NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Technical Report No. 32-876

The Dynamic Environment of Spacecraft Surface Transportation

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JET PROPULSION LABORATORY
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W. Shipley, *Manager*
Environmental Requirements

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FIGURES (Cont'd)

ABSTRACT

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The data in this Report result from a study of the shock and vibration environment imposed on a spacecraft during surface transportation. Acceleration amplitude statistics and predominate frequencies of different locations within a typical air ride suspension van are presented.

The Appendix discusses instrumentation requirements associated with the acquisition of transportation data.

Author

I. INTRODUCTION

The shock and vibration environment imposed on spacecraft during surface transportation was determined by the Jet Propulsion Laboratory (JPL) in evaluation tests and instrumented spacecraft shipments. All flight spacecraft built by JPL have been transported by air-suspension vans to the launch site at Cape Kennedy.

The data presented in this Report include shock and vibration measurements over rough irregular roads plus vibration measurements over smooth highways. Comparisons are made between different vans, smooth and rough roads, and three different locations within the same van. Data plots envelope the maximum, 95, and 50 percentile levels of shock spectra and power spectral densities.

The Appendix discusses instrumentation applicable to measurements of transportation dynamic environments. Electrical and mechanical instrumentation are included.

The decision to instrument spacecraft shipments was made primarily for the following reasons:

1. Limited information was available on the dynamic environment of surface transportation.
2. It is desirable to have shock and vibration measurements in the event of an accident. Once the normal environment is determined, this becomes the underlying reason for continuance of instrumentation.

It is hoped the statistical study presented in this paper will aid in predicting transportation environments.

II. DESCRIPTION OF TRANSPORTATION STUDIES

The data measurements for this study were made during a van evaluation test and two spacecraft shipments to Cape Kennedy. The evaluation test is referred to as the *Ranger Block III* test since it was performed in support of Block III configuration *Ranger* shipments. The trips to the Cape involved the *Ranger VIII* spacecraft that recently photographed the Moon and a structural model of the *Surveyor* spacecraft.

The load distribution of the evaluation test included the *Ranger* TV tower at the aft position, the *Ranger* bus structure and electronics at the middle and a solar panel trailer at the front. Steel plates were located in the middle also as ballast. The ballast was intended to load the van suspension system to its nominal loading for improved dynamic characteristics. The *Ranger VIII* van was loaded approximately in the same manner except no ballast was included. A structural model constituted the payload of the *Surveyor* shipment.

The *Ranger* equipment was installed in transportation structures secured to the van floor with no shock or vibration isolators. Structural integrity between the van floor and the spacecraft equipment was assumed so that measurements at the van floor were considered the input to the equipment itself. The *Surveyor* model, however, was installed on an isolated trailer that did not linearly transmit the vibration and shock of the van floor to the spacecraft. Consequently the spacecraft structure and transport trailer were instrumented in depth to determine the transfer functions and resonant frequencies of the system. Only one data channel was determined applicable to this report. The *Ranger* vertical axis measurements used piezoelectric accelerometers located midway between the sides of the van in the locations depicted in Fig. 1. Two accelerometers were also installed in the longitudinal and horizontal axes.

The *Surveyor* measurements were made only at the aft position. The accelerometers were mounted on aluminum plates secured to the van floor with lag bolts.

Mechanical accelerometers were also employed. These units were also mounted on metal blocks secured to the floor.

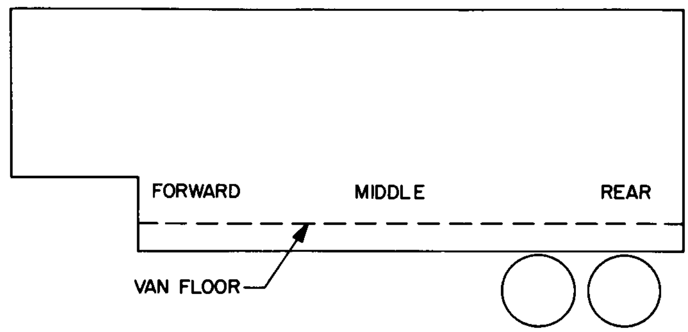

Fig. 1. Accelerometer locations

III. DISCUSSION OF DATA

The data to be discussed were measured with piezoelectric accelerometers and recorded with a magnetic tape recorder. The analyses were performed with digital computer programs.

During the trips to Cape Kennedy from Pasadena, California, about 85% of travel time involved smooth highways in good repair. However, the greatest percentage of vibration and shock analyses were with rough road measurements. The data analyses were performed sequentially as follows:

1. The magnetic tapes were coded with the NASA 36-bit time code.
2. Oscillograph records of the data channels, reference channel and time code were produced. The reference channel recorded only the standard FM carrier frequency. The demodulated signal from the channel was recorded on the oscillograph records.[1]
3. Data were selected from the oscillograph records for power spectral density (PSD), and shock spectrum analysis. These data selections were identified on the tapes with the time code. The quality of data selected was determined by the reference channels.
4. Preliminary PSD and shock spectra were evaluated for required resolution and frequency content.
5. The final PSD and shock spectrum analysis plots were programmed and computed.
6. Selected PSDs were analyzed for amplitude statistics. (The method of analysis was determined by

[1]This channel is discussed in the Appendix.

evidence of noise content in the data.) The existence of apparent noise dictated a statistical analysis to estimate the energy distribution.

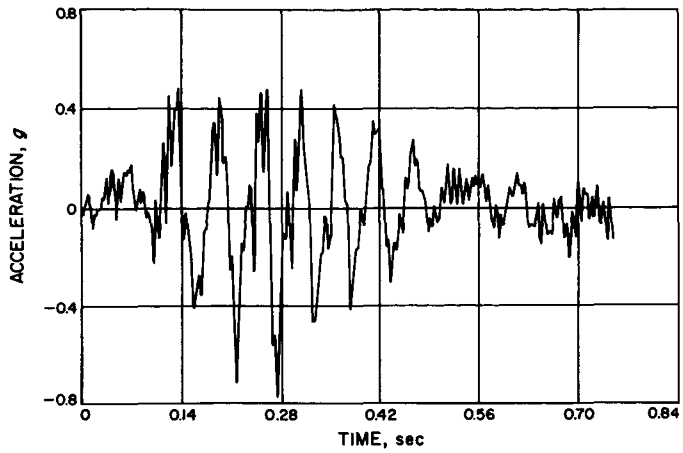

Fig. 2. Observed transient, *RA-8* aft position

A. *Shock Analysis*

The analyses of all shocks were performed in the sequence listed above. Figure 2 contains an amplitude-time history of a transient measured at the aft position of the van during the *RA-8* shipment. The transient was located on the tape via the time code, digitized and run through the shock analysis program producing Fig. 2 and 3. Figure 3 contains the shock spectra calculated with an assumed damping ratio of 0.050 or a Q of 10, i.e., $Q = 1/[2(c/c_c)]$. The spectrum represents the response of a single degree of freedom oscillator to the shock measured.

The assumed Q of 10 represents the Q of the hypothetical oscillator. The theoretical steady state sine equivalence of the shock may be calculated simply by dividing the spectra by the value of Q. The data were low pass filtered at 200 cps. Although not well defined, the spacecraft fragility at low frequencies was of greatest concern.

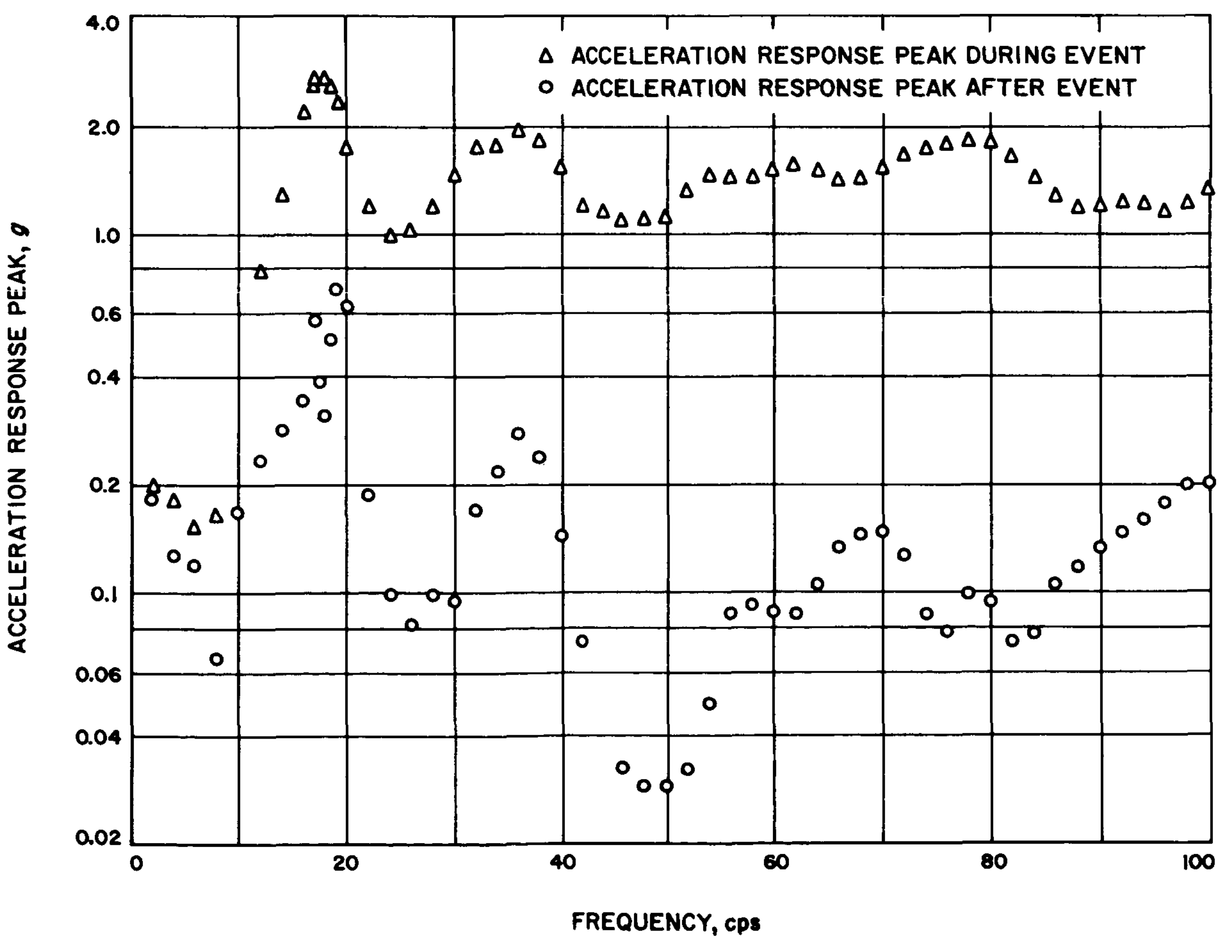

Fig. 3. Shock spectrum, *RA-8* aft position

Although low pass filtered at 200 cps, the analyzed data are plotted to 100 cps only. It was determined that little energy existed above 100 cps. At frequencies below 5 cps, it should be borne in mind that the frequency response rolls off somewhat. The general trend of the data below 5 cps is probably valid, however.

The observed transient plot is useful as a cursory check of the shock amplitude envelope, but does not readily associate energy levels with frequencies. The shock spectrum plots must be referred to for frequency information and will therefore be the basis of discussion in this Report. A Q of 10 will be assumed to limit the quantity of data plots. Damping ratios of 0 and 0.025 were also used to compute shock spectra, but are not discussed in this Report.

Three shocks measured by each vertical axis accelerometer in the *Ranger VIII* van were selected as data to compare the response of the three channels to a given excitation. The maximum envelope of the three shock spectra is plotted for each of the three locations in Fig. 4. The aft position response contains a peak at 18 cps, a notch at 25 cps and a second major peak at 75 cps. The center and forward position responses peak at about 14 cps and decrease in level to a minimum at 25 cps similar to the aft response. Below 40 cps the van center indicates the lowest level response. Above 40 cps, however, the center position becomes more severe than the forward section and approaches the amplitude of the aft response at 60 and 88 cps. It is apparent from the figure that the environment at all van locations produces a similar response below 40 cps, but is dominated by local dynamic characteristics above this frequency. The response g levels are quite low with a maximum of 3.8-g pk (peak). The equivalent sine input at this frequency would be 0.38-g pk.

Figure 5 compares the maximum shock spectra of nine *Ranger* shocks measured at the aft section and twelve *Surveyor* shocks. The spread in response levels varies with frequency although some consistency in the responses is apparent. An important similarity is the peak response at 18 cps in spite of the differences in vans, load weights and distribution. This peak may result from a phenomenon such as wheel bounce. The *Surveyor* response is generally between 2- and 4-g pk, whereas the *RA-8* response is primarily between 2- and 3-g pk. In

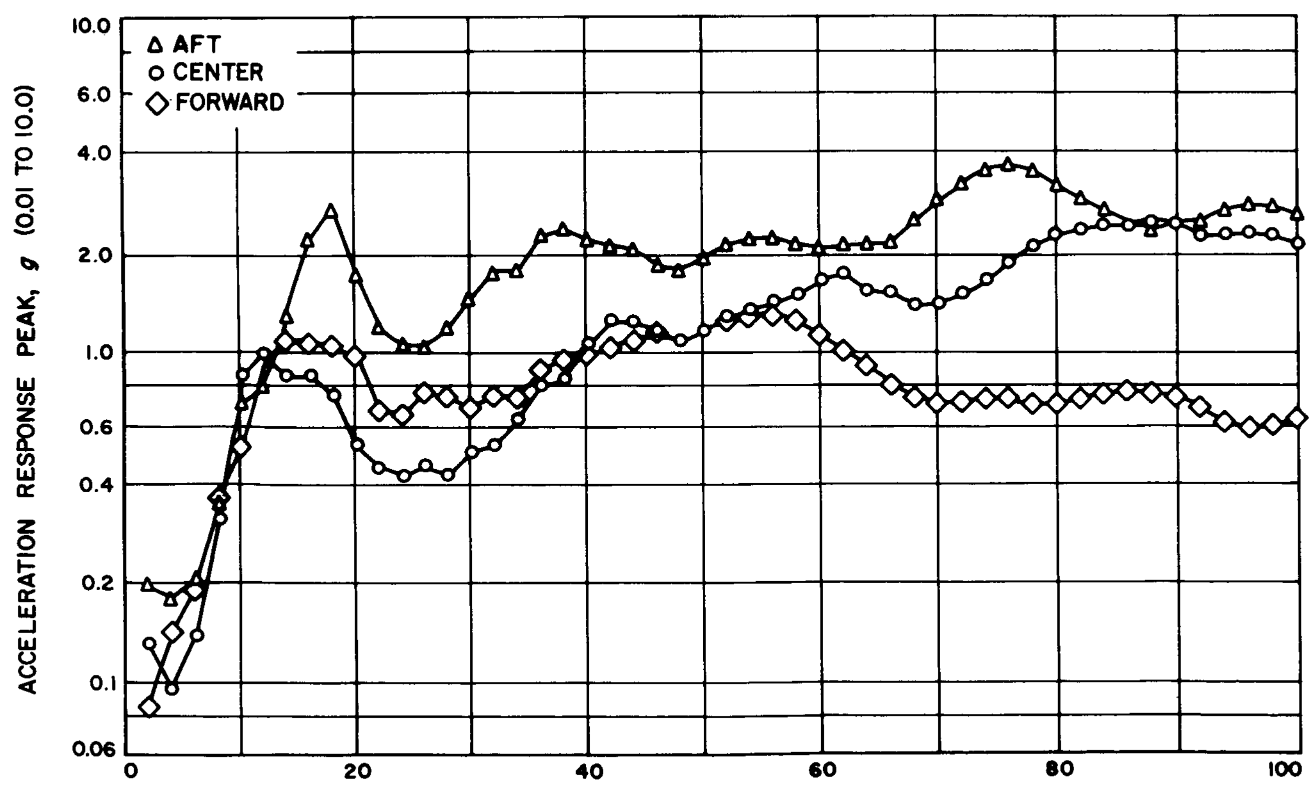

Fig. 4. Maximum shock spectra *RA-8* aft, center, and forward positions

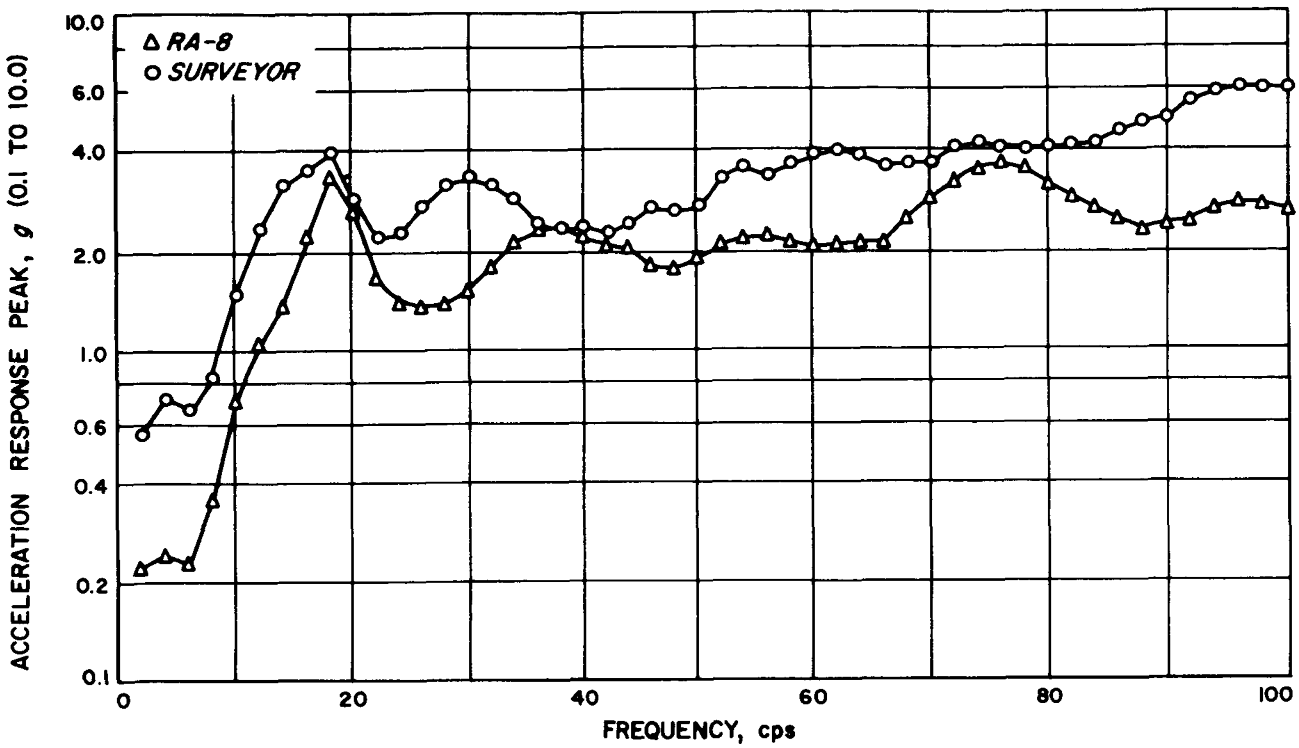

Fig. 5. Maximum shock spectra *RA-8* and *Surveyor* aft positions

both cases the energy levels of the response as a function of frequency generally increase above 25 cps.

Perhaps the most significant data yet presented are contained in Fig. 6. The shock spectra plotted in this figure present the maximum, 95, and 50 percentile levels of a data sample of 21 shock spectra including nine from *Ranger VIII*, and twelve from *Surveyor*. The spectra were computed with an assumed normal distribution. The 21 spectra were all van aft position data. As in previous plots, peak amplitudes are very prominent at 18 cps indicating a common van characteristic based on a significant sample of data.

The maximum peak amplitude of response is 6-g pk at 95 cps. The maximum amplitude at 18 cps is 4-g pk. The 95 percentile and maximum spectra have generally the same shape with a maximum dispersion of about 1.5-g pk. The 50 percentile or average spectra plot is also similar in shape and often 2 g less than the maximum curve at various frequencies. This indicates the spread or variation in shock levels to be rather small. It is apparent from the spectra that shock mounted equipment should have a system resonant frequency well below 18 cps.

The spectra presented in Fig. 6 could be used to establish transportation tests for equipment to be transported by air-suspension van. The relatively large data sample provides confidence that the spectra envelope typical road shocks. Equipment degradation resulting from shock loading should be insignificant. The maximum equivalent sinusoidal input would be 0.6-g pk at 95 cps if derived from maximum spectra of Fig. 6 or 0.4-g pk at 18 cps.

B. Vibration Data Analysis

The results of vibration data analysis are contained in Power Spectral Density (PSD) plots. The data selected for PSD analyses were low pass filtered at 180 cps. The accuracy of data below 5 cps is somewhat impaired by frequency response roll off. Each plot contains the spectral density in db with a reference of 1 g^2/cps. The frequency scales start at 1 cps and often include frequencies beyond 180 cps. Data beyond 100 cps are usually of little significance.

PSDs were computed from data measured in the *Ranger Block III* test, *Ranger VIII* shipment and *Surveyor* model shipment. Both rough and smooth road data are presented. Data measurements during the

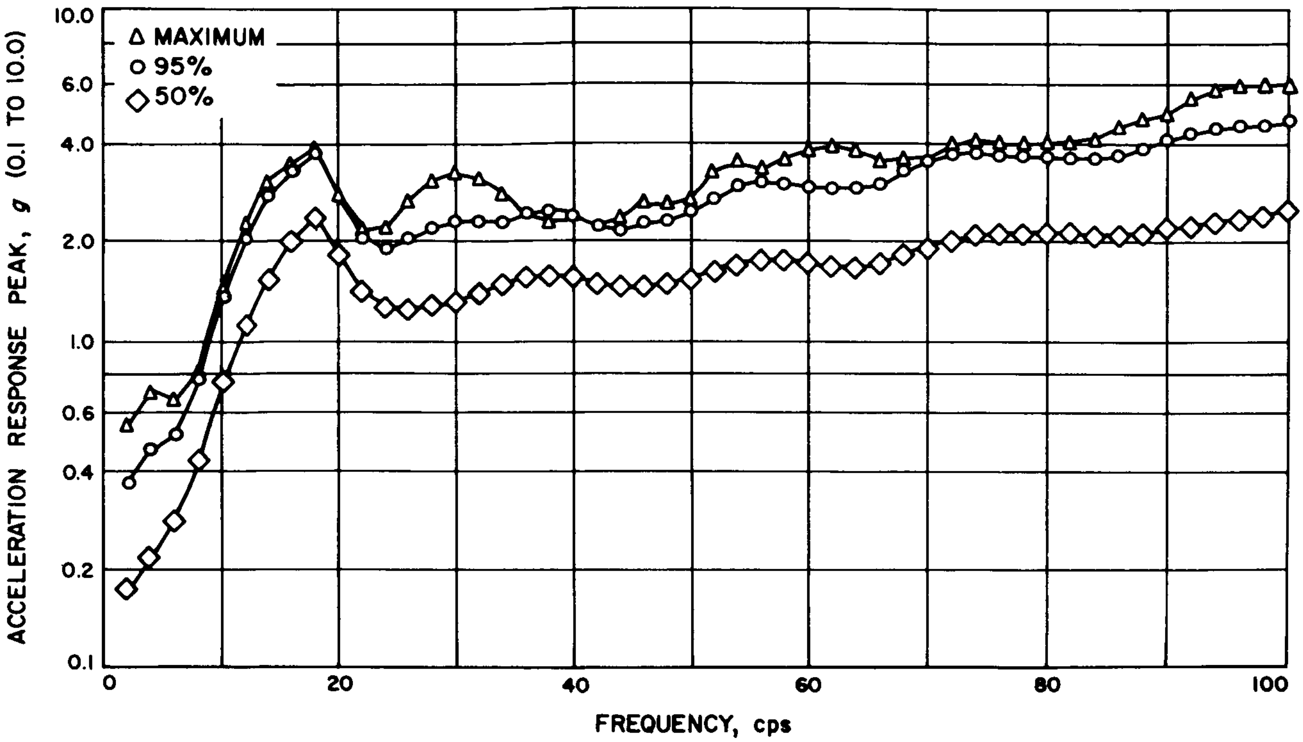

Fig. 6. Maximum, 95%, and 50% level shock spectra, *RA-8* and *Surveyor* aft positions

Ranger Block III test are from rough or detour road surfaces only. The vibration data represent the same accelerometer locations as the shock spectra.

The maximum, 95, and 50 percentile level spectral densities of *Surveyor* shipment vibration data are shown in Fig. 7 for a normal distribution. The data measurements were made during rough road travel. The maximum and 95 percentile curves are very consistent and show little difference in amplitude. Below 9 cps the average energy levels deviate from the maximum by 3–4 db. This difference decreases to about 2 db above 9 cps. An energy peak at 18 cps appears in the PSD as it did in the shock spectra. A lower frequency peak at

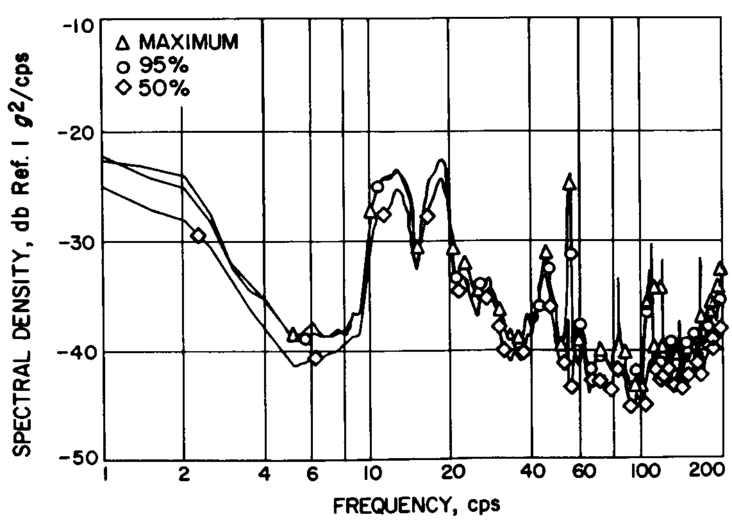

Fig. 7. *Surveyor* spectral density, maximum, 95%, and 50% rough road

12–13 cps is also contained in the PSD, however. All data samples comprising this statistical analysis prominently display the two peaks indicating a characteristic response of the van to road vibration. The spectra shape between 1 and 5 cps may be evidence of a van resonance in contrast to assumed wheel bounce excitation between 10–20 cps. The explanation for data characteristics cannot be definitely made at this time.

Figure 8 compares the maximum PSD of rough road *Surveyor* data with smooth road *Surveyor* data. Both plots contain the characteristic peak at 18 cps and are very similar in spectral shape with the exception of the frequency band 6–15 cps. In this region more peaks are displayed by the smooth road data. Amplitude differences between the plots substantiate a significant difference in road conditions. Energy differences of

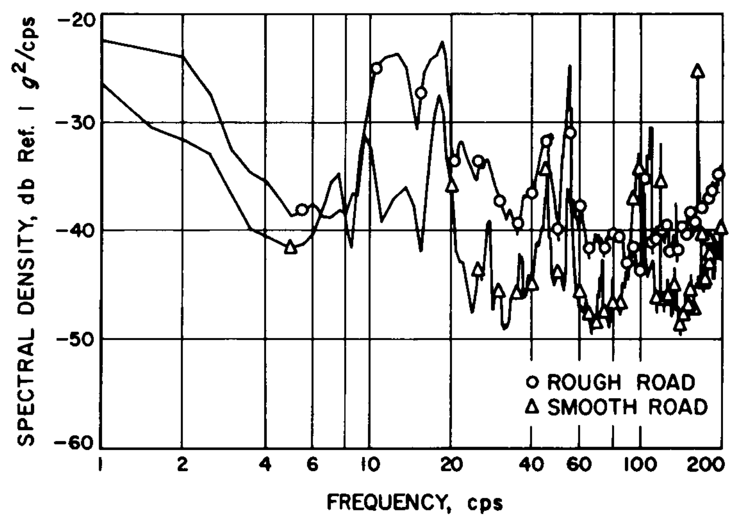

Fig. 8. *Surveyor* maximum PSD envelope—rough vs smooth road

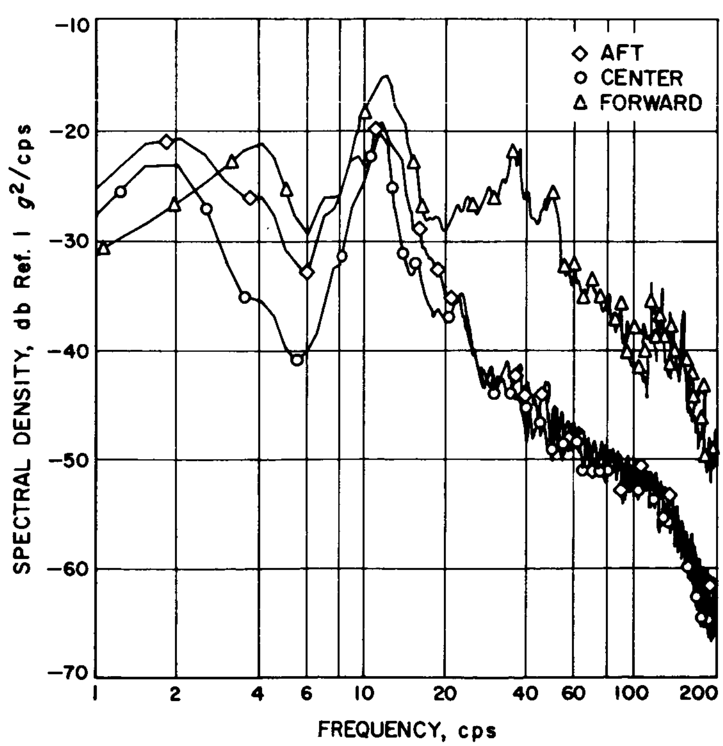

Fig. 9. Test—*RA Block III* rough road—aft, center, and forward positions, maximum envelope PSD

4–5 db are common and often far exceed this. It is interesting to note that the greatest margin occurs at 12 cps. Low level excitation does not seem to excite this frequency perhaps indicating a non-linearity in the van.

Although not shown in the figures, the spread between the maximum density plot and the 50 percentile remained quite consistent between rough road data and smooth road data.

Figure 9 contains a composite of the maximum PSD envelopes at the three accelerometer locations in the *Ranger Block III* van. Each envelope was derived from a total of 7 vibration data samples. As was previously noted in the shock spectra, the measurements indicate both consistencies and inconsistencies between channels. Measurements at the van rear and middle positions contain a peak at 2 cps. The corresponding peak at the forward position occurs at 4 cps with an amplitude of −21 db. These peaks are probably van resonant frequencies. The second peak occurs at approximately 12 cps at all three locations and may result from wheel bounce excitation. At 12 cps the spectral density amplitudes are close to −20 db at both the rear and middle positions. The level is greater at the front, however, and reaches a maximum of −15 db. Beyond 12 cps the rear and middle measurements rolled off in amplitude, whereas the forward measurements indicate a peak at 35 cps.

It is apparent that the environment of the forward position was most severe during the *Ranger Block III* tests. At the 3-db-down points of the forward position 12 cps peak, the spectral density value is −18 db and is about 3 cps in bandwidth producing a level of 0.22 g rms.

Figure 10 indicates a different comparison between the locations for *RA-8*. The aft spectral density has the greatest envelope with a few exceptional frequencies. The forward position is less severe below 2 cps, but exceeds the center measurements at higher frequencies. The comparison of amplitudes for the three locations varies with frequency so that a maximum level position may become the minimum level position at a different frequency.

Figure 11 compares the maximum spectral densities of the aft position of the three van measurements. The important comparison to be made from this figure is the relative shape of plots. *RA-8* and *Surveyor* vans indicate an energy peak at 18 cps. *Ranger Block III* data does not show a peak in amplitudes at 18 cps, but does peak at 12 cps similar to the first peak of the *Surveyor* data. Both these peak frequencies should be considered if shock mounts are used. The spread in amplitudes is of little significance since the road conditions were different.

A plot of the maximum, 95%, and 50% PSD levels computed from all PSD analysis is contained in Fig. 12.

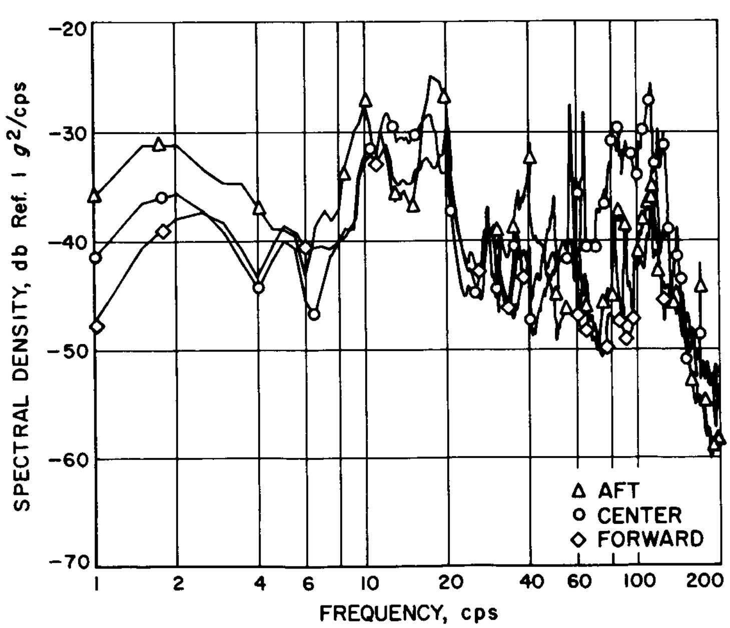

Fig. 10. Test—*RA-8* power spectral density—smooth road, maximum envelope aft, center, and forward positions

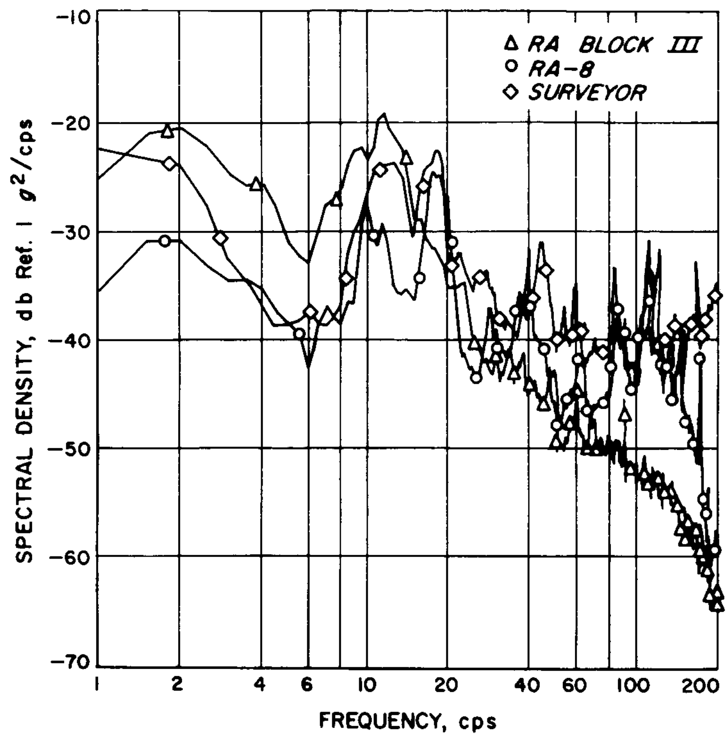

Fig. 11. ***RA Block III, RA-8, Surveyor* aft position, maximum PSD levels**

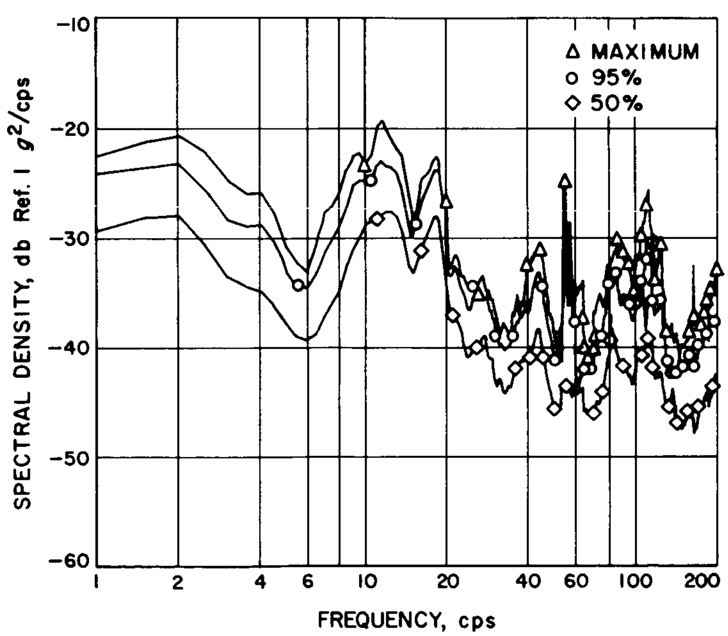

Fig. 12. ***RA Block III, RA-8, Surveyor* aft and center positions, maximum, 95%, and 50% PSD levels**

Normal distribution was assumed. Thirty-seven data samples comprise this statistical analysis. It is apparent in the figure that a considerable difference in amplitude exists between the curves due to the varied surface conditions represented. The *RA Block III* measurements were made over a very rough detour road whereas *RA-8* and *Surveyor* measurements are from highway driving. These energy levels therefore cover severe, rough highway and normal surface conditions and should envelope the vibration environment of any eventuality in a cross country trip (barring accidents). Again the peak frequencies of 12 cps and 18 cps are prominent. An energy amplification is also indicated at 2 cps.

In general, the vibration data presented indicate low energy levels at all frequencies within the 1–180 cps band of analysis. Approximately 56 PSDs were included in the data presented. The maximum amplitude of vibration contained in the plots is −19 db at 12 cps. The percent attenuation of this amplitude depends on the frequency, but is usually significant. It should be noted here that Fig. 9 contains −15 db pk at 12 cps. This peak energy was measured at the forward position of the van, however, and is not contained in the plots of Fig. 12 which cover only the center and aft positions. Figure 12 does envelope, therefore, the vibration energy at the recommended van locations for installing payload equipment.

No discussion of the longitudinal and horizontal axis data is included in the report. The measurements in these axes were as much as 40% less than the vertical axis measurements.

IV. CONCLUSIONS

Based on the experience with the measurement and analysis of transportation data at JPL, the following conclusions can be drawn from the data presented and from the instrumentation discussed in the Appendix: The Appendix on instrumentation was warranted by significant problems in this area.

1. The shock and vibration environment of an air-suspension van should present no degradation problems if safe driving regulations are imposed on the truck operator, and no accidents occur. Speed limits and periodic truck inspections should be imposed regulations.
2. Equipment should be hard mounted to the floor of the van if the dynamic characteristics of a support structure or shock mount have not been accurately determined. The mount or structure dynamics may be coincidentally "tuned" to the input and the response amplified. The amplitudes measured at the van floor are rarely greater than 1-g pk. At low frequencies the center of the van floor, length- and width-wise, has the less severe environment.
3. The position of least vibration or shock severity in a van is dependent on the frequency, the individual van characteristics, and to some extent the amplitude of excitation. The aft and center positions seem most consistent although their amplitudes often exceed the forward position. For this reason, it may be desirable to design shock mounts for the aft or center positions if mounts are required. The center and aft positions are most predictable.
4. When selecting the mode of instrumentation for a van shipment, forethought should be given to the purpose of instrumentation. The underlying reason for data acquisition should influence the sophistication of the instrumentation, the location of transducers, or mechanical recorders, the sampling of data required, and the final data analysis.
5. Magnetic tape recorders should be selected with caution for this application. The tape transport should definitely be a closed loop design.[2]
6. A method should be developed to code the magnetic tapes if a tape recorder is used. Time coding is required for identification/computer control for shock or PSD analysis and correlates events with road conditions.
7. A reference channel should be included with data channels as a means for cursory evaluation of data quality and for identification of microphonics.
8. The requirement for shock and vibration measurements aboard an air suspension van is primarily important to record the loading that may occur in the event of an accident. Normal surface transportation should produce little concern.

[2]The design is discussed in the Appendix.

APPENDIX

Appraisal of Instrumentation Techniques

The effort involved in acquiring transportation vibration data has resulted in considerable revision of instrumentation techniques.

Recognizing the fact that the final data quality is dependent on the instrumentation, a brief appraisal of instrumentation techniques is warranted.

I. PIEZOELECTRIC ACCELEROMETERS

The data discussed previously were measured with piezoelectric or crystal accelerometers. These accelerometers or other electrical accelerometers with the same capabilities must be used to record data signals adaptable to detailed analysis.

The accelerometers used in the JPL studies were 1-ounce instruments with a frequency response of 2–7000 cps. An advantage realized with these accelerometers is their minute size which facilitates installation. Charge amplifiers were used to amplify the input to the tape recorder. They were set at 3-g 0-pk full scale. The full scale voltage output of the amplifier was attenuated with a series resistor making the amplifier output compatible with the recorder full scale deviation but yet maintaining low frequency response.

Associated with the use of electrical accelerometers is the tape recorder. Two different tape recorders were used in the JPL data acquisition. Both recorders were by the same manufacturer, but differed in the number of channels available. The recorder used in the evaluation tests was a 14-channel recorder whereas the other used for the S/C shipment was a 7-channel machine. A motor generator set powered the recorders since van power was not available.

In each application, the data were acquired in the FM mode. The standard FM carrier frequency related to the record speed was direct-recorded on the reference channel. No transducer outputs were recorded on this channel.

The primary function of the reference channel was to identify data distorted by recorder wow and flutter. This provided further assurance that data selected for analysis was valid and not recorder microphonics. As was expected, the channel did indicate periods of spurious noise. This occurrence was most common during the *RA-8* shipment when a record speed of 1⅞ in./sec was used. Wow and flutter were problems in spite of an attempt to shock isolate the recorder. In vibration tests conducted prior to shipment, the shock mount system demonstrated a resonant frequency of 4 cps which was acceptable assuming the dominant van excitation would be from wheel bounce at approximately 12 cps. The attenuation of the isolation mount was approximately 50% at 12 cps. The maximum gain or amplification was 2.5 at 4 cps. The recorder was operational during the shake test and recorded a 10 cps sine wave as a reference input. The point to be made here is that the recorder was the weak link in the instrumentation chain and caused some loss of data. Recorder deficiencies are avoided, however, if the recommendations below can be followed:

1. A recorder with a closed-loop tape transport should be used. The JPL recorder was an open-loop machine and simply not designed for the application. Figure A-1 depicts a closed-loop transport as compared to the open loop in Fig. A-2. The closed-loop transport is designed to maintain a constant tape velocity over the record head regardless of transient changes in the tape reel speeds. It also maintains contact between the tape and record head.
2. As high a record speed as possible should be used if the recorder does exhibit susceptibility to shock and vibration. The record speed seemed to influence the susceptibility of the recorder to its dynamic environment. Data recorded at 7½ and 30 in./sec showed much less evidence of distortion than the 1⅞ in./sec data. Data recorded at 30 in./sec were

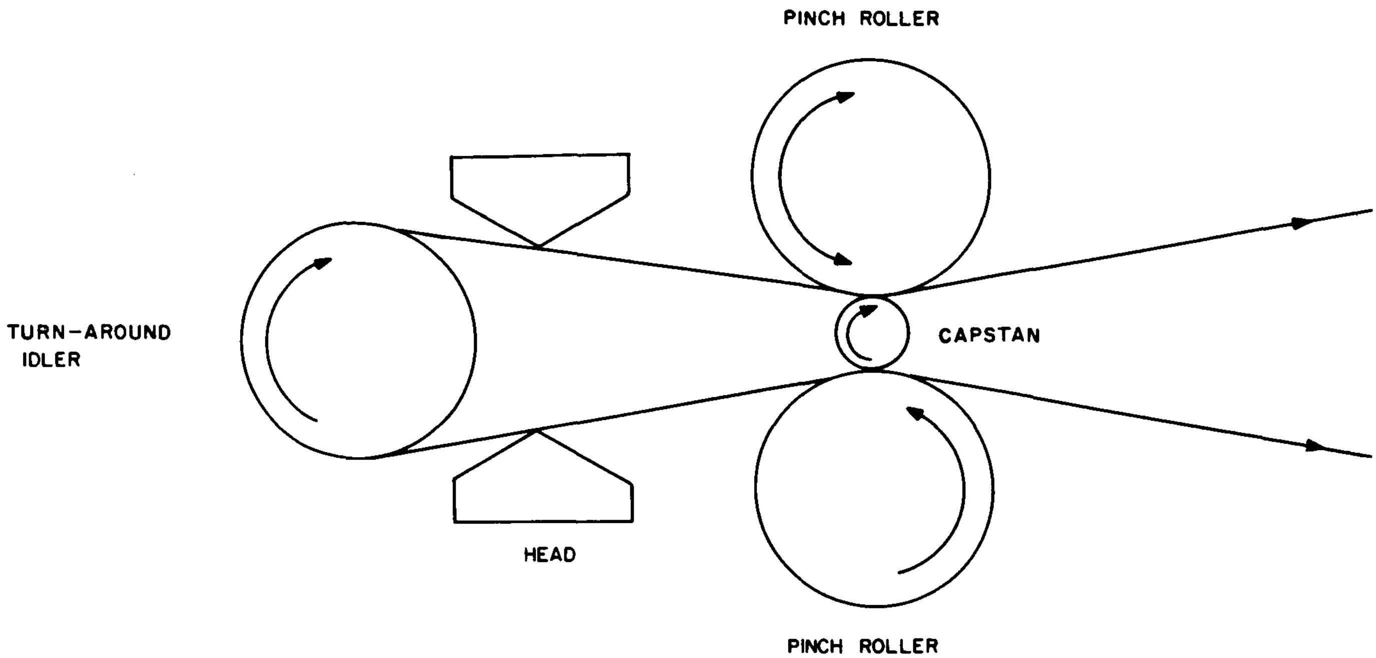

Fig. A-1. Closed-loop tape drive

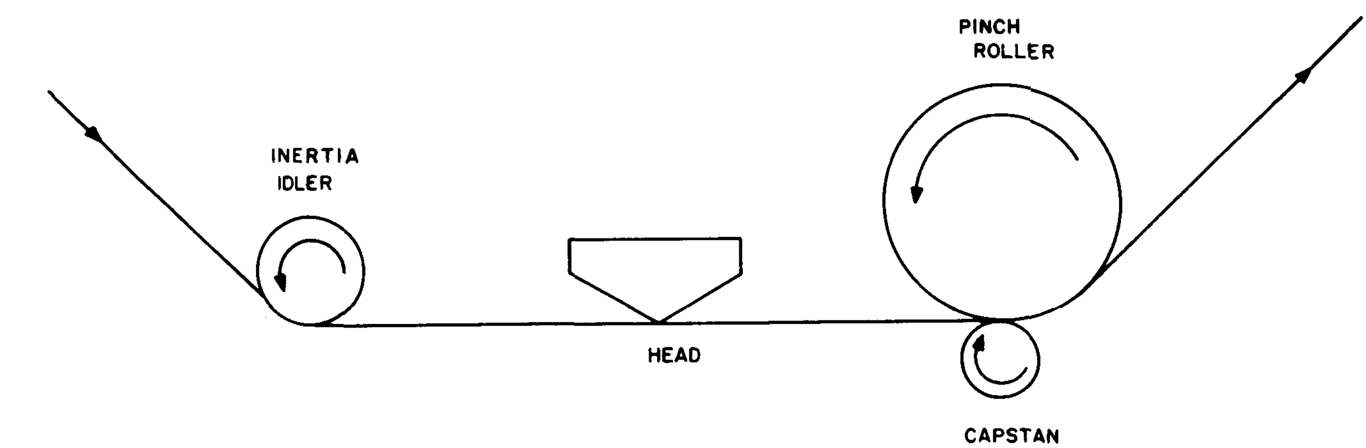

Fig. A-2. Open-loop tape drive

"cleaner" than at 7½ in./sec. Since the data channels were FM recorded, the record speed did not affect the low frequency response which would indicate a steadier tape velocity across the record head must exist at higher speeds due to tape reel inertia.

3. Arrangements far in advance of the shipment should be made to perform an evaluation of the ability of the recorder to operate in the service environment. If necessary, corrective measures can be taken to improve the probability of quality data acquisition.

Off-the-shelf recorders are available that have been designed for operation in a dynamic environment. If the application requires sophisticated instrumentation, these recorders should certainly be considered.

II. MECHANICAL SHOCK RECORDERS

An immediate appraisal of the amplitudes of shock and vibration occurring during transportation of delicate equipment is often requested by cognizant personnel. An instrument applicable to this requirement is the mechanical shock recorder. These devices simply count the occurrence of amplitudes of shock and vibration that exceed calibrated g levels. No frequency information or time correlation can be obtained from the shock recorder. Typical *g*-level calibrations on a 4-channel recorder are 1, 2, 3, and 4 *g*.

A number of these recorders have been used by JPL in parallel with the accelerometer instrumentation for enroute checks of amplitudes. Most of the devices were 4-channel accelerometers calibrated at 1, 2, 3, and 5 *g*.

Prior to the use of these recorders, they were tested on a shaker for calibration data. A set of sample calibration curves is shown in Fig. A-3. The vibration input consisted of narrow band noise at selected center frequencies. A noise source was routed through a tracking filter to obtain the 1.5 to 5 cps narrow band noise. Table A-1 contains the center frequencies and the noise durations.

Table A-1. Center frequencies and noise durations

Center frequency, cps	Time duration, sec	Filter bandwidth, cps	
15	60	1.5	5
20	60	1.5	5
25	60	1.5	5
30	30	1.5	5
40	30	1.5	5
50	30	1.5	5

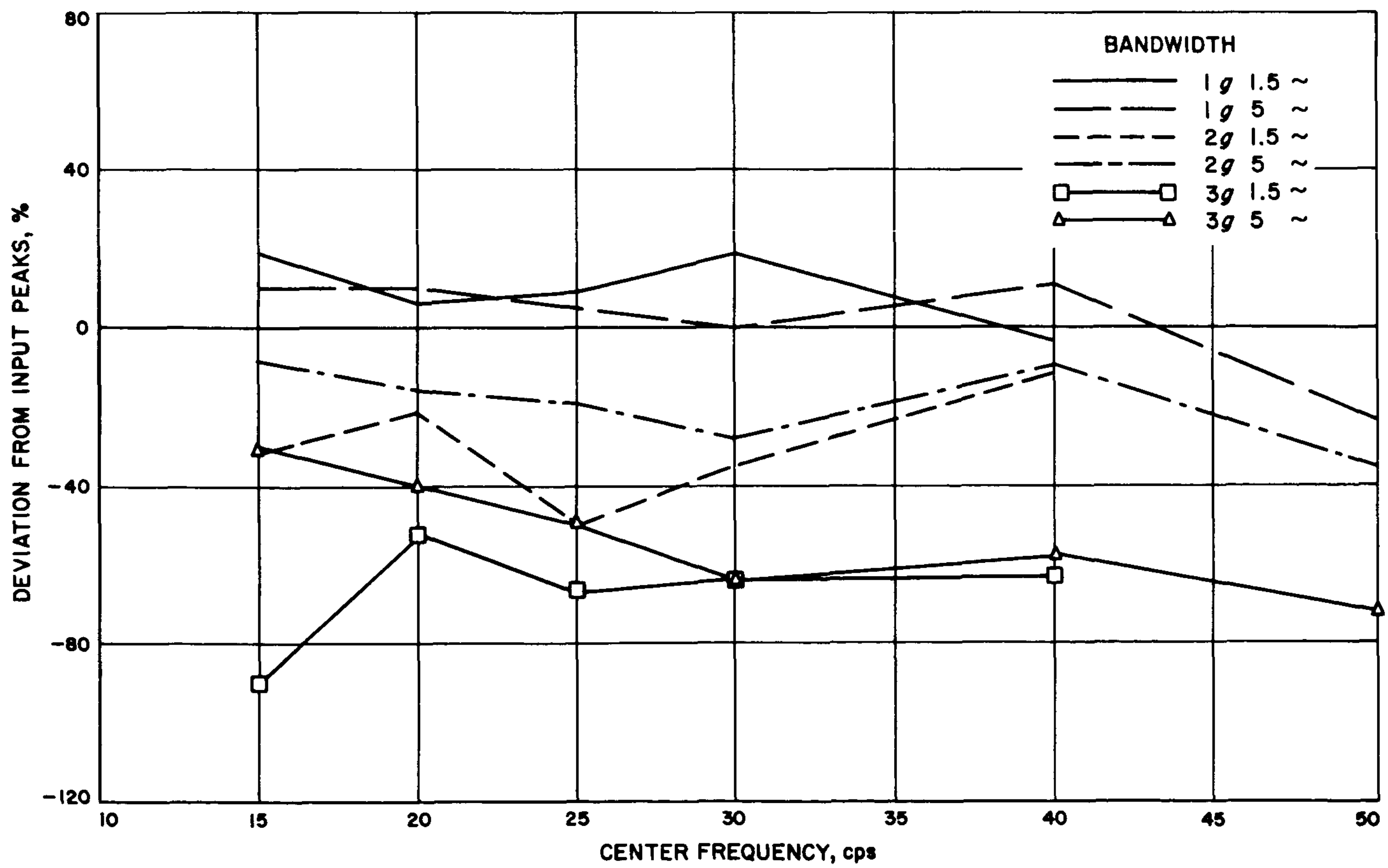

Fig. A-3. Mechanical accelerometer calibrations, filter bandwidths 1.5 and 5 cps

The rms amplitude of the noise was limited by the shaker displacement at the lower frequencies, but at 25 cps and above all 4 channels including the 5-g channel were actuated. The curves in Fig. A-3 were derived from amplitude density plots of the input vibration.

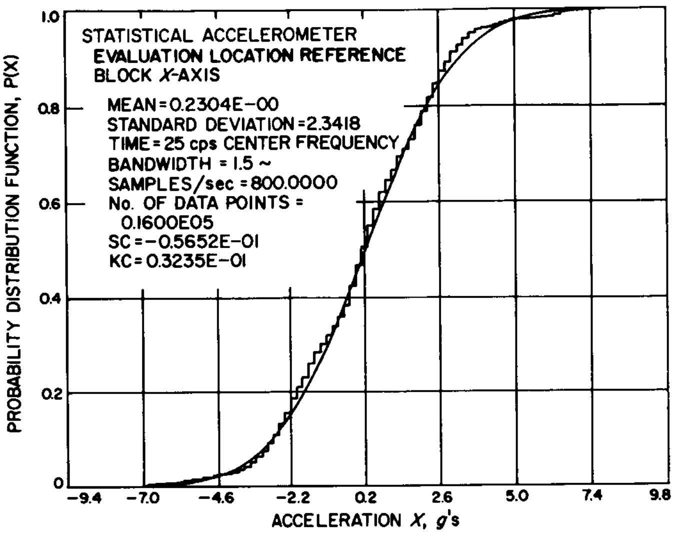

Fig. A-4. Probability distribution function, peak acceleration

Figure A-4 contains a density plot of 1.5 cycle bandwidth noise. Knowing the noise duration and the center frequency, the number of peaks with amplitudes corresponding to the recorder channels were calculated. The percent deviation in the calibration curves is the percent difference between the recorder channels and the actual number of input peaks at each center frequency. Negative percentages indicate the recorder count was below the actual number of peaks. A sample calculation is shown below for clarification. The plot of Fig. A-4 contains the distribution of peaks at the center frequency of 25 cps with a noise bandwidth of 1.5 cps. The calculations are performed for the 1-g channel.

1. Plot indicates 65% of pks are less than 1 g; therefore, 35% are equal to or greater than 1 g.

2. Total number of input pks = (center frequency) × (Duration) × (2) = (25)(60)(2) = 3000

3. Total number of pks exceeding 1 g = [% from Item 1 above] (Total pks) = (3.5)(3000) = 1050

4. Mechanical recorder 1-g counts = 1166

5. Percent Deviation = 116/1050 = 11%

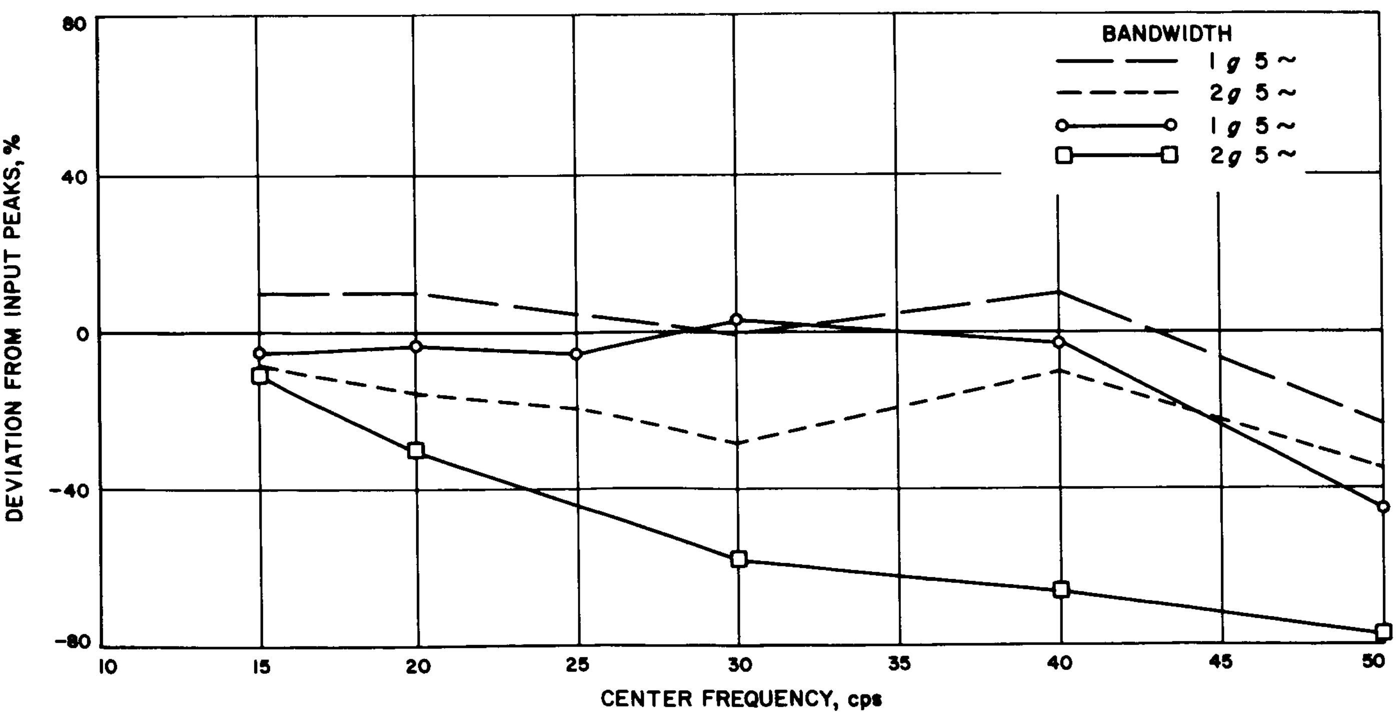

Fig. A-5. Comparison of two mechanical accelerometer calibrations, filter bandwidths 5 cps

The plots of Fig. A-3 and A-5 indicate the following mechanical recorder characteristics:

1. The percent deviation between actual number of peaks and the recorder counts is quite high for most channels. These percentages are, of course, affected by the tolerances in time duration of the noise and by the reading of the density plot data.

2. The recorders demonstrate a lack of consistency in side-by-side tests. This is demonstrated by Fig. A-5 which is a composite plot of two accelerometer calibrations performed with the units mounted side by side. The curves have different values for comparative channels.

3. One probable cause for recorder readings being below the input values is the noted tendency of some channels to stick when the counter contains an arrangement of digits such as 999. This seems to be a deficiency in the mechanism.

The use of mechanical recorders should not be discounted in spite of the problems noted above, however. The JPL data curves indicate that the devices are useful tools for convenient shock and vibration amplitude measurements at the most predominant levels of 2 *g* or less. The suitability of instrumentation techniques in general is dependent on the data parameters required, the sensitivity of the payload to the environment, and the funding and manpower available to support the project. In many applications adequately calibrated mechanical accelerometers or recorders are most practical.

Calibration of the mechanical recorder can require considerable effort and planning. Figure A-3 indicates the recorder response to vary with noise bandwidth and frequency. Figure A-5 gives evidence the recorders are inconsistent from one unit to another. These limitations require each channel of each unit to be calibrated and to be calibrated for the predicted service environments if reasonable accuracy of measurements is required.

In the case of the recorders evaluated by JPL, narrow band noise of 1.5 and 5 cps bandwidths was used to simulate the service environment excitation. Shaker displacement limitations eliminated center frequencies less than 15 cps which is unfortunate since the calibration data proves the accuracy to increase as the frequency decreases. However, the calibrations are adequate in that the minimum center frequency of 15 cps does put the prominent peak at 18 cps within the calibration frequency range. These peaks are generally 3–4 cps at the 3-db-down points which is compatible with the calibration bandwidths of 1.5 and 5 cps. The JPL calibration should be adequate for an approximation of the vibration and shock maximum amplitudes. If transients or significant vibration amplitudes are noted in a sampling of data from a trip, the shock recorders provide useful information in estimating the number of these amplitudes that occurred.

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