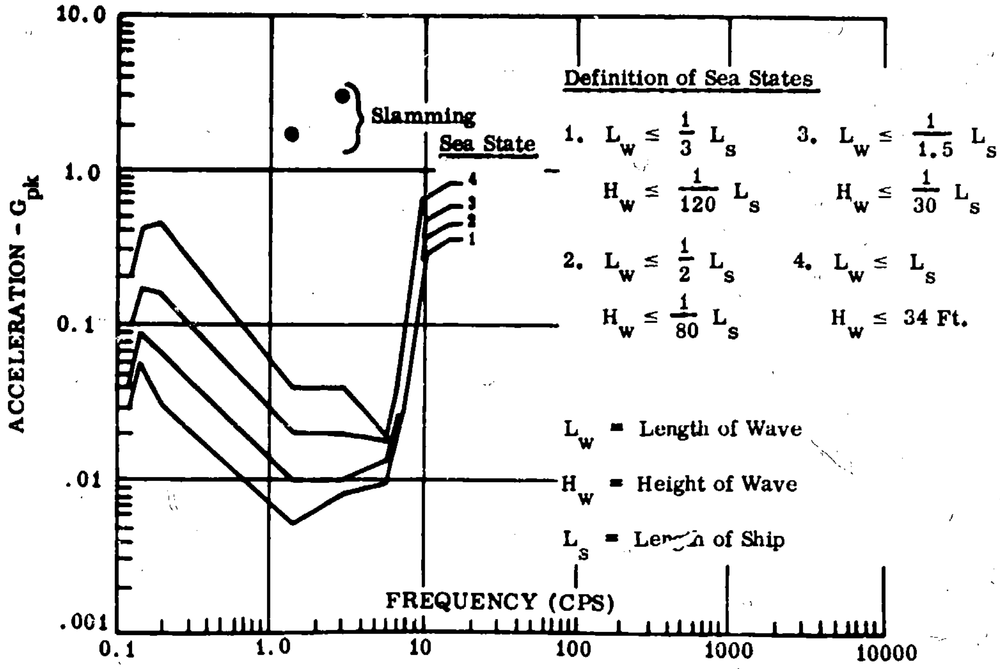

Fig. 23. Ship acceleration envelopes (L_s = 380 ft)

The higher vibration frequencies (>10 cps) are due to machinery vibration, and are less a function of sea state than the lower frequency rigid body motions.

Truck

Figure 24 shows the effect of road condition on the vibration environment.

The upper curve in Fig. 24 has been obtained by enveloping data from a number of individual test programs. This curve includes peak values representing the environment experienced in traversing rough roads, ditches, potholes, railroad crossings, and bridges. Data reduction procedures vary from one report to another, but in most cases the method used was to record the data oscillographically, and visually determine the peak (zero-to-peak) acceleration and predominant frequency. This method has been used extensively in transportation studies, since it requires little auxiliary equipment, and since the magnitude of the significant predominant frequencies can be conveniently and immediately determined.

The lower curve in Fig. 24 has been obtained by enveloping paved road data. The combination of these two curves show the differences in vibration levels between vibrations which occur while traversing potholes, ditches, railroad crossings, etc., and the maximum vibration environment occurring during operation on paved roads.

Figure 25 shows the effects of cargo load on the vibration environment. These curves are the result of a single measurement program. The tests were conducted with three standard commercial semitrailers, each having one of three basic types of suspension (air-ride tandem suspension, stable-ride single suspension and single-axle spring suspension). Tests were run at two load conditions, empty and full, over a first-class asphalt road. Vertical accelerations were monitored at three locations on the cargo floor (over the fifth wheel, the center of the van floor, and over the rear axle). These curves show that the vibration levels are practically unaffected by load in the lower frequency ranges. Higher frequency components, however, are reduced on loaded trucks.

CONCLUSIONS AND RECOMMENDATIONS

The most severe transient environment associated with transport vehicles occurs during railroad car coupling or humping operations, whereas the most severe steady-state environment occurs during phases of aircraft transportation. Railroad, truck, and ship follow aircraft in order of decreasing levels of environment.

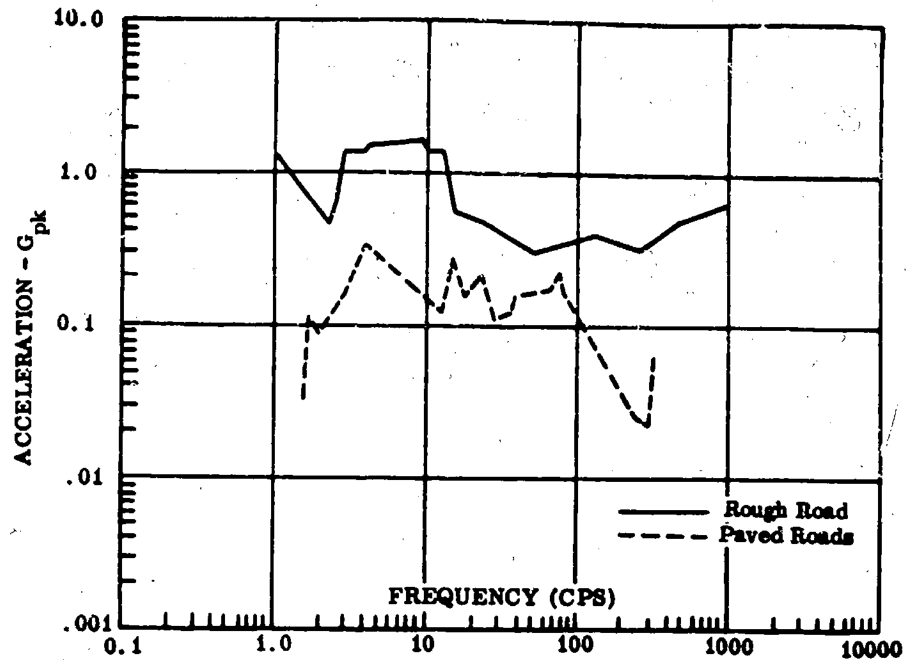

Fig. 24. Truck acceleration envelopes

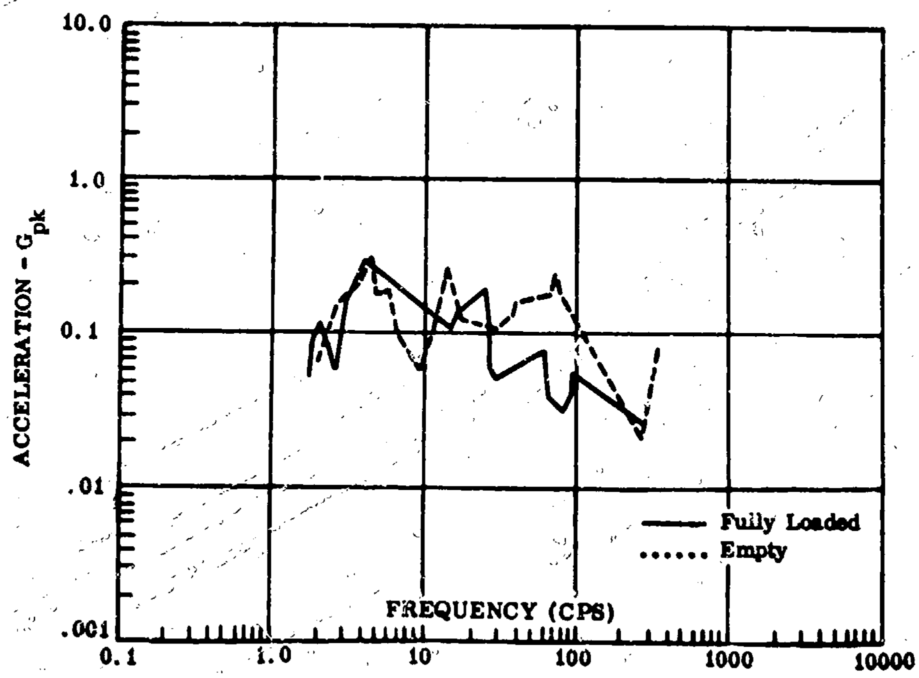

Fig. 25. Truck acceleration envelopes

The levels of vibration presented in this paper are considered reliable, even though they are derived from data analyzed by diverse reduction methods. This conclusion is based on the relatively close correlation between data from various reports (for similar test vehicles and conditions).

Data are sufficient at the present time to define adequately the transportation environment in terms of maximum acceleration versus frequency; however, the term maximum should be emphasized. For example, because of the paucity of data describing the environment in the cargo area of ships, data from the extensively monitored fantail area were utilized. Since this is the highest encountered shipboard environment, it does not represent the cargo hold, but does set an upper bound on the expected cargo hold environment. The philosophy of enveloping all data lends itself to a conservative environmental definition with a very high (99 percent) statistical confidence level.

Future studies of interest that would greatly enhance and supplement this investigation could include (a) correlation of fantail to cargo hold shipboard environments, (b) a more extensive breakdown of transportation modes, (c) a statistical processing of accumulated data, (d) a continuing effort of environmental definition, particularly in the truck mode, and (e) an investigation of terminal handling environments.

Due to the increased nationwide interest in transportation environments, many programs are currently being conducted in the previously outlined areas, and should go far to supplement the basic criteria contained herein.

ACKNOWLEDGMENT

The assistance and contributions of the survey's principal investigator, Mr. Fred E. Ostrem of General American Transportation Corporation, are acknowledged and appreciated.

DISCUSSION

Mr. Markson (E.R.A. Inc.): The set of ship acceleration curves appears to be a combination of vibration accelerations and shock accelerations. Is that correct?

Mr. Schock: Yes, the impact vibrations are transient in nature although they are of rather long duration. It could be termed a shock vibration. It is a response, but over a longer duration than one would normally consider a shock response.

Mr. Markson: What kind of instruments did you use to pick up the two different types of accelerations?

Mr. Schock: We used accelerometers, mounted in the fantail area.

Mr. Markson: Did you use the same accelerometers for reading vibration at 100 cps on the ship as you did for reading the low frequency shock impact?

Mr. Schock: No, there were two different studies. One was for vibration, and the other was specifically to pick up the slam modes. Different accelerometers were used in each study.

Mr. Markson: This is a summary of several different reports?

Mr. Schock: Yes, over 300 reports were reviewed.

Mr. Fitzgibbon (Mechanics Research): Why did you not present your vibration data in terms of the power spectral densities rather than g's rms? In this manner you could show an envelope of all of the power spectral densities from the various environments which would be a criterion for all environments.

Mr. Schock: We had spectral analyses in some cases during the course of the study, while others presented only data from peak detection meters or oscillograph records. Most of the data on aircraft were in spectral analyses and given in psd. We reduced these to g-rms to get them in a form comparable with the other data.

Mr. Fitzgibbon: Are you suggesting that the rms g's be taken from your curves and converted to psd to arrive at specifications for shock and design?

Mr. Schock: No, I would not use these curves in specifications. The paper itself breaks these curves down in much more detail with more detailed parameters, such as the direction of measurements, and individual aircraft measurements. This will greatly facilitate the definition of a better specification.

I would not try to envelope curves such as these for use in a specification. It gives the designer a feel for what the maximum levels will be and what to design for.

Voice: Could you classify the helicopter and the propeller excitation as being one of the most severely characterized as steady state?

Mr. Schock: Yes, the helicopter data was characterized as steady state. It is caused by the response of the structure to the steady state prop wash.

Mr. Krachman (TRW Systems): That truck data seems to be a little low. Was this on any special type of truck?

Mr. Schock: The maximum environment was on trucks that had standard truck gear. Some of them did have air-ride and some had only coil springs and single axles. The data in the lower environment were taken over very good first class asphalt roads, whereas the data in the upper environments were taken on a typical rough road which had pot holes, railway crossings, and bumps. It was not as rough as the Munson course.

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