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A QUANTITATIVE METHOD OF TAILORING INPUT SPECTRA FOR RANDOM VIBRATION SCREENS

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This report presents a rational method by which an effective random vibration screen may be developed efficiently and quantitatively. In summary, a Flaw Precipitation Threshold (FPT) was derived from measurements of vibration response at known flaw locations. Responses were measured on a variety of modern electronic and electro-mechanical equipment, manufactured by five different manufacturers, during ongoing vibration screens. A vibration screen can be tailored for a piece of equipment by performing a global vibration response survey and adjusting the input spectra so that the responses fall within the FPT.

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CONTENTS

ILLUSTRATIONS

TABLES

Table | Page

FOREWORD

To date, progress in understanding vibration screens has been inhibited by a failure to appreciate an inherent and fundamental difference between establishing traditional vibration design (or test) requirements and establishing vibration conditions for screens.

Vibration requirements to be used for design purposes are based on estimates or measurements of the vibration environment of the item to be designed or whose design adequacy is to be proven. Generally, these requirements are applicable at the interface between the item and its supporting structure, since this is the location at which the data is available. Furthermore, the data can be conveniently labeled as an "input," even though it is actually an estimated response to some unknown excitation. This permits an unambiguous analysis to be performed and test to be controlled and is, of course, helpful in defining interface requirements. The implication of all this is that the internal responses of the item, be they high or low, must be survived by one means or another.

To date, vibration screens have been defined in essentially the same manner as those for design purposes. As a practical matter, this will continue to be the case for the prescription and control of screens. However, for the understanding and derivation of suitable screens, this is inappropriate. The objective of a vibration screen is to precipitate a flaw, i.e., to change an undetected defect into an observable failure. It must do this without either creating flaws or damaging sound hardware. The ability of a screen to meet this objective is not a function of the "input" to the item, but rather of the responses within the item. It is the vibration environment in the immediate vicinity of the flaw which changes it into a failure, regardless of the input to the item. Therefore, *understanding* of screens must be achieved by understanding the environment which precipitates the flaws. The Random Vibration Screening Process Development Program was undertaken in an effort to understand this environment and through this understanding, develop a process for "tailoring" vibration screening conditions to match the characteristics of the equipment to be screened.

The Random Vibration Screening Process Development Program was originally sponsored out of the Office of the Chief of Navy Material. After a reorganization, sponsorship was transferred to the Office of the Assistant Secretary of the Navy, Shipbuilding and Logistics. Technical guidance was provided by Mr. D.O. Patterson (OASN) throughout the program. This report documents the performance and results of the study program, while the title describes the end product.

1.0 INTRODUCTION

The Random Vibration Screening Process Development Program was sponsored by the U.S. Navy Material Command. The study program was performed by the Tactical Engineering Division of Hughes Aircraft Company's Electro-Optical and Data Systems Group in El Segundo, CA between March 1983 and March 1987. IBM-Owego, Litton, OECO, Rockwell and Unisys were the manufacturing participants in the study. This report describes the performance and results of the study program. It also makes recommendations and provides guidance for the application of these results.

2.0 OBJECTIVES

The primary objective is to establish a rational method by which an effective random vibration screen may be developed efficiently and quantitatively. A secondary objective is to incorporate the method into the Navy Manufacturing Screening Program document, NAVMAT P-9492, for general usage.

3.0 STUDY STRUCTURE

The essence of the study is the establishment of the Flaw Precipitation Threshold (FPT) by measurement of the vibration response at known flaw locations during normal screening. The flowchart of this approach is shown in Figure 1.

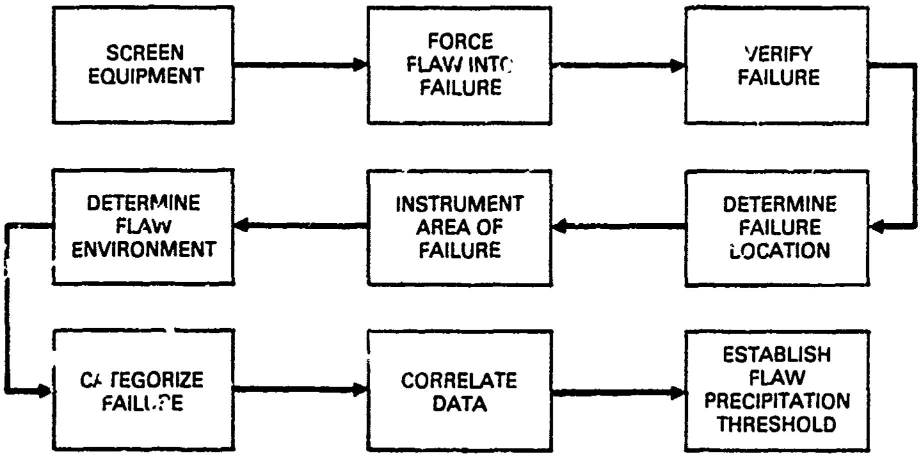


Figure 1. Basic approach flow chart.

For the study results to be universal in application, it was necessary that the measurements be made on a variety of modern electronic or electro-mechanical equipment manufactured by several different manufacturers. From an initial list of 18 manufacturers with ongoing vibration screens, five manufacturers were selected to participate with Hughes in the study. The number of participants was limited to five to stay within the program budget. The five participants were selected on the basis of diversity of screens and equipment. The activities undertaken by the manufacturers are charted in Figure 2. Two situations are depicted. In the top lefthand block, the manufacturer already possessed a data bank of failure data which was sufficiently complete to permit almost immediate selection of vibration measurement locations. (It should be noted that detailed failure location data is seldom of significance for customary monitoring of screens.) The top righthand block illustrates the situation where failure data were gathered during ongoing screens until sufficient data to select measurement locations were accumulated. In general, the final list of measurement locations was selected from a combination of the two data sources.

Once sufficient measurement locations were identified for an equipment, a representative unit was removed from the production line and instrumented with accelerometers at each identified location. The equipment was then subjected to the normal vibration screen, i.e., same exciter, fixture, control accelerometer locations, input spectrum, etc., and the response accelerometer outputs recorded on magnetic tape.

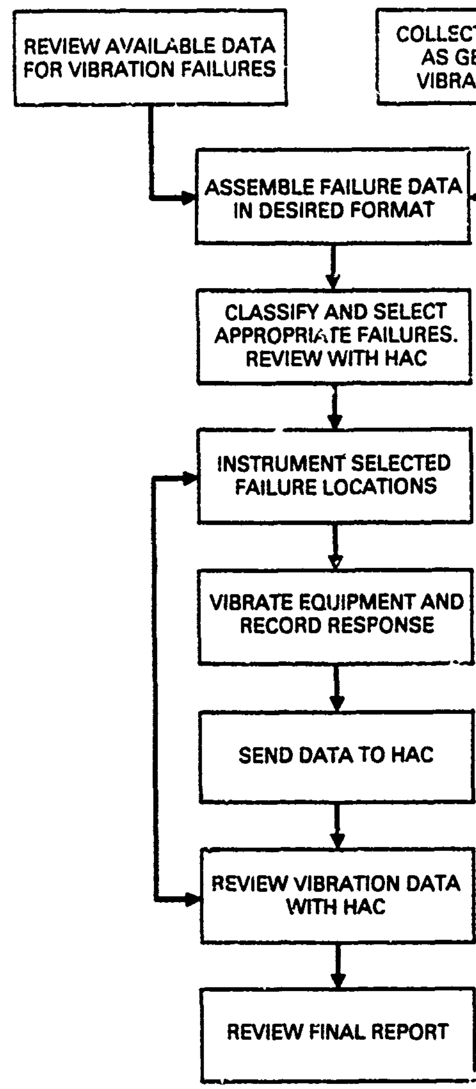


Figure 2. Manufacturer's activities.

The vibration data recorded by each manufacturer were forwarded to Hughes for detailed spectral analysis. It was considered important that spectral analysis of all data be performed using common analysis parameters such as bandwidth, degrees-of-freedom, etc., thus mandating analysis of all data by Hughes. The analyzed data were then evaluated to determine the FPT.

4.0 DATA BASE

Participating manufacturers were selected to obtain vibration response data that is sufficiently diverse so the study results will be universal in nature. Diversity was sought in the following areas:

- Manufacturers—Different techniques and processes.
- Type Equipment—Radio, computer, power supply, etc.
- Deployment—Airborne, shipboard, and ground mobile. Space hardware does not have sufficient production rate to qualify for this program.
- Type Vibration—Broadband random, quasi-random, swept sinusoidal, multiaxis, etc.

Table 1 summarizes the diversity in the last three areas. The equipment was manufactured by five different firms thus giving diversity in the manufacturing area.

TABLE 1. VIBRATION DATA BASE

Equipment	Deployment	Size and Weight	Screen	Number of Measurement Locations	Number of Sum-ASDs
Digital Computer Power Supply	Missile	6 × 12 × 6 17 lb	Controlled Spectrum Random, 10 to 2 kHz, 5.8 grms, 10 min/axis sequentially.	9	16
Avionics Control Unit	Airborne	8 × 10 × 20 57 lb	Controlled Spectrum Random, 10 to 2 kHz, 6.0 grms, 15 min normal to cards.	8	8
Digital Computer	Airborne	8 × 13 × 16 41 lb	Controlled Spectrum Random, 10 to 2 kHz, 4.0 grms, 5 min/axis sequentially.	6	9
Power Supply	Shipboard	4.5 × 6 × 15 24 lb	NAVMAT P-9492, 10 min, 1 axis	21	21
Inertial Navigation System	Airborne	8 × 12 ×15 35 lb	NAVMAT P-9492, 3 axes sequentially, 5 min/axis.	13	21
Transceiver	Airborne	4.7 × 5 × 8.4 7 lb	Quasi-random, Triaxial Input, 30 min, 16 to 2 kHz, 6.4 grms composite.	18	18
Control/Display Unit	Airborne	7.1 × 5.7 × 6.5 10 lb	NAVMAT P-9492, dual axis exciter, 5 min X-Y axes and 5 min Y-Z axes, Y axis normal to cards.	5	10
Fiber Optics/ Electronic Boxes (2 Units)	Ground Mobile	17 × 12 × 7.7 35 & 37 lb	MIL-STD 781 C, Figure 2, 20 to 2 kHz, 6.33 grms, 10 minutes, normal to cards.	12 12	12 12
Totals				104	127

The last two columns in Table 1 show the spread of response measurement locations and Sum-ASDs among the pieces of equipment. The Sum-ASD is the basic vibration function used to derive the Flaw Precipitation Threshold and is developed in Section 5.0. It is evident from these columns that measurement locations and Sum-ASDs were well spread among the various equipment. If the equipment was sequentially screened in multiple axes prior to a flaw precipitating, multiple Sum-ASDs were derived for that specific location. For example, a "three axes sequentially" screen, which precipitates a flaw during the second axis, dictates two Sum-ASDs. Table 2 shows how the number of Sum-ASDs was arrived at for the sequential axis screens.

TABLE 2. FLAW MATRIX/SEQUENTIAL AXES SCREENS

		Flaw Precipitated				
Equipment	**Screening Axes**	**No. of Meas't. Locations**	**1st Axis**	**2nd Axis**	**3rd Axis**	**Sum ASDs**
Digital Computer/ Power Supply	3, Sequence not mandated.	9	5	1	3	16
Digital Computer	3, Sequence not mandated.	6	4	1	1	9
Inertial Navigation System	3, Sequence not mandated.	13	8	2	3	21
Control/Display Unit	X-Y axes and Y-Z axes	5	Data were not available to ascertain when flaws precipitated. Therefore Sum-ASDs were derived for each dual-axis excitation.			10

Failure data received from participating manufacturers were catalogued in a format to enable selection (or rejection) of any failure for vibration measurement. The information used to make such a selection was:

- Is the failure type appropriate to a screen? i.e., workmanship or part, not design.
- If so, which of a few general failure types can be used to describe it? For example, bad component, poor wiring, loose hardware, etc.
- Is the failure location accessible for vibration measurement?
- Even though observed in a subsequent functional test, is it a reasonable judgment that the flaw was precipitated by vibration?
- What was the stress-history of the equipment prior to failure detection? i.e., prior screens, etc.

The selection decisions were jointly made with the manufacturers, generally after several correspondences, telecons and direct meetings.

The study was designed to select the measurement locations from a data base composed of raw manufacturing failure data accumulated during manufacturer's past and ongoing screens. No detailed failure analysis was planned. These failures would then be assigned to a few broad categories and the vibration response data evaluated to determine if the categories dictated different FPTs. Also, it was felt that a body of measurements overwhelmed by a particular failure type could be biased. For the aforementioned reasons, a concerted effort was made to ensure that the total population of selected failures was as diversified as possible by failure types. The diversification was inhibited by the limited body of qualified failures from the manufacturers, a problem which was not anticipated in the design of the study. Only 14 of the qualified failures in the data base had been categorized as other than component. These were all used in the study, as shown in Table 3. However, it is believed that many of the remaining 90 failures which had been categorized as "component" failures would have been categorized differently if detailed failure analysis had been performed. Without detailed failure analysis, a component is designated the culprit when it is replaced as a result of a failure detection. In all likelihood, many of these failures are caused by damage during assembly or improper assembly.

TABLE 3. DATA BASE BY FAILURE CATEGORY

Failure Category	Number of Failures
Component	90*
Mechanical Assembly	7
Mechanical Breakage	5
Wiring/PC Board	1
Wiring/Interconnect	1
	104

*Failure classifications taken from raw data. "Component" failures probably include many categories.

5.0 DATA PROCESSING

Previous sections have described the vibration data base available to the study. The data were delivered to Hughes by the participating manufacturers as FM–FM recordings of the analog accelerometer signals together with appropriate data logs to identify failure location, accelerometer sensitivity, etc. The measurements defined the vibration in each of three orthogonal directions at each failure location. After usual checks to verify data quality, etc., the acceleration spectral density (ASD) of each signal was obtained, using a 10 percent constant percentage bandwidth analyzer and a minimum of 35 seconds averaging time. The ASD was obtained for the frequency range from 20 to 2783 Hz although tape recorder frequency response was good only to approximately 2.5 kHz. However, data evaluation was confined to 2 kHz. The resultant ASD was stored in digital form so that desired arithmetic operations could be performed on individual or groups of ASDs. Most usefully for this study, it was possible to compute the average, the envelope and the standard deviation of selected groups of ASDs. Further, the rms acceleration within selectable frequency ranges could be obtained by integration of the ASD within those ranges. After initial evaluation of the data, it was decided that the vibration function to be used to derive the Flaw Precipitation Threshold would be dubbed the Sum-ASD. The Sum-ASD was simply the arithmetic sum of the ASDs for each of three orthogonal axes at a specific location. No consideration of coherence, phase relationships, etc., was attempted.

Sum-ASDs were derived for each unique excitation at each failure location, yielding a total of 127 Sum-ASDs. Of these, 99 were measured during single-axis excitation, 10 during dual-axis excitation and 18 during quasi-random three-axis excitation. Where a failure was identified after a screen which consisted of sequential excitations in different directions, a Sum-ASD for each excitation was created for inclusion in the pool and was treated as a single-axis ASD. The Sum-ASDs were tagged so that the groups of Sum-ASDs for single-axis, two-axis and three-axis excitations could be readily formed. As explained later, two trial sets, known simply as Set I and Set II, were created by randomly selecting, for each set, 20 Sum-ASDs from the 99 single-axis Sum-ASDs.

6.0 DATA EVALUATION

As shown in Table 1, approximately 80 percent of the measurements were responses to single-axis excitation. Of course, there is some unknown cross-axis excitation during any vibration excitation but hopefully this is relatively small except in a few narrow bands at high frequencies. However, even with essentially single-axis excitation, significant cross-axis responses may be expected for complex asymmetric structures. When multi-axis excitation is employed one would expect multi-axis responses. It was necessary to adopt a relatively simple function to describe the vibration at a failure location which took account of the triaxial nature of the responses. Based on examination of the measured spectra, this turned out to be merely the sum of the three ASDs at that point. Typical data are shown in Figures 3 through 7. Each figure contains four spectra, which are the individual spectra for the three orthogonal directions and their sum, which is referred to as the "Sum-ASD". Figures 3 and 4 are from single-axis excitation while Figures 5 and 6 are from two-axis excitation and Figure 7 is from a triaxial quasi-random excitation. Figure 3 exhibits some significant cross-axis responses in the 100–300 Hz range. However, Figure 4 must be viewed as essentially uniaxial response dominated by a single resonant peak at about 300 Hz. Figure 5 for two-axis excitation shows one axis to be generally dominant although the second axis response is very evident. However, in Figure 6, the resonant response between 350–400 Hz is essentially uniaxial. Figure 7 presents three very "peaky" spectra expected from early quasi-random exciters.

While more complex methods of accounting for the triaxial nature of the responses could be contemplated, it was concluded that a simple sum would suffice for the purpose at hand.

The data processing described in the previous section yielded a total of 127 Sum-ASDs, i.e., the function selected to describe the vibration level which precipitated a flaw. Initial evaluation was performed to examine if the Sum-ASDs could be treated as a single population or if there were identifiable differences between the responses to the three types of excitation. Since the two and three axis data each represent a single screen, i.e., a single equipment, one cannot ascribe differences too authoritatively to the differences of excitation. Rather, one must examine whether it is plausible that the three groups can be considered subgroups of a single population. Figure 8 shows the mean Sum-ASD for each group while Figure 9 shows the mean Sum-ASDs for single-axis excitation and for all excitations as a single group.

Considerable variation in responses within each group were observed as shown in Figures 10 and 11. Figure 10 is a plot of the envelope of the Sum-ASDs for each type of excitation which may be compared to the mean values of Figure 8, while Figure 11 is a measure of the variability within each group, i.e., the ratio of the standard deviation to the mean value at each frequency. It is interesting that while the mean Sum-ASDs for the two-axis and three-axis groups are generally higher than and lower than the single-axis group, respectively, the envelopes of the two-axis and three-axis groups are comparable, though both lower than the single-axis envelope. Of course, envelopes can only increase as data samples are added. The smaller variabilities for two and three axis excitations in Figure 11 must be due to the single test items of these groups.

Based on the preceding data, it was concluded that it was acceptable to include the data from the two and three axis excitations within the single axis data to form a single group, when appropriate.

Although the main thrust of the study is directed toward responses, it is interesting to compare the mean response, i.e., mean Sum-ASD, to the input spectrum of P-9492, since this was the most common input spectrum used to generate the measured responses (Reference Table 1). This is shown in Figure 12 and indicates that, on the average, amplification is of the order of 7 to 10 dB which is considered moderate [a Q of 10 is 20 dB]. It also indicates that responses above 1000 Hz decrease as much as 10 dB/octave.

As will be discussed later, a vital part of the process will be the performance of a vibration survey. To conduct a survey, i.e., to sample responses, one must select the number and location of measurement points. To derive an adequate yet reasonable number of measurements, two randomly chosen sets of 20 Sum-ASDs from the 99 single axis group were formed. The mean Sum-ASDs and the variability, σ/μ, of these sets were compared to the total group, as shown in Figures 13 and 14, from which it was concluded that 20 locations would suffice for a satisfactory survey.

From the data presented so far, it is clear that ASDs are not entirely satisfactory to describe the Flaw Precipitation Threshold. Therefore, for each Sum-ASD, the rms accelerations from 20 Hz up to the following cutoff frequencies were calculated: 100 Hz, 300 Hz, 500 Hz, 1 kHz, 1.5 kHz and 2 kHz. Histograms were then prepared to examine the probability of failure versus rms level for each cut-off frequency. The histograms for all failures are shown in Figures 15 through 20. It is evident that the failures most frequently occurred at rms levels equal to one third to one half of the maximum values. Integration of the histograms of Figures 15 through 20, and normalization to a precentage basis yield Figure 21 which can be viewed from two aspects. First, it depicts the grms level to a given cutoff frequency required to precipitate a given precentage of flaws. Second, since the vibration survey will make measurements at potential flaw locations, it depicts the desired statistics of the survey data points.

From Figure 21, the following is apparent. Approximately 50 percent of the failures were precipitated at grms levels about one third the maximum value and 90 percent were precipitated at about two thirds the maximum value. An alternative view is that a fairly significant reduction in level would allow very few escapes. The potential of this figure to define an adequate screen is discussed in the next section.

An alternate method of presentaion of these data is shown in Figure 22. Here grms is plotted versus cutoff frequency for the median (50th percentile) and 90th percentile of cumulative failures, i.e., slices through Figure 21. The third and middle curve on Figure 22 is the grms versus cutoff frequency for the mean Sum-ASD shown in Figure 9. Fortunately, the 90th and 50th percentile curves differ from the mean by very close to 3 dB in each direction across the frequency band. The same process used to develop Figure 22 was then applied to the two 20 sample randomly selected sets, to simulate the results of a vibration survey. The results for the two sets are shown in Figures 23 (mean) and 24 (50th and 90th percentiles). The adequacy of a 20 measurement survey is evident.

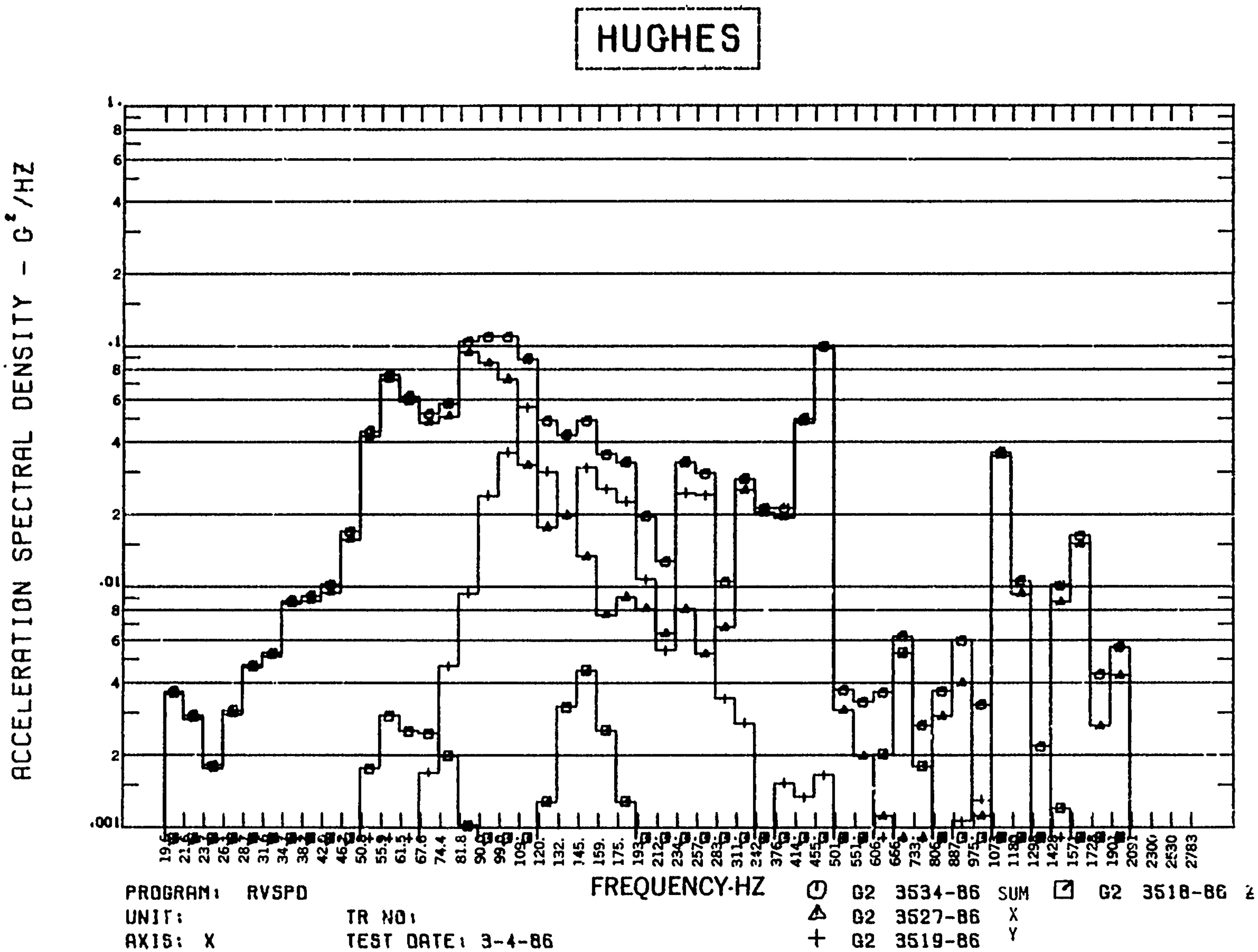


Figure 3. Typical response ASDs — single-axis excitation (X).

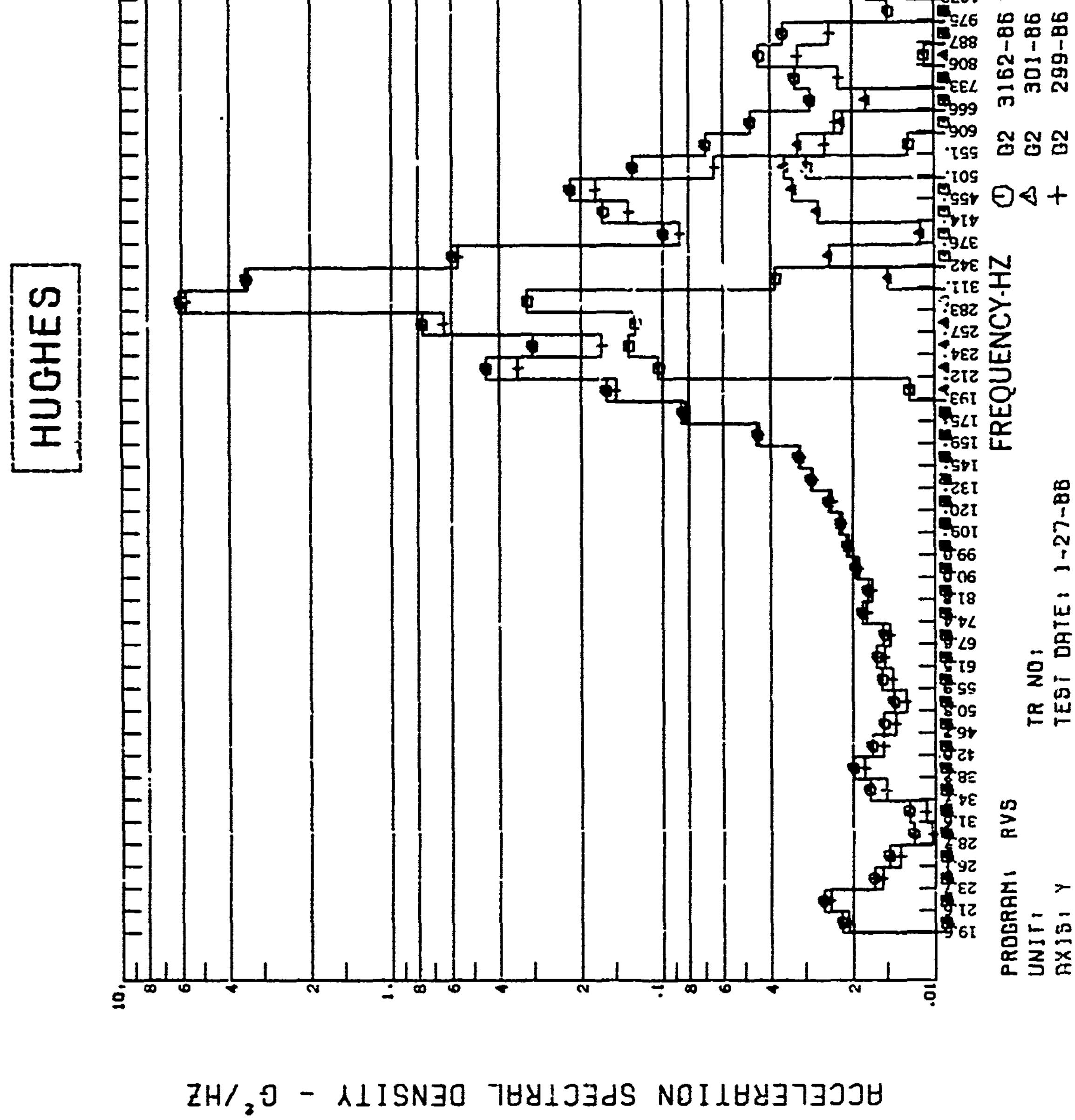


Figure 4. Typical response ASDs (M2) — single-axis excitation (Y).

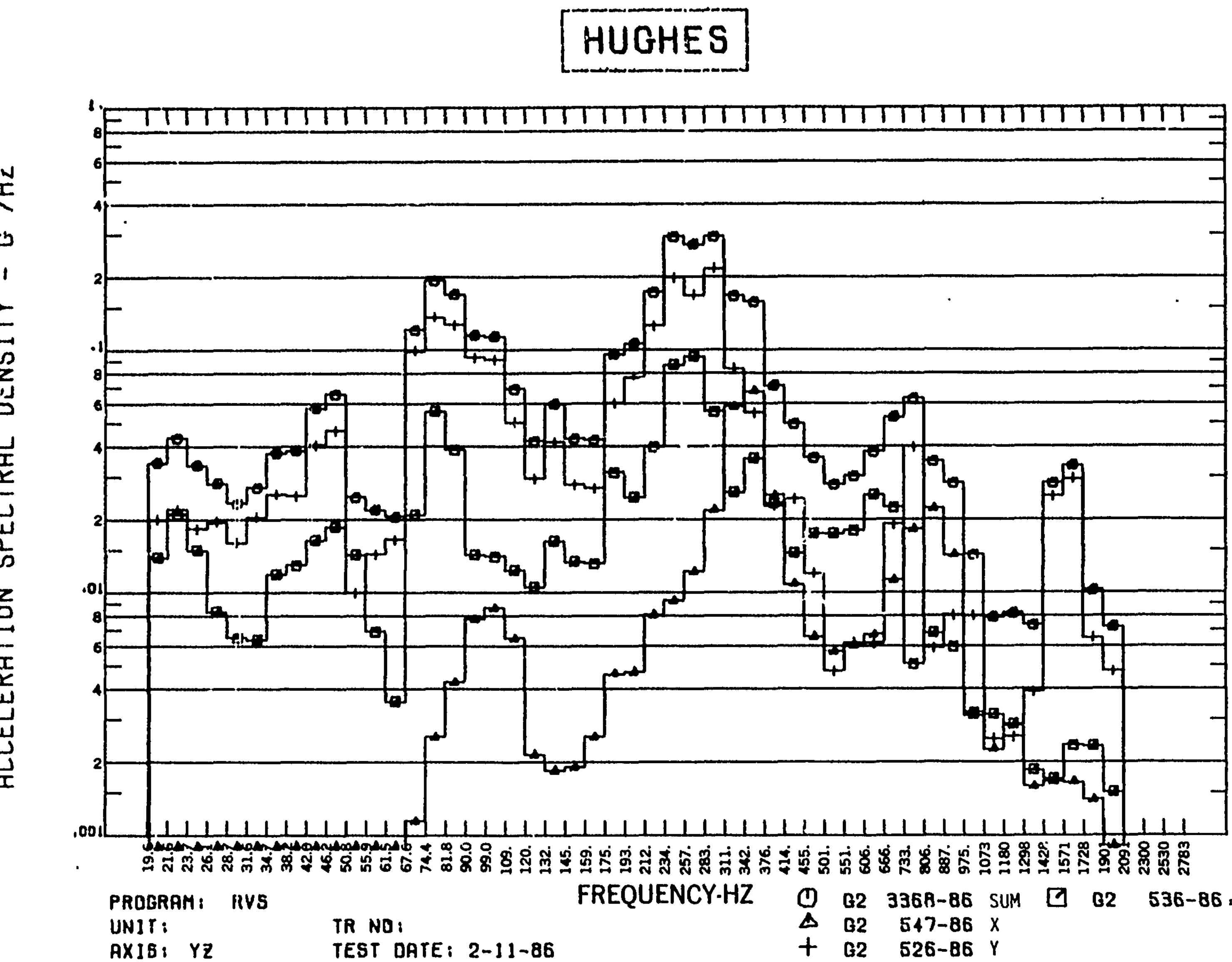


Figure 5. Typical response ASDs (M1) — two-axis excitation (YZ).

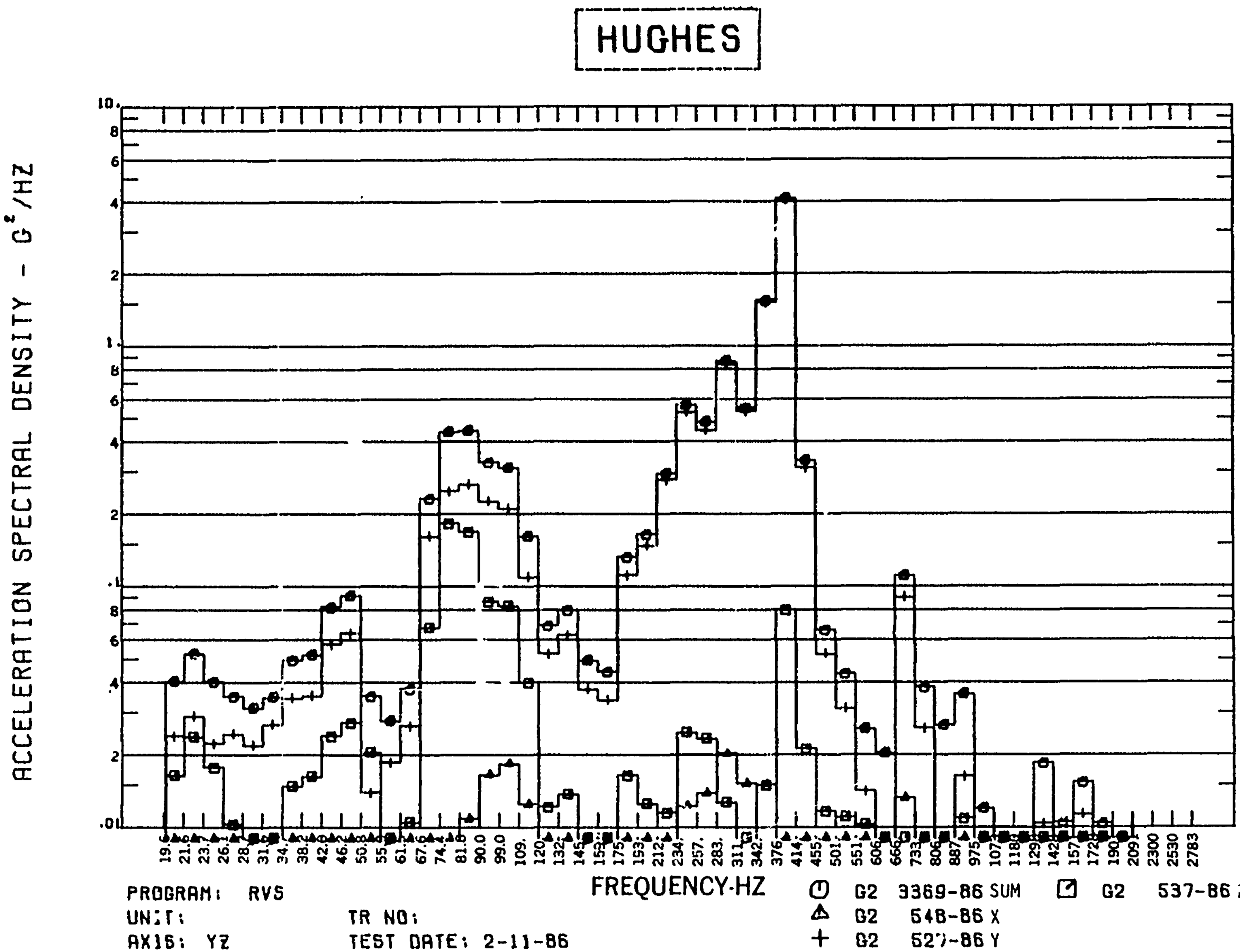


Figure 6 Typical response ASDs (M2) — two-axis excitation (YZ).

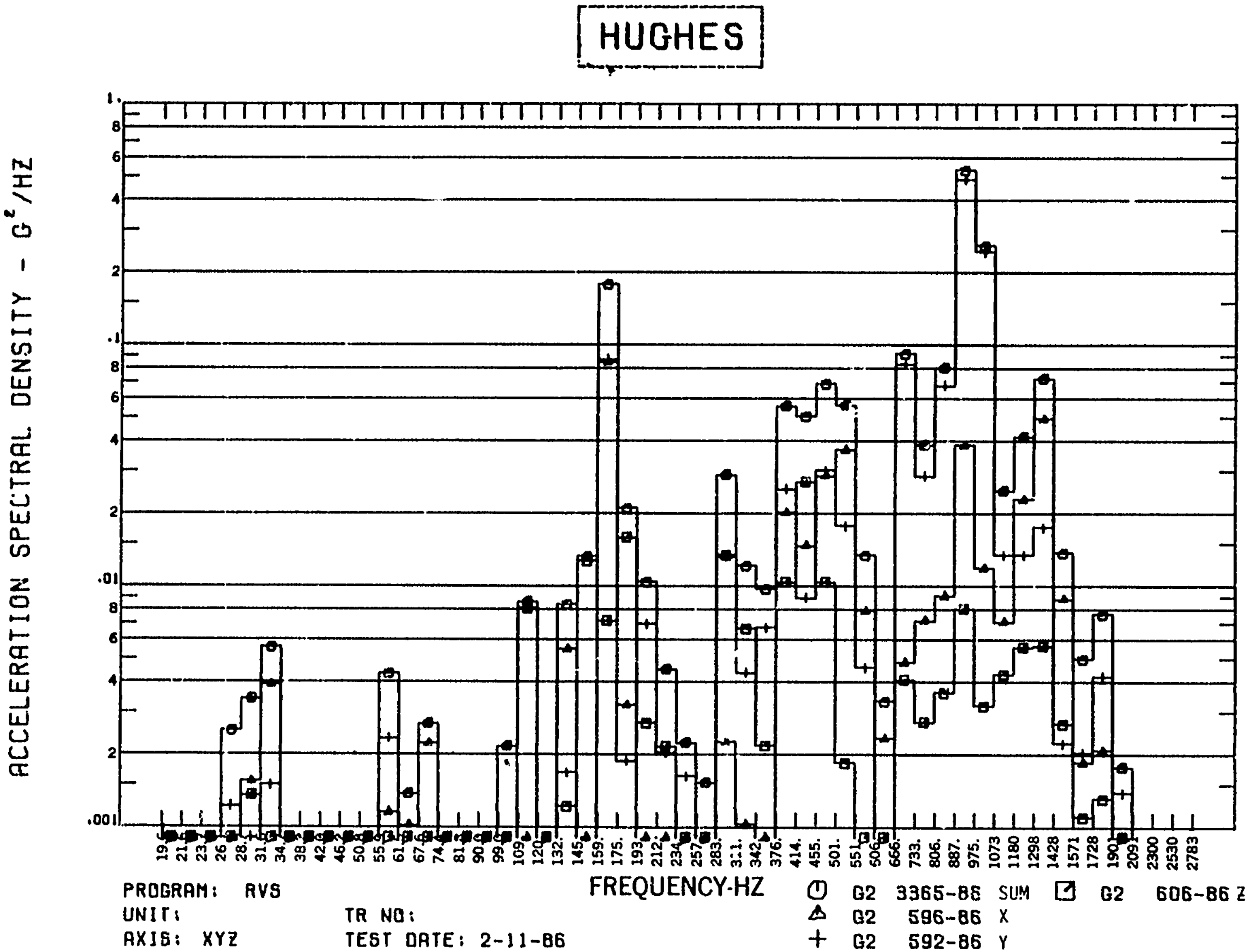


Figure 7. Typical response ASDs (M12) — three-axis quasi-random excitation.

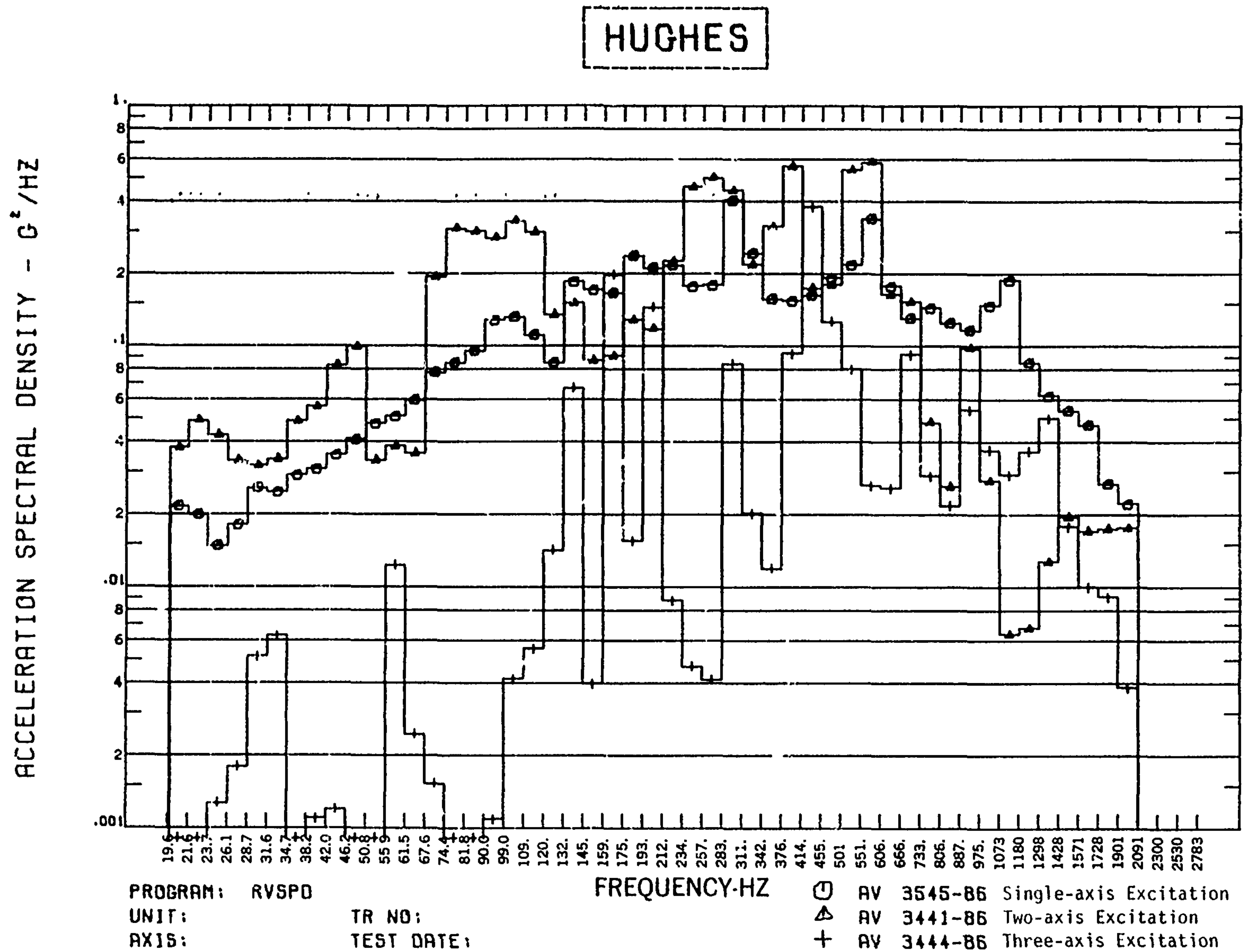


Figure 8. Mean Sum-ASDs — 1, 2 and 3 axis excitations.

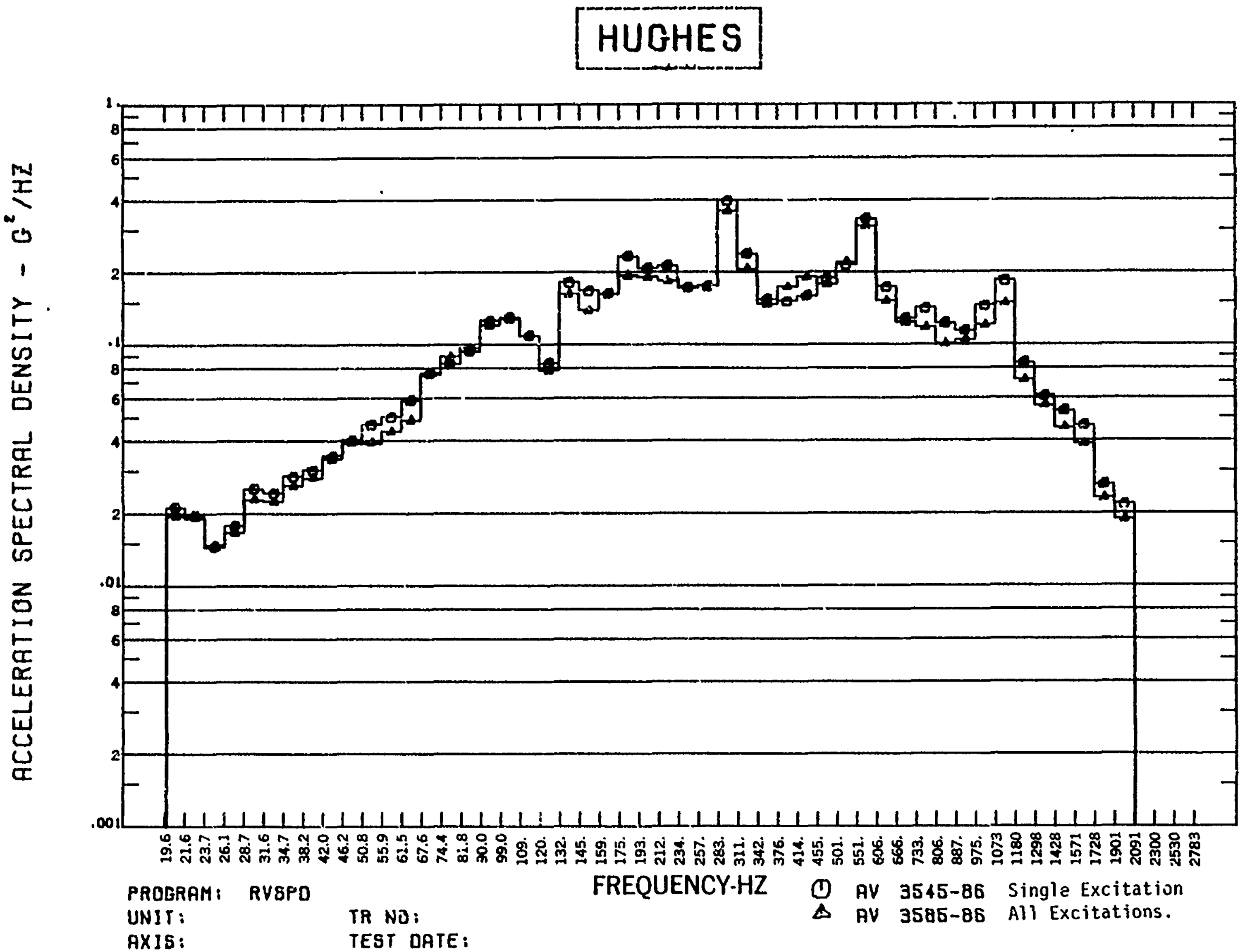


Figure 9. Mean Sum-ASDs — single-axis and all.

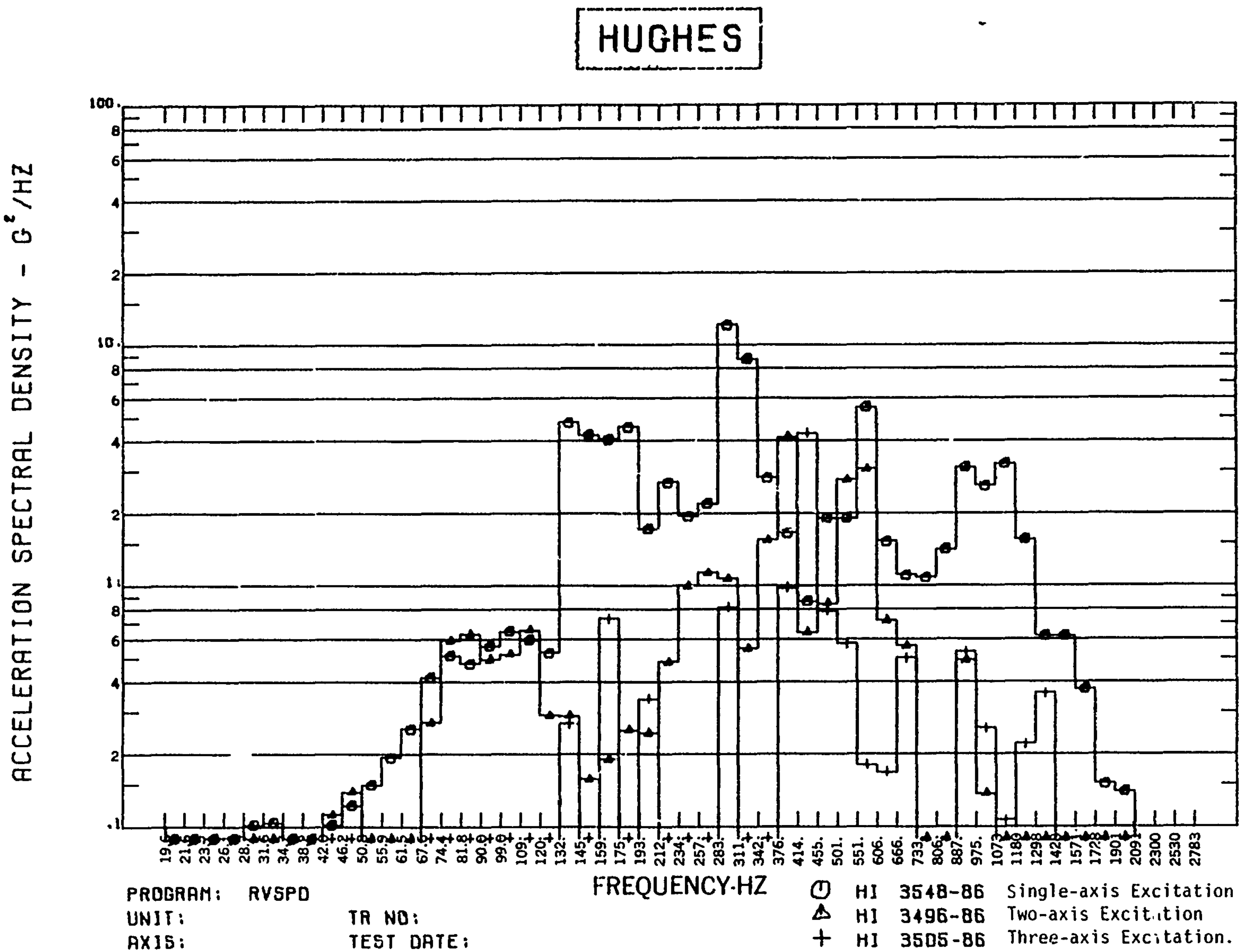


Figure 10. Envelop of Sum-ASDs — 1, 2 and 3 axis excitations.

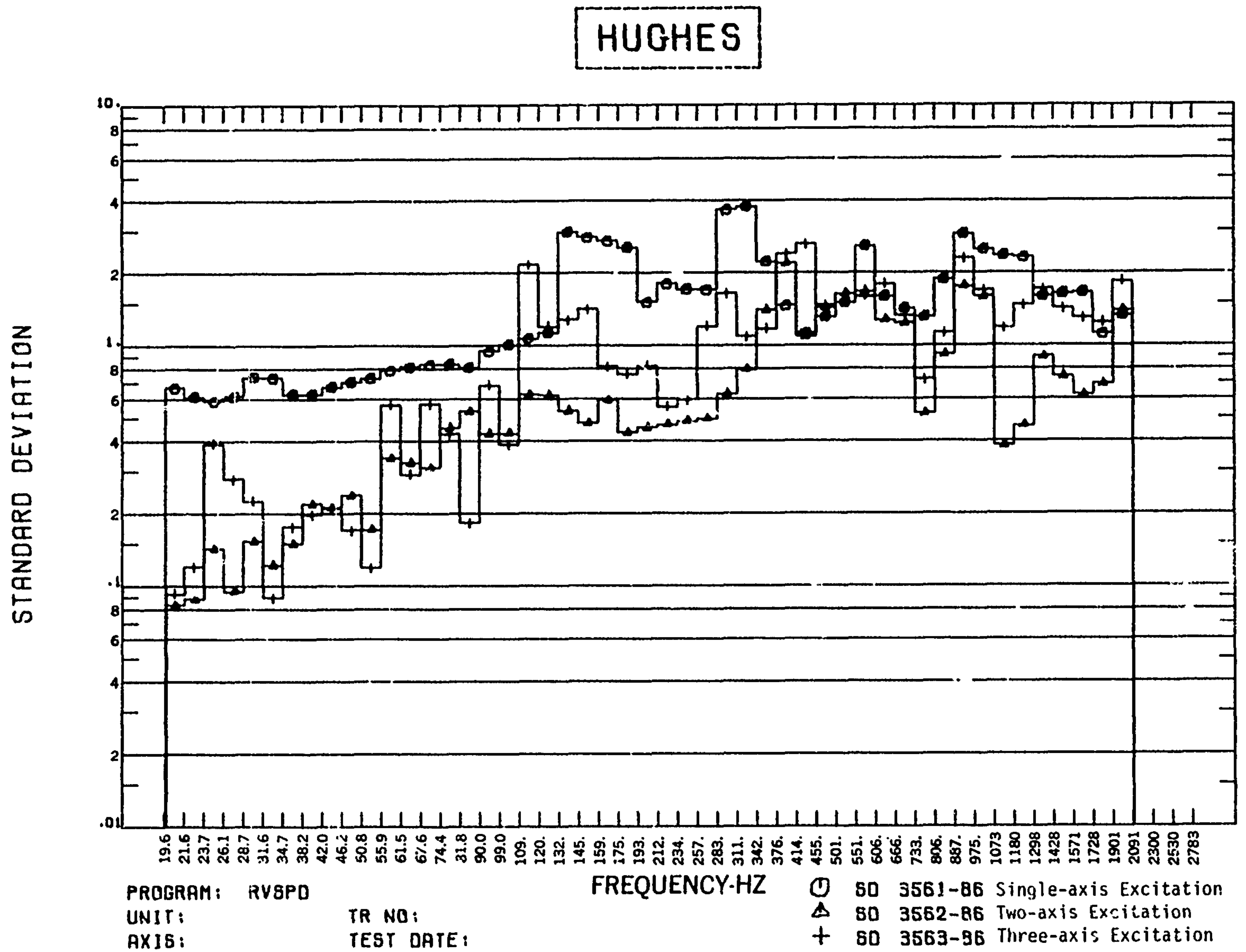


Figure 11. Variability (σ/μ) of Sum-ASDs — 1, 2, and 3 axis excitations.

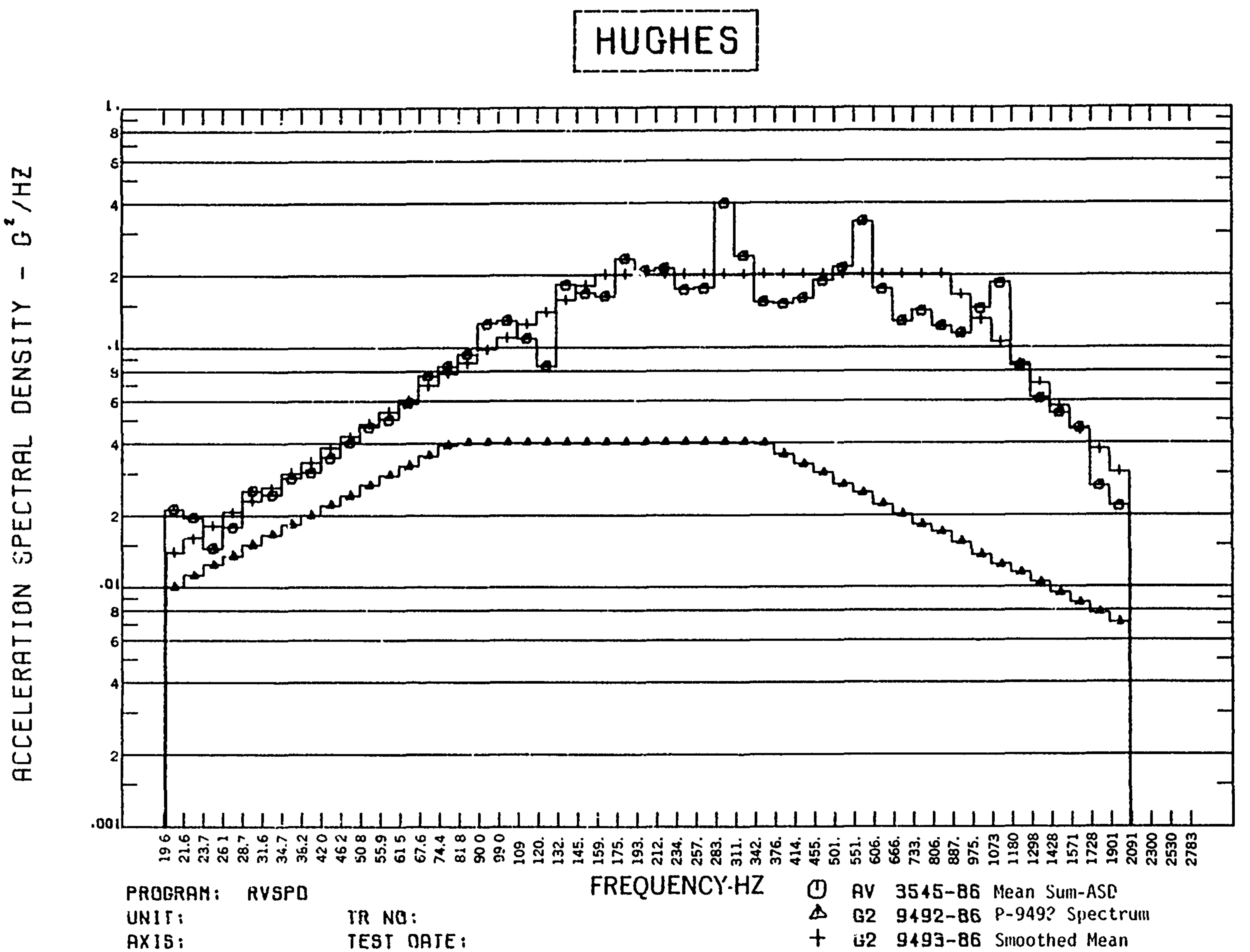


Figure 12 Mean Sum-ASD response vis-a vis P-9492 input.

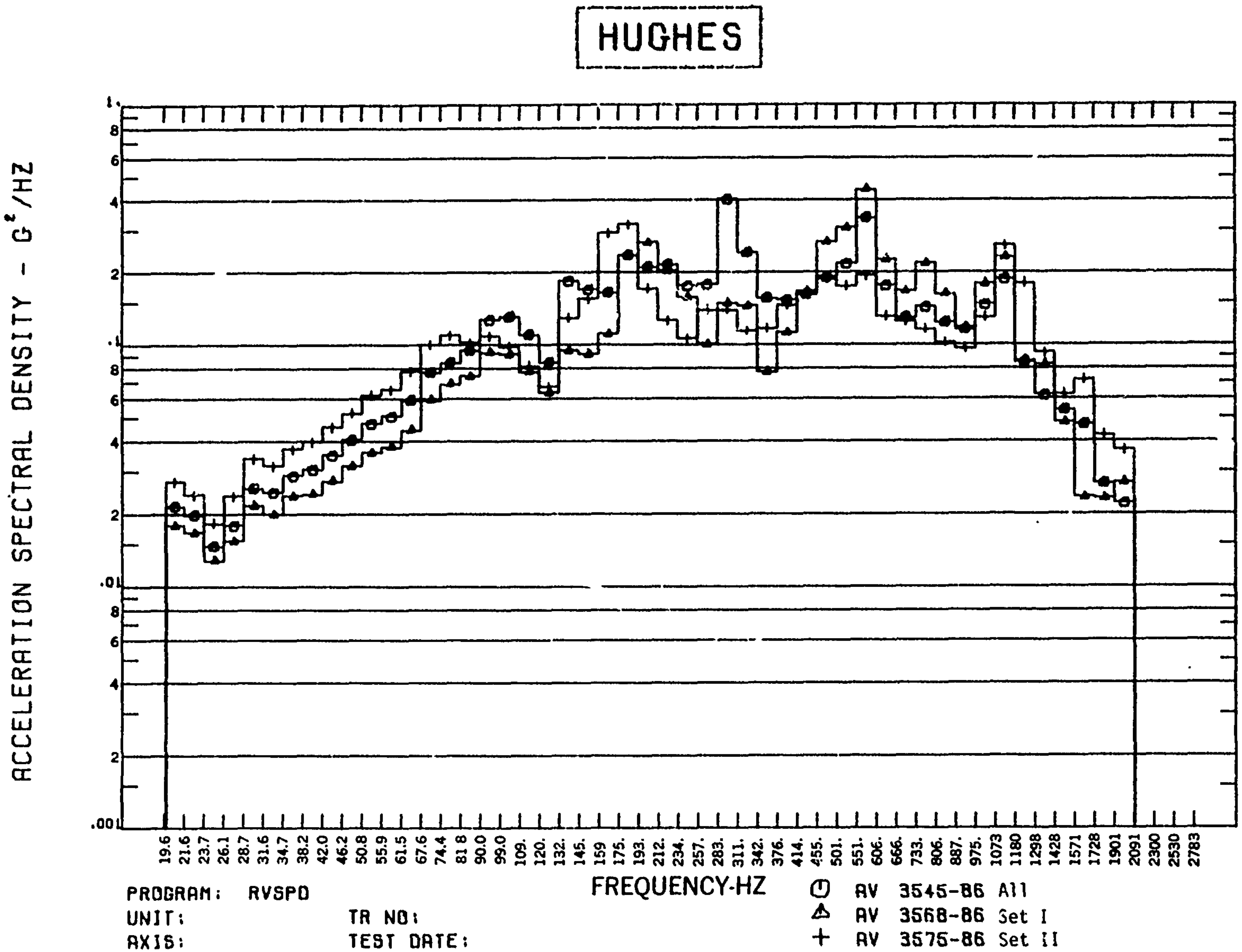


Figure 13. Mean Sum-ASDs single-axis excitation, All, sets I and II.

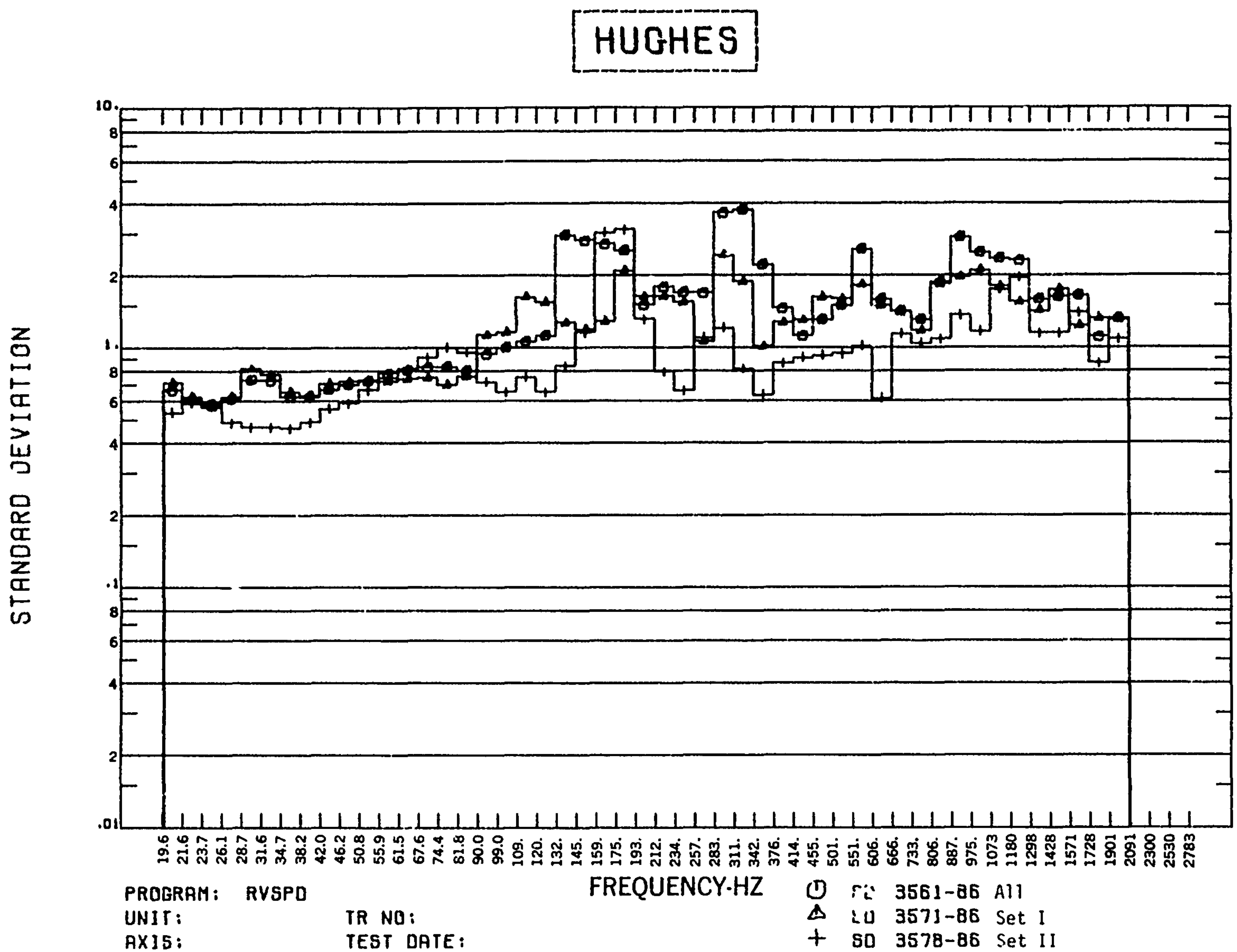


Figure 14. Variability (σ/μ) of Sum-ASDs — all, sets I and II.

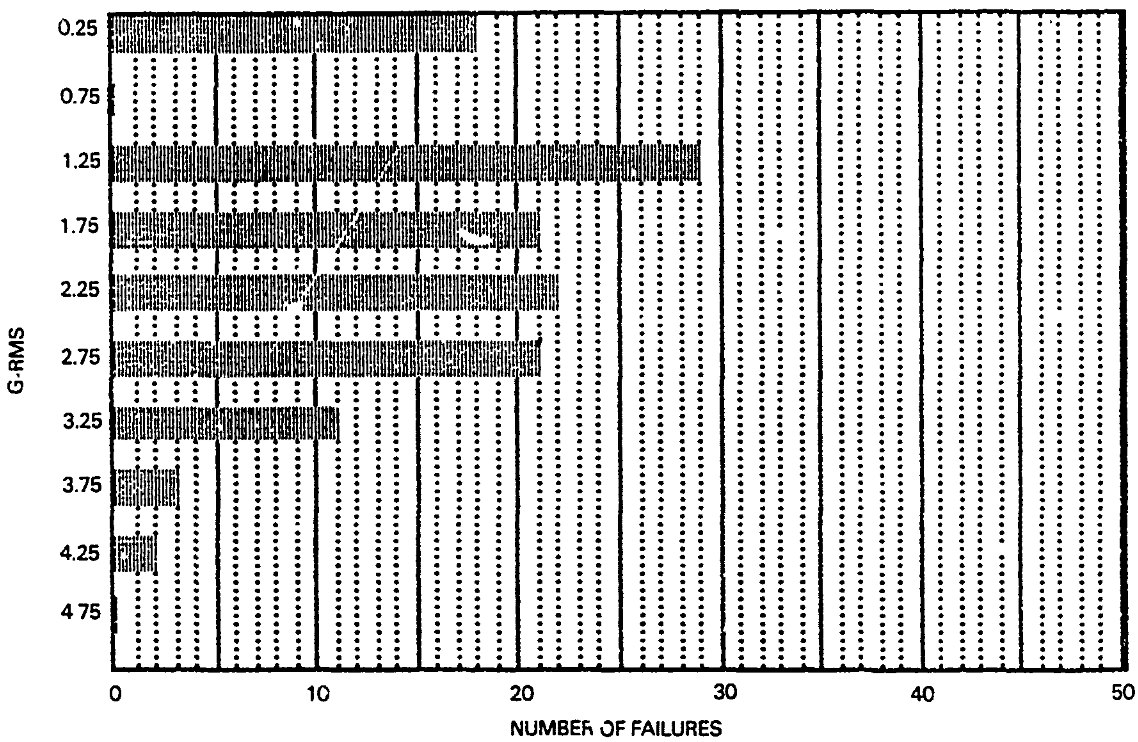


Figure 15. Distribution of failure levels, all failures, 20-100 Hz.

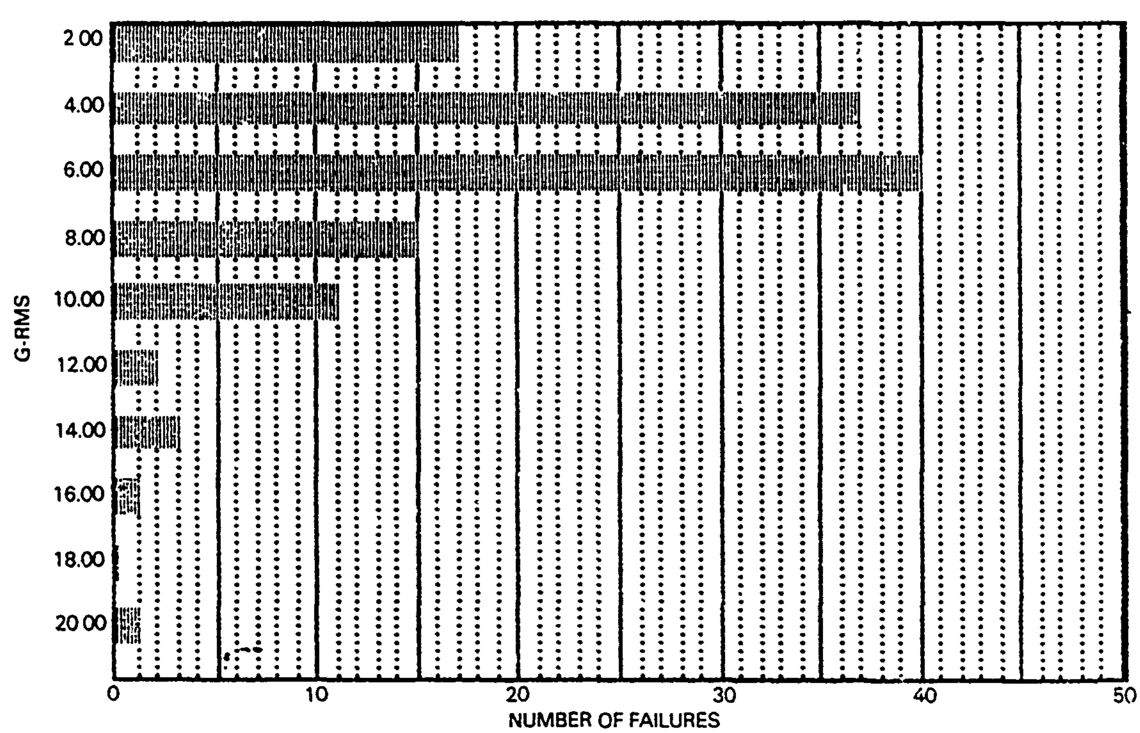


Figure 16. Distribution of failure levels, all failures, 20-300 Hz.

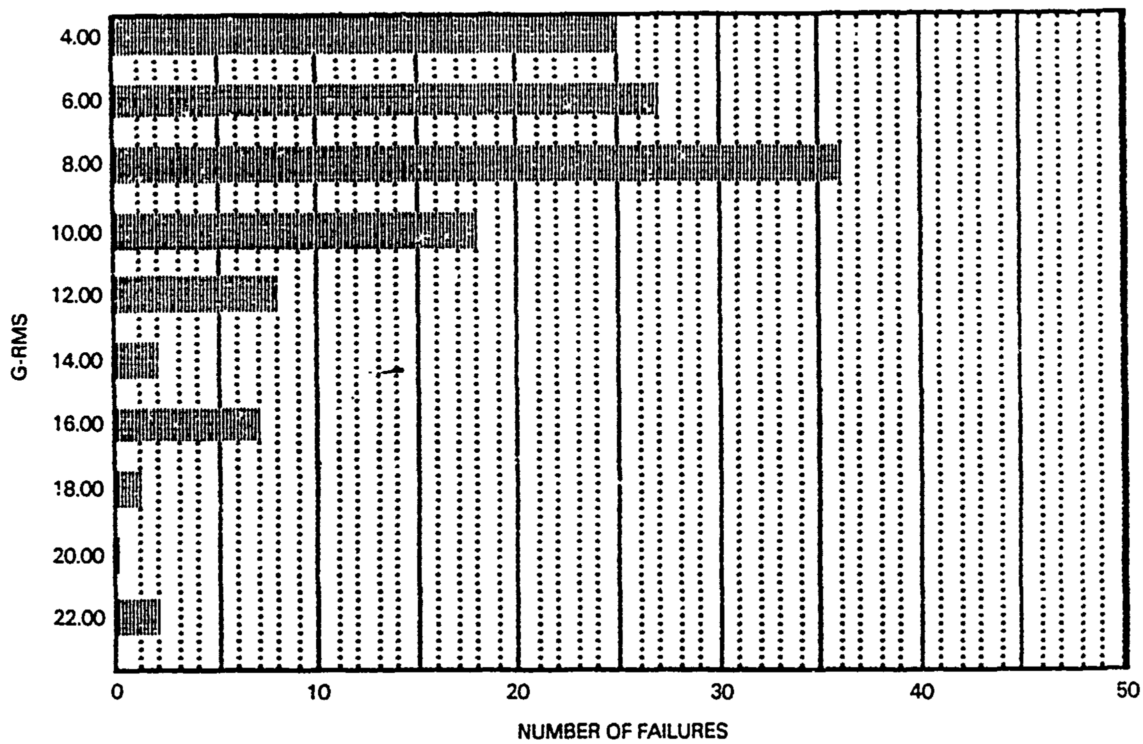


Figure 17. Distribution of failure levels, all failures, 20-500 Hz.

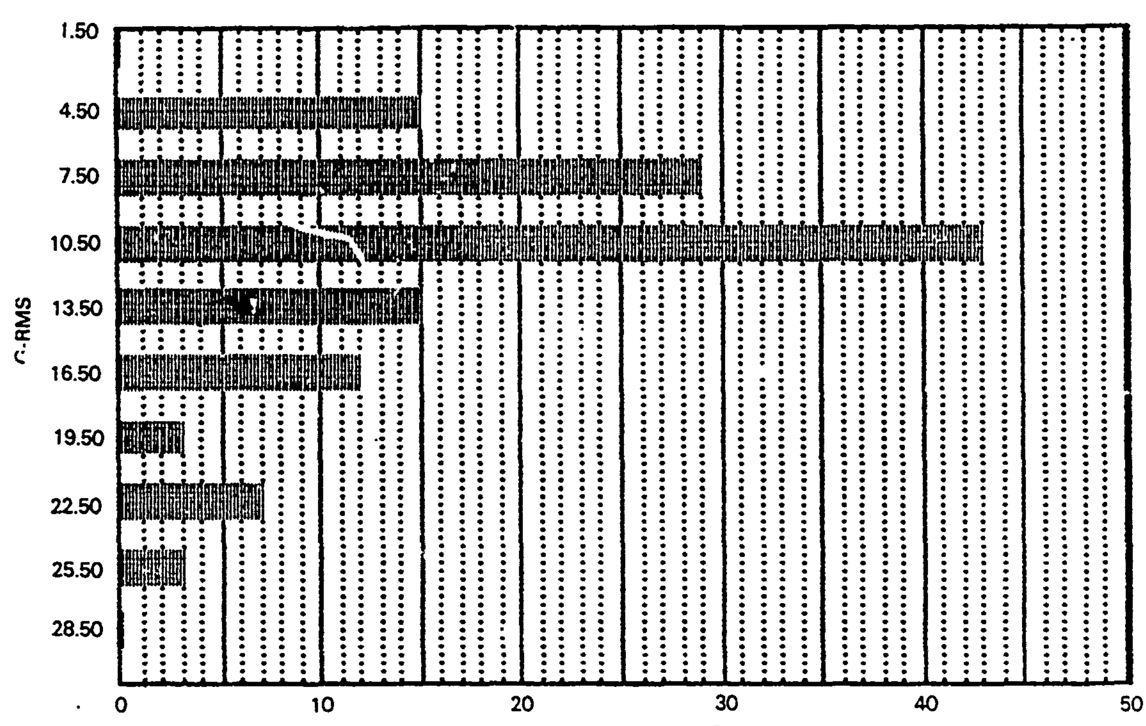


Figure 18. Distribution of failure levels, all failures, 20-1000 Hz.

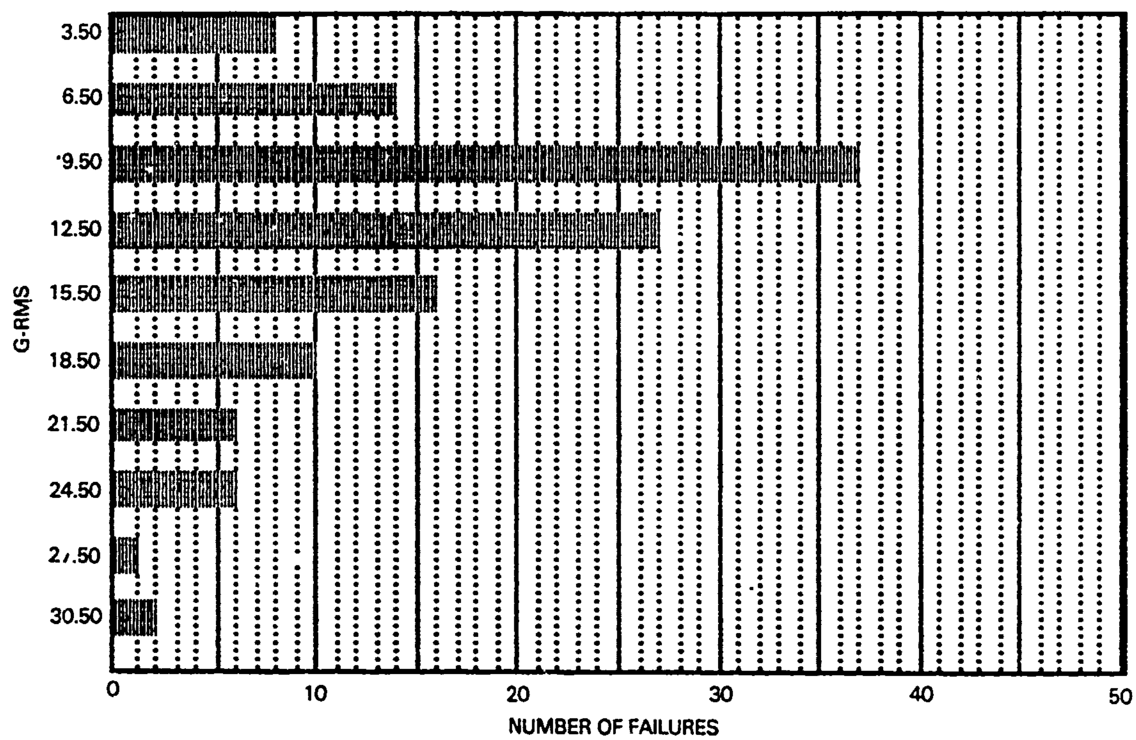


Figure 19. Distribution of failure levels, all failures, 20-1500 Hz.

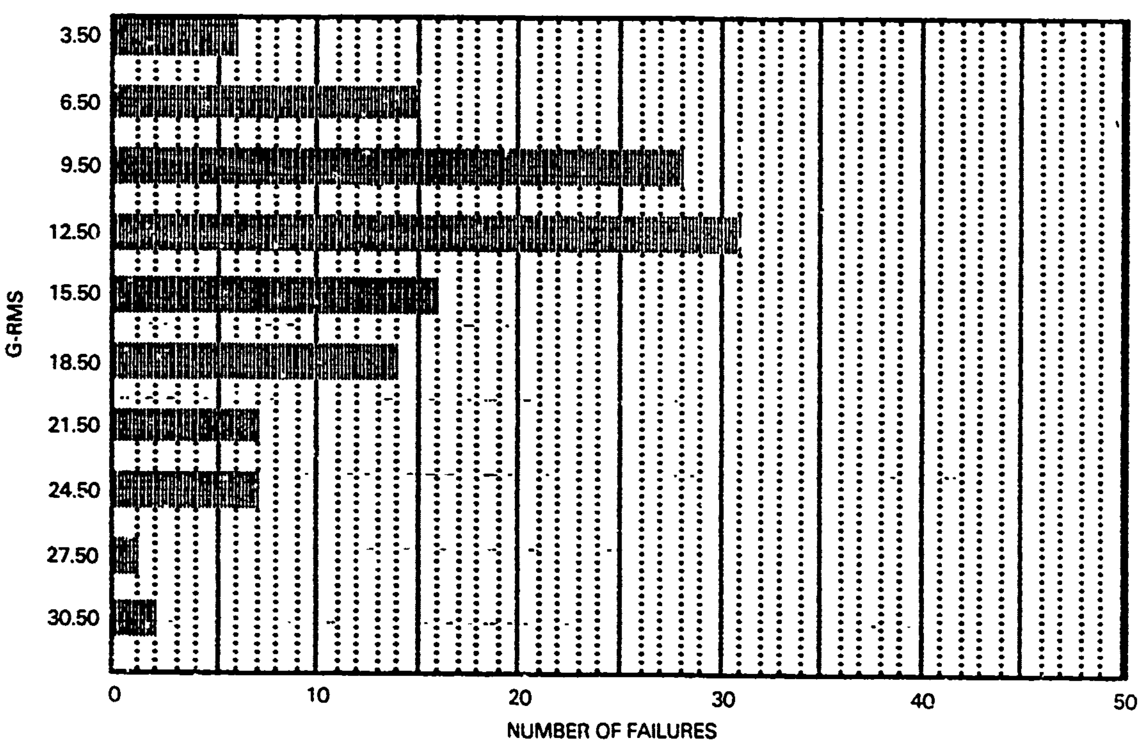


Figure 20. Distribution of failure levels, all failures, 20-2000 Hz.

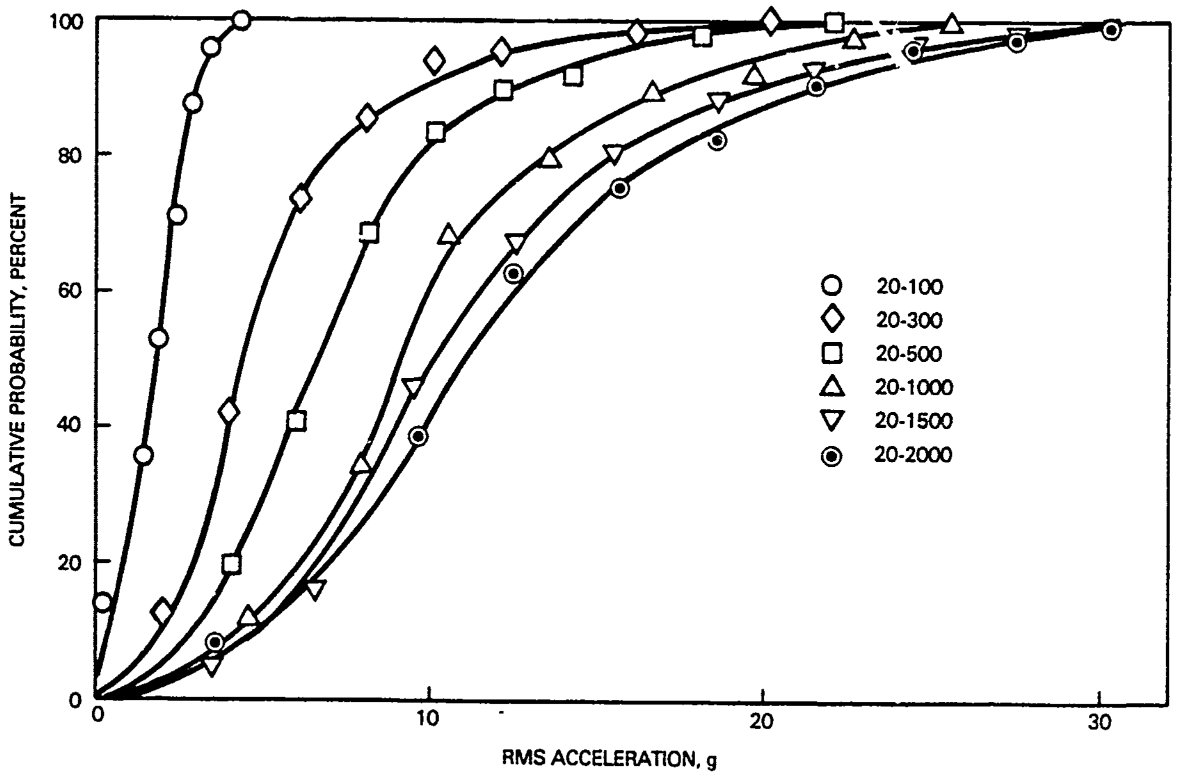


Figure 21. Cumulative failure probability vs RMS acceleration.

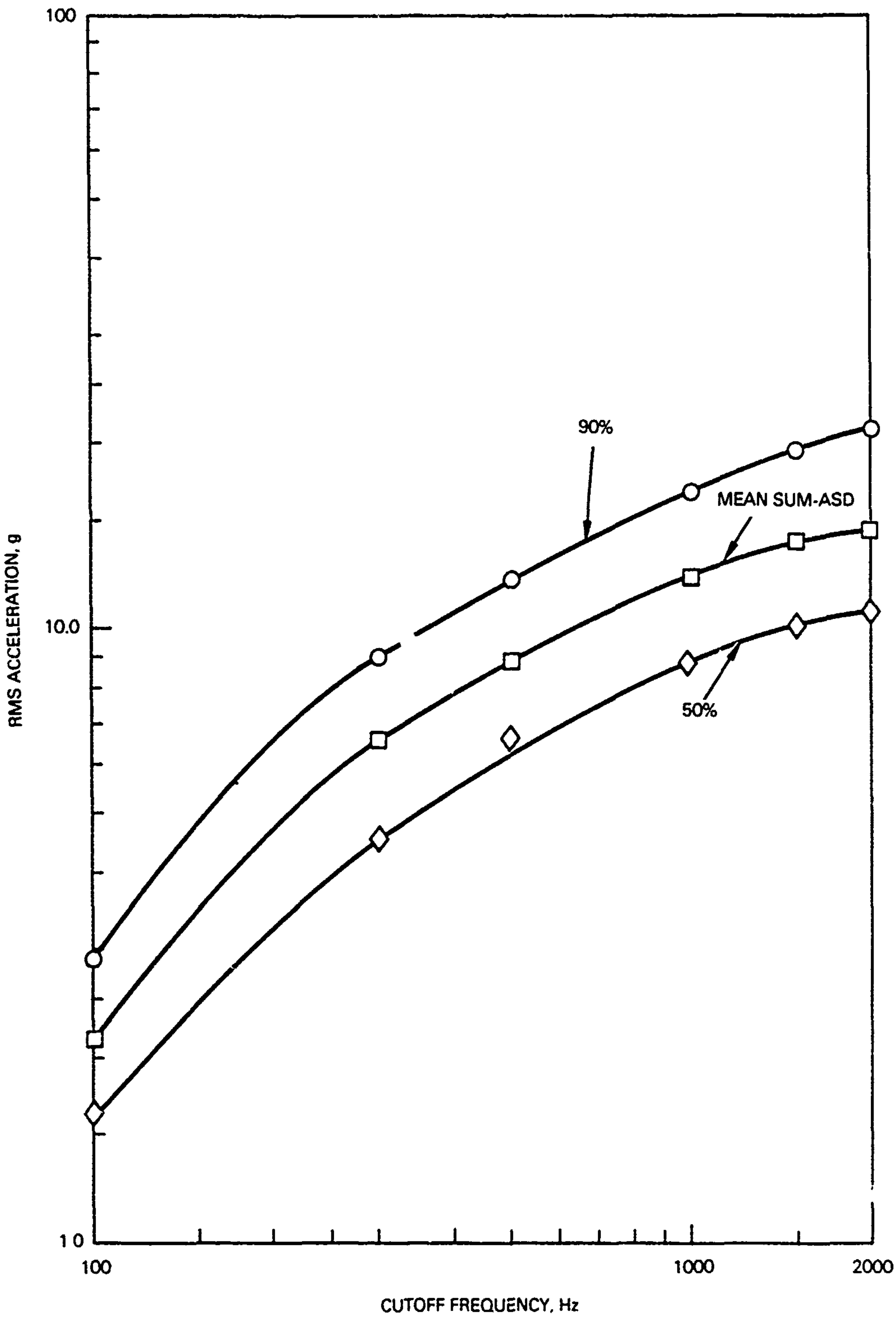


Figure 22. RMS acceleration vs frequency, all failures.

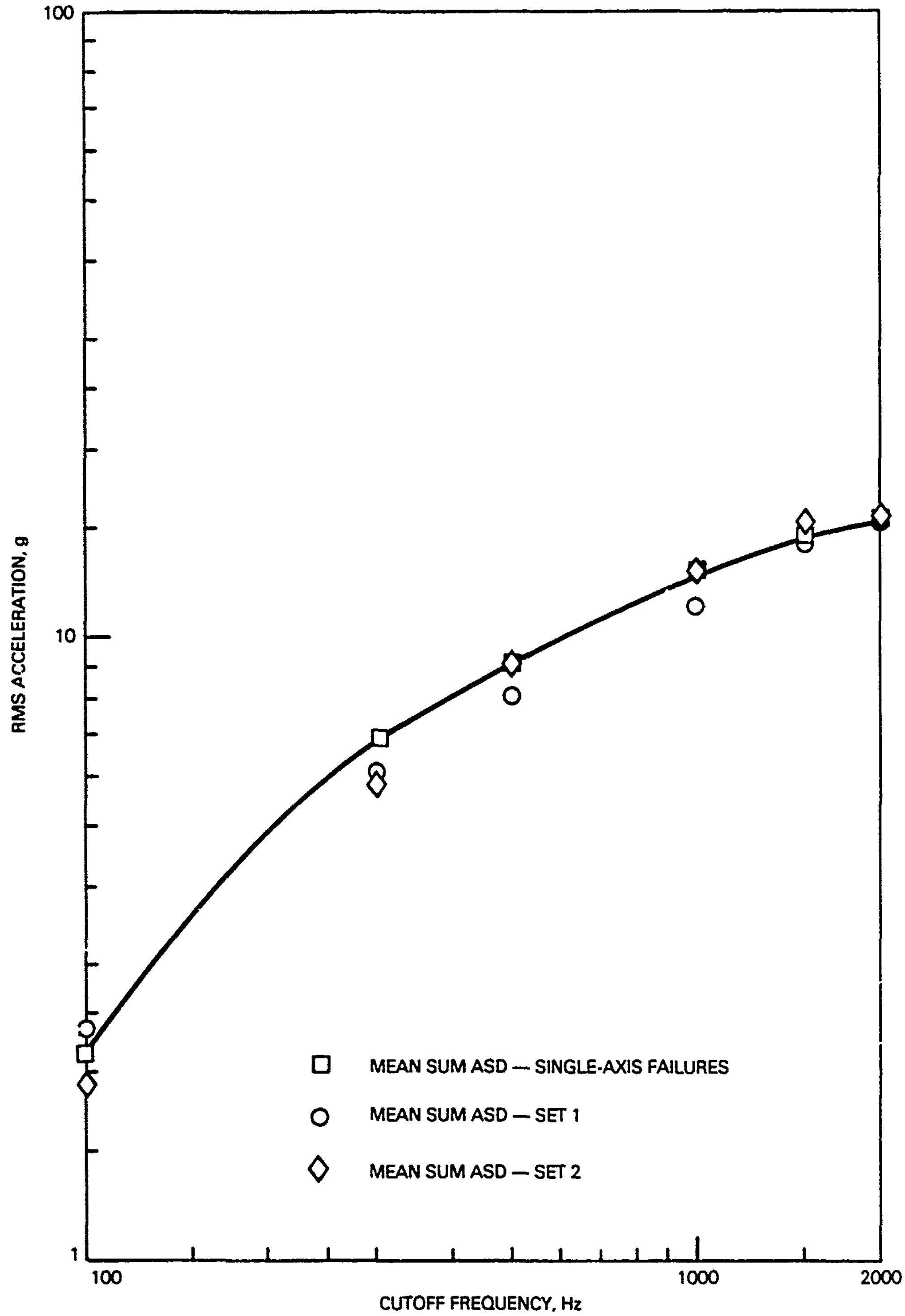


Figure 23. RMS acceleration vs frequency, set means.

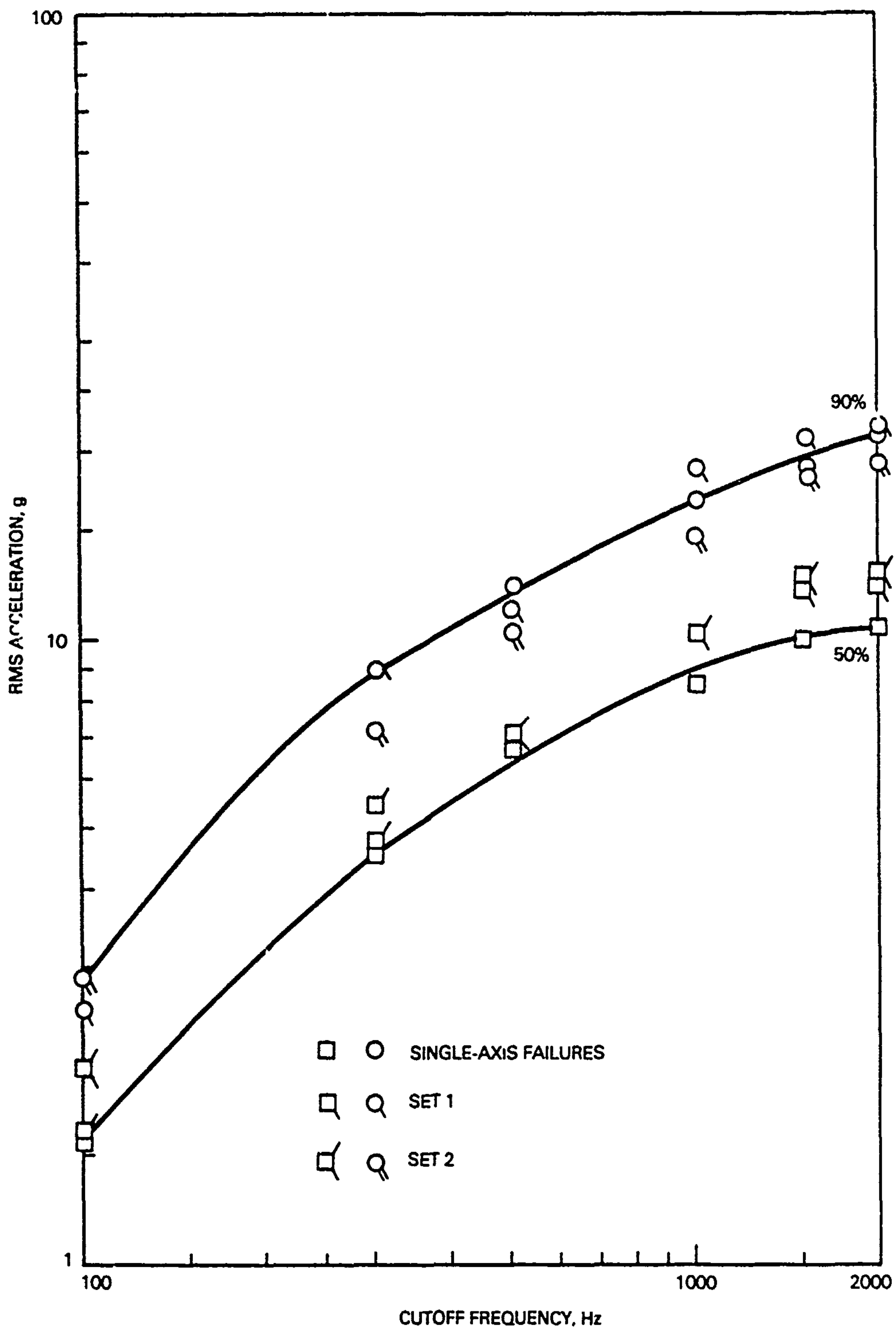


Figure 24. RMS acceleration vs frequency, 50 and 90 percentiles.

7.0 FLAW PRECIPITATION THRESHOLD (FPT)

It is simple to postulate the existence of the Flaw Precipitation Threshold, that is, the vibration level sufficient to precipitate a flaw into an observable failure. Clearly, it cannot be a simple number unique to every flaw. Nor could one create a screen which would generate the same vibration level at every point of the item to be screened. Thus, it is necessary to describe the FPT in terms of some global response of the item, permitting a rather broad range of responses from point to point. Thus, the FPT has evolved to be the characteristics that the global response of the item will exhibit under a satisfactory screen. Further, the global response can be determined from a vibration survey in which responses are measured at approximately 20 locations, depending on the size and complexity of the test item. Based on the evaluation of the measured responses described in the previous section, the following FPT is recommended for inclusion in revised guidelines for stress screening.

The FPT is defined in terms of the response sum acceleration spectral density (Sum-ASD) which is defined as the sum of the three response spectral densities at a point in three orthogonal directions. For a satisfactory screen, the mean Sum-ASD should be within the boundaries of the cross-hatched area of Figure 25. In addition, the rms acceleration versus cutoff frequency of the mean internal response Sum-ASD shall be as shown in Table 4 and Figure 26. Further, the 50th and 90th percentile values of the rms acceleration of individual Sum-ASDs should be within +6 dB and −6 dB, respectively, of the actual measured values.

It will be noted that the upper limit in Figure 25 has been set to the straightline approximation of the measured value plotted in Figure 12. In addition, the upper limit in Figure 26 has been set to the measured mean value plotted in Figure 22. In both plots, the lower limit is set 6 dB lower. It is appropriate to set the upper limit to the measured value since the measurements were made at locations where flaws had indeed been precipitated, i.e., there is no need to exceed that value. It then remains to select and justify a lower limit. Figure 21 indicates that the reduction in flaws precipitated by a 6 dB reduction in response might approach 20 percent if every measurement represented exactly the minimum vibration level required to precipitate the failure which occurred at that point. Unfortunately, little specific data is available to substantiate a lower limit. However, data prepared by J. Popolo for the third IES ESSEH Conference, September 1984, showed that 3 grms was as effective as 6 grms in flushing out bad solder joints though ineffective in flushing out unsecured components, for which 6 grms was only 30 percent effective at 10 minutes. A Hughes program which had been using 3 grms screening level was recently changed to a 6 grms level. Both levels were excited by a quasi-random three-axis shaker. The effects of the change, if any, have been very difficult to identify from either factory or field failure data. This suggests no dramatic difference between 3 and 6 grms. Therefore, it is believed the upper and lower limits of Table 4 and Figures 25 and 26 will provide satisfactory bands within which to develop the required screen.

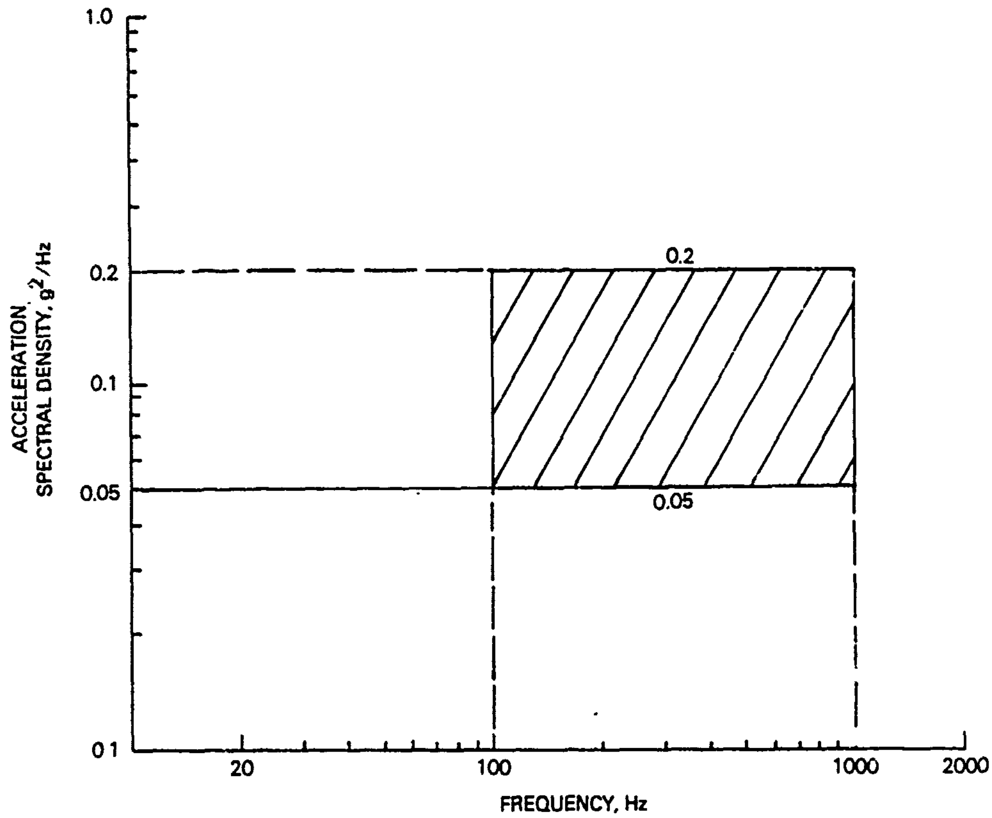


Figure 25. Range of mean response Sum-ASD.

TABLE 4. FLAW PRECIPITATION THRESHOLD RMS ACCELERATION VERSUS CUTOFF FREQUENCY

Cutoff Frequency (Hz)	Lower Limit (grms)	Upper Limit (grms)
100	1.0	2.0
300	3.3	6.6
500	4.5	9.0
1000	6.0	12.0
1500	7.0	14.0
2000	7.5	15.00

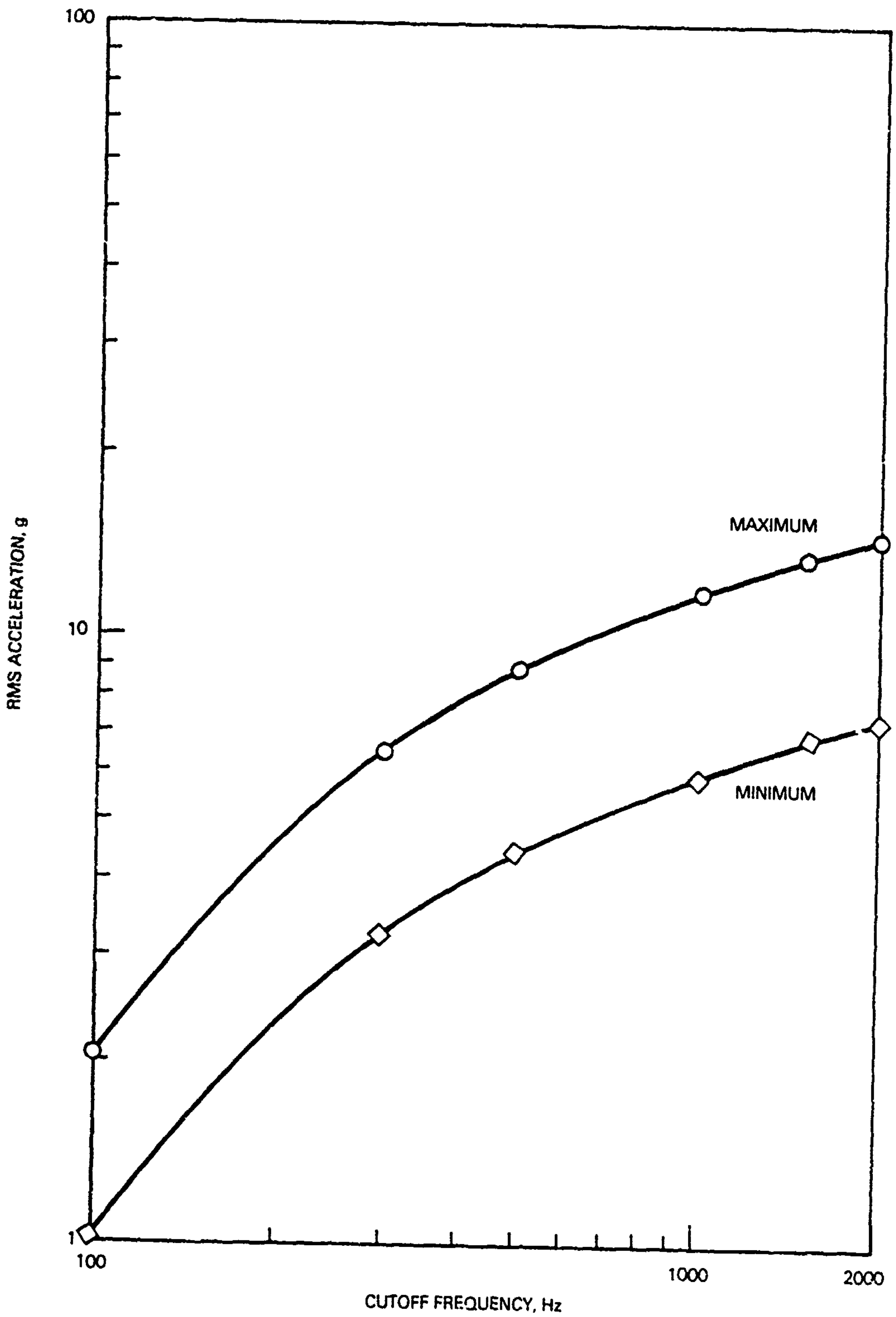


Figure 26. RMS acceleration vs frequency range for mean Sum-ASD.

8.0 DERIVATION OF A TAILORED VIBRATION SCREEN

With the FPT defined as described in the last section, it is now appropriate to describe the process to derive a suitable vibration screen. The process steps are outlined in the flowchart of Figure 27. Details of the process are included in Appendix B.

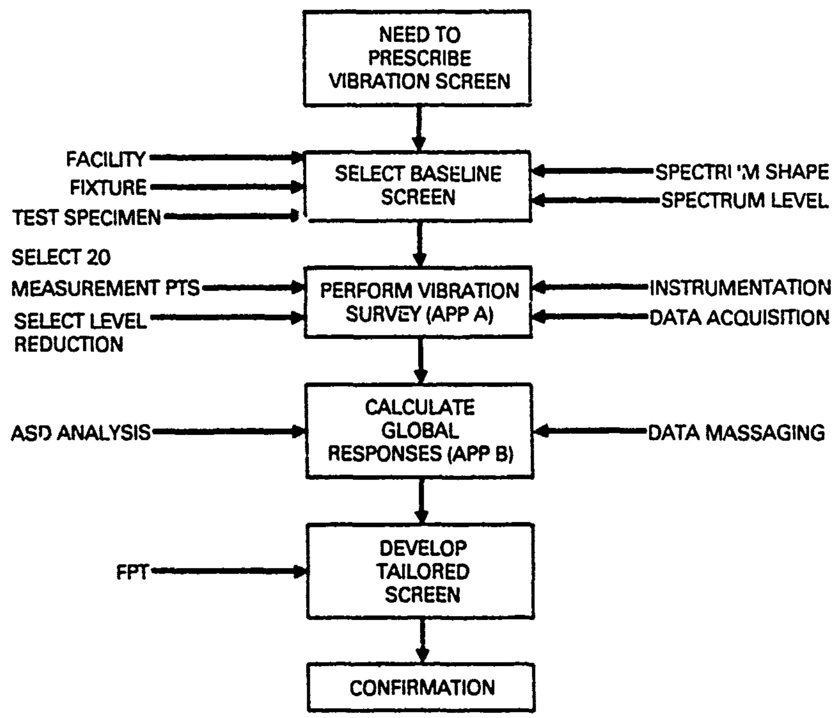


Figure 27. Flowchart of vibration screen derivation.

Using Figure 27 as a reference, once the need for a vibration screen has been determined, the basic configuration for the screen must be defined. The hardware portion of the configuration includes the equipment to be screened, a vibration facility, and a fixture attaching the equipment to the vibration facility. The basic configuration should also include a proposed screening input spectrum from which the tailored spectrum will be derived.

A vibration survey should then be performed using a test specimen structurally representative of the equipment to be screened. The vibration facility and fixture should replicate the configuration of the actual screen. The object of the survey is to acquire triaxial acceleration responses at approximately 20 measurement locations within the test specimen. Guidelines for performing the vibration survey are presented in Appendix A.

The acceleration response data from the survey should be reduced to Sum-ASDs for each measurement location. These Sum-ASDs will be averaged to form a mean Sum-ASD. The Sum-ASDs and mean Sum-ASD will then be integrated to obtain rms acceleration versus frequency curves representing the 50th percentile (median) response, 90th percentile response, and mean response. To reflect response to the proposed input spectrum, the rms acceleration curves and the mean Sum-ASD should be scaled to compensate for the reduced excitation level.

After scaling, the mean Sum-ASD and its rms acceleration versus frequency can be compared to the FPT curves (Figures 25 and 26). Further, it can be verified that the 50th and 90th percentile rms accelerations are within approximately ±3 dB of the values from the mean Sum-ASD. From this comparison, it can be determined how to tailor the input spectrum so that the test specimen responses fall within the FPT. An example of this tailoring is presented in Appendix C.

If the responses of the test equipment are not a linear function of input level, it is possible that the responses due to the tailored input spectrum would not fall within the FPT. For this reason, if program schedule and budget permit, the vibration survey should be repeated using the tailored input spectrum. Acceleration data should be processed in the same manner as the initial vibration survey. The results should be compared to the FPT to either validate or modify the tailored input spectrum.

9.0 VIBRATION SURVEY

The previous section referred to the performance of a vibration survey. If an appropriate screen is to be developed, it is important that the vibration survey be performed in a manner consistent with the techniques employed to derive the Flaw Precipitation Threshold. Therefore, a set of guidelines has been prepared and is included in Appendix A of this report. It is expected that these guidelines will also become an appendix in a future revision of NAVMAT P-9492.

10.0 RECOMMENDATIONS

The objective of the study program described in this report was to develop a rational, quantitative method of tailoring a vibration screen to fit the characteristics of the equipment to be screened. It is believed that the objective has been achieved. It remains to disseminate the information to the ESSEH community so that it may be used and, if necessary, modified to improve its utility. Within the Navy and its contractors, the recognized vehicle for disseminating ESSEH information is clearly NAVMAT P-9492. Therefore, it is recommended that a revised version of P-9492 be published. This revision should accomplish the following in the area of vibration screening:

1. Retain the present spectrum as a reasonable baseline screen absent other applicable experience.
2. Mandate the performance of a vibration survey in the manner suggested in Appendix A of this report.
3. Include Appendix A as an appendix in the revised version.
4. Mandate the tailoring of the screen based on the FPT of Section 8.
5. Remove the present restrictions on the vibration spectrum, particularly the implied spectral tolerance that inhibits the use of innovative excitation methods in lieu of electro-dynamic vibration systems.
6. Encourage the use of innovative configurations, e.g., fixtures, unit mounting, etc., which will generate desired internal responses and precipitate flaws.

In addition to the above "paper" action, it is also recommended that a Navy program, which is or soon will be in early production, be targeted for a trial use of the method. Further, if such a trial can be arranged, it is recommended that the originators of the method be retained to assist and monitor the results.

11.0 CONCLUSIONS

The previous sections have described in some detail the development of a method of tailoring to derive a suitable random vibration screen. It is believed that the method is a viable one that will lead to a screen which is both vigorous enough to precipitate flaws and yet not so severe that "good" hardware is damaged. If anything, it is felt that the method leads to a screening level higher than needed to precipitate the flaws.

Though it may not appear thus, every effort was made to keep the method simple and pragmatic, realizing that complexity would doom the method to obscurity. However, it is believed that the cost of processing the measured ASDs, which is perhaps new and complex to many potential users, should represent no more than a 15 percent increase in the cost of a vibration survey which should be part of any screening program.

At the inception of the study, it was hoped to include the duration of the vibration as a parameter of the Flaw Precipitation Threshold. The reader has probably noticed that this is the first mention of duration. Since no parametric data on duration were available, it can only be concluded that the typical duration of 10 minutes is still suitable.

The subject of duration does raise the question of retest criteria and, more recently, failure-free period. These topics have nothing to do with developing the appropriate screening level but are certainly related to the perceived success or failure of a particular screening regimen.

Regarding retest criteria, it is generally recommended that the failure, i.e., precipitated flaw, be repaired, the screen completed and the equipment delivered without any further vibration screen. However, if repair involves significant teardown and rework, then a rescreen, perhaps at lower level and/or shorter duration should be entertained. The contractor should be permitted to treat each case on a judgement basis, (e.g., FRB or MRB action) rather than the rigid rules associated with Flight Acceptance Testing of space hardware.

Recently, it has become common for screening regimen, including vibration, to call for a failure-free period. It is believed that a call for a failure free period under vibration, which pragmatically includes the post vibration functional test period, will be counterproductive. First, it can easily create a "do-loop" which builds up vibration time for reasons unconnected to vibration-induced failures. Secondly, it is counter to the hard-to-remember adage that screening "failures" are successes and will undermine the motivation for effective screens. Failure-free vibration screening does little more than hasten the occurrence of the next failure.

APPENDIX A
VIBRATION SURVEY GUIDELINES

APPENDIX A
VIBRATION SURVEY GUIDELINES

1.0 GENERAL

The vibration input to electronic hardware for an effective environmental stress screen can be derived utilizing internal response data and the Flaw Precipitation Threshold. These guidelines define the instrumentation, performance, data acquisition and data processing requirements to be used to acquire the internal response data. Response data acquired in conformance with the guidelines will be compatible with the data used to define the Flaw Precipitation Threshold, thus assuring the validity of the derived vibration input.

2.0 TEST CONFIGURATION

The vibration survey test configuration should replicate the configuration for the proposed screen.

2.1 Test Item

The test item should be representative of hardware to be screened. It should be permissible to mount accelerometers internally within the test item and accumulate vibration time on the test hardware.

2.2 Test Level

The vibration survey should be conducted at a level between 6 and 10 dB below the baseline screening level.

2.3 Test Strategy

The survey should be performed for each input axis or combination of input axes specified for the screen. For instance, a screen performed by the sequential excitation of three orthogonal axes requires three surveys. A screen performed as the combination of a dual axis test and a single axis test requires two surveys. A triaxial input screen requires one survey.

The controller, control strategy, and the number and location of control accelerometers should be the same as for the proposed screening test.

2.4 Excitation System

The excitation system used for the survey should be the same as for the screen.

2.5 Fixturing

The fixture, slip-plate, and head expander used for the survey should be the same as for the screen.

3.0 MEASUREMENT PHILOSOPHY

3.1 Selection of Measurement Locations

In the extreme, vibration response would be measured at each component, wire connection, mounting screw, etc., within the test item. This clearly is neither feasible nor desirable. What is desirable is to measure vibration responses at locations throughout the volume of the test item that are representative of responses at a majority of the potential failure locations. Approximately 20 locations should suffice for mapping most test items.

A typical test item is shown in Figure A-1 and will be used to illustrate the selection of response locations. The test item is an electronic card box with cable connectors and a time meter mounted on the front panel and transformers mounted on the rear panel. There are 11 standard cards spread throughout the box; four heavier, stiffer cards are located in the center; and an encased, thick module is located at the rear. The cards and module have connectors on the bottom which mate with the motherboard at the bottom of the box.

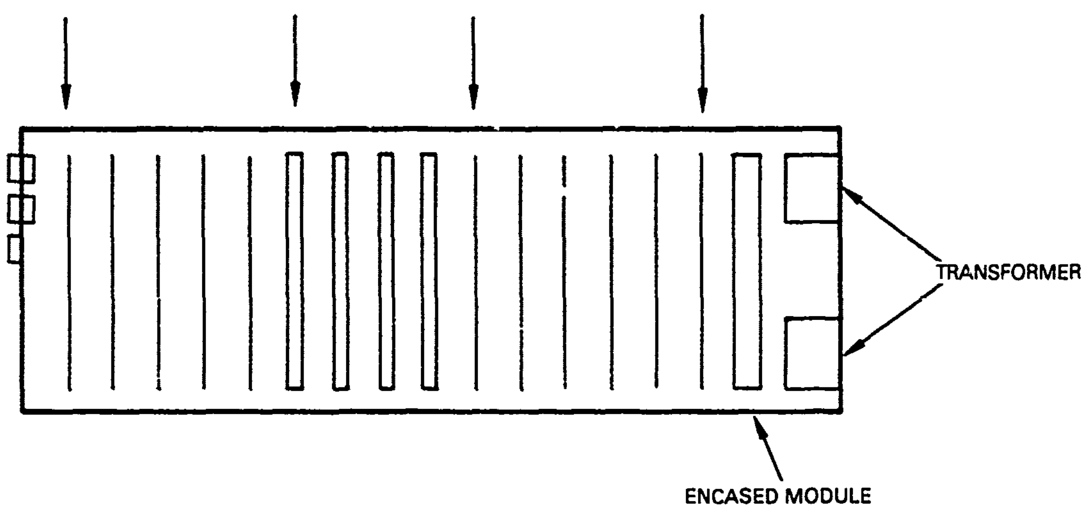


Figure A-1. Typical test item, plan view.

Twenty measurement locations to map the Figure A-1 test item could be allocated as follows:

• Three locations on each of the four cards indicated by arrows.	12
• Three locations within the encased module on the component mounting surfaces.	3
• One location on front panel near connectors and time meter.	1
• Two locations on motherboard.	2
• Two locations on rear panel at diagonally opposite corners of one of the transformers.	2
	20

The three measurement locations on the cards are depicted in Figure A-2.

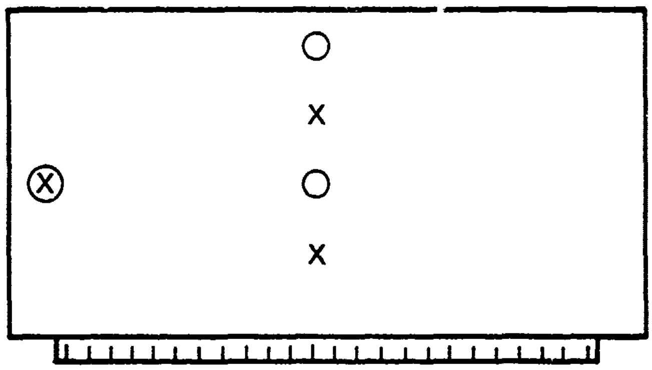


Figure A-2. Response measurement locations on rectangular card with base connector.

The locations indicated by "X" are suggested for a rectangular card with components mounted uniformly over the surface, supported along the short edges and a connector on the bottom. If the top of the card is supported by compression of a rubber gasket on the lid, the locations depicted by "0" would perhaps be a better choice. A square card equally supported on each edge could be sufficiently mapped with two locations; one in the center and the other at the middle of one edge. Obviously there are many location choices within this typical test item and within other test items that differ significantly from the typical test item unit. The example merely illustrates mapping of the entire volume and that engineering judgment must be exercised in the selection of measurement locations.

3.2 Accelerometers

3.2.1 Physical Characteristics. Accelerometers should be sm. l enough so that they can be mounted in the chosen location and light enough so that they do not alter the dynamic characteristics of the test item. In most surveys a mix of accelerometer types can be used. In the example illustrated by Figure A-1, relatively large, heavy accelerometers could be used to measure the acceleration input to the connectors/time meter on the front panel. Similar accelerometers could be used on the rear panel at diagonally opposite corners of the transformer. Medium size and weight accelerometers could probably be used on the motherboard and stiffer cards. The standard cards normally require the smallest, lightest accelerometers available so as to not alter the dynamic characteristics and to find mounting space.

3.2.2 Triaxial Measurement. To develop the Flaw Precipitation Threshold, the acceleration in three orthogonal directions must be known for each chosen measurement location. This does not mandate a triaxial measurement at each location. A measurement from another location may be substituted for one of the triaxial measurements if the response is judged to be the same over the frequency range of interest. As an example, triaxial response at the three measurement locations depicted on the card in Figure A-2 can be acquired by using five accelerometers. A single accelerometer is needed at each of the three measurement locations with the sensitive axis oriented perpendicular to the plane of the board. The in-plane response should be the same for all locations on the board and can be acquired by placing the two accelerometers wherever there is adequate space.

3.2.3 Installation. Accelerometers should measure the input to components or parts, not the response of a particular component or part. In the typical test item of Figure A-1, this means placing accelerometers on the boards, not the components, and on the front and rear panels, not the parts mounted to the panels.

4.0 DATA ACQUISITION

It is assumed that the control and response acceleration data will be recorded on an analog tape recorder and played back to a spectrum analyzer for data analysis. Alternatively, if the spectrum analyzer has enough data channels, the data analysis could be performed "on-line," obviating the need to record and later play back data for spectral analysis.

4.1 Data Acquisition Equipment

The data acquisition system, i.e., accelerometers, signal conditioners, and tape recorder system should have a frequency response flat to ±10 percent over the frequency range of interest. The system should also have sufficient dynamic range to observe and record the response accelerations. The system should be compatible within itself and with the data analysis equipment.

4.2 Tape Recorder Setup

The tape recorder speed should be sufficient to obtain the desired frequency response for the acquired data.

For the first data acquisition run in each survey, all control accelerometers should be recorded along with the response accelerometers. For all remaining data acquisition runs in each survey, one control accelerometer should be recorded with the response accelerometers. The control accelerometer should remain the same for all remaining runs to validate repeatibility in case of questionable response data. Also, voice or a standard time code signal, IRIG, should be recorded on a tape channel to identify the beginning and end of calibration and vibration runs. One channel could also be used to record the charge amplifier gain codes.

4.3 Documentation

Documentation for the data acquisition should include the following information:

—test identification

program name	tape speed
test item name	test engineer
test station	test date
tape recorder	excitation system

—channel information

accelerometer identification	charge amplifier gain
accelerometer serial number	charge amplifier serial number
accelerometer sensitivity	

—run information

run identification
frequency range and level of excitation
IRIG time/tape footage, beginning and end of run
IRIG time/tape footage, beginning and end of full level vibration

4.4 Calibration

A calibration signal, preferably a sinewave representing the full scale g level of the instrumentation, should be placed on each tape data channel. The run identification should note the voltage level, equivalent g level, and frequency of the calibration signal. The calibration should be recorded for at least two minutes at the beginning of each tape reel, after any changes in the patching of charge amplifiers to the tape recorder, or any time that there is a question as to whether the input gains have been adjusted since the previous run.

It is desirable for a broadband, approximately white noise, random signal to also be recorded on tape. The frequency range of the noise signal should extend over the frequency range of the excitation and its voltage amplitude should be within the dynamic range of the tape recorder. This signal, coming from one source, should be recorded simultaneously on all active tape data channels at the beginning of each tape reel for a period of one minute. Record the true rms voltage level of this signal during playback on the tape sheet. This signal permits the frequency response of each tape channel and the transfer function between any two tape channels to be measured. Any discrepancies that are found can be compensated for during analysis.

4.5 Data Recording and Review

The minimum duration for recording of data should be the time necessary to calculate acceleration spectral density (ASD) functions over the desired frequency range, using 50 averages. This minimum time will vary, depending on the analysis blocksize and bandwidth, the number of channels processed simultaneously, and the analyzer computational speed. The entire run should be recorded if the screen is a non-stationary process. The data should be reviewed after the run to confirm that the amplitudes are appropriate, that the waveforms appear reasonable, and that the data segment is properly identified by IRIG or voice signals. The gain settings of each channel should also be verified.

5.0 DATA PROCESSING

The end result of the vibration survey should be a collection of ASD functions on a mass storage device available for "massaging." ASD functions should be calculated for all control and response accelerometers.

5.1 Data Analysis Equipment

It is recommended that the data processing be performed by playing back the recorded analog data to a digital Fourier spectrum analyzer. The analyzer should have the capabilities to calculate ASD functions, label the functions, and store the functions and labels on a mass storage device such as disc or tape. Additionally, the analyzer should be able to retrieve a stored ASD, integrate the function over selected frequency ranges to obtain grms values, and print the grms values.

5.2 Data Analysis Parameters

ASD functions should be calculated with 50 averages An analysis bandwidth of approximately 5 Hz should be used for ASD calculation over the frequency range of 20 to 2000 Hz. Alternatively, a constant percentage bandwidth analyzer may be used if the bandwidth does not exceed 1/6th octave.

5.3 Documentation

Each ASD function should be stored with a unique identifier. A data analysis log should record the following run information and analysis parameters:

program name	frequency range
unit name	number of averages
test date	charge amp gain
run identification	tape recorder channel
block size	mass storage device and location number
frequency resolution	measurement I.D.

6.0 TEST PROCEDURE

The following is a procedure for performing the vibration survey. The procedure assumes that data is recorded on analog tape and played back to a spectrum analyzer for ASD calculation. The procedure can be modified for use with an on-line spectral analysis system.

The procedure also assumes that the excitation system is an electrodynamic shaker. Therefore, for other types of excitation systems, not all steps will be relevant.

1. Record the calibration signal on all data channels of the tape recorder.
2. Record the white noise on all data channels of the tape recorder.
3. Attach any accelerometers and cables to the unit that require special treatment (disassembly of unit, cleanroom facilities, obstructions when installed in the fixture, etc.).
4. Create or retrieve input specification on the controller.
5. Mount fixture to shaker table.
6. Mount control accelerometer(s) to fixture and patch to the controller and data acquisition system.
7. Perform vibration dry run(s) to ensure that the control system performs properly.
8. Mount unit in fixture.
9. Attach remainder of response accelerometers and cables for this data run (attach accelerometers and cables for all runs if available).
10. Patch response accelerometers for this run to data acquisition system.
11. Tap check all accelerometers to verify that they are properly patched to the input of the tape recorder and that all instrumentation functions properly.
12. Install all lids, covers, and unit cabling that will be on during screening.
13. Perform vibration run, recording all data.
14. Verify that the recorded data is valid before proceeding to the next run.
15. Repeat steps 9 through 14 for remaining groups of response accelerometers.
16. Repeat steps 4 through 15 for additional surveys, if applicable.
17. Analyze recorded data to obtain ASD functions. Label and store functions on mass storage device for later retrieval and "massaging."

APPENDIX B

DERIVATION OF A TAILORED VIBRATION SCREEN

APPENDIX B
DERVIATION OF A TAILORED VIBRATION SCREEN

A flowchart of the process to derive a tailored vibration screen is depicted in Figure B-1. Given the need to prescribe a vibration screen, certain resources are needed and, ideally, certain conditions exist. These are indicated beside the second block of Figure B-1:

1. The screening facility has been identified and is available to perform a vibration survey.
2. The vibration fixture has been proven and is available for use during the survey.
3. A sample of the equipment, which is closely representative if not identical to the screenable equipment and which can be instrumented internally, is available for the vibration survey.
4. Based on prior experience, a trial screening spectrum is available as the baseline from which the final screen will be tailored. In lieu of prior knowledge, the spectrum of Figure B-2 is a suitable spectrum.
5. The level by which the baseline spectrum should be reduced for the survey should be selected. (e.g., 6 to 10 dB down)

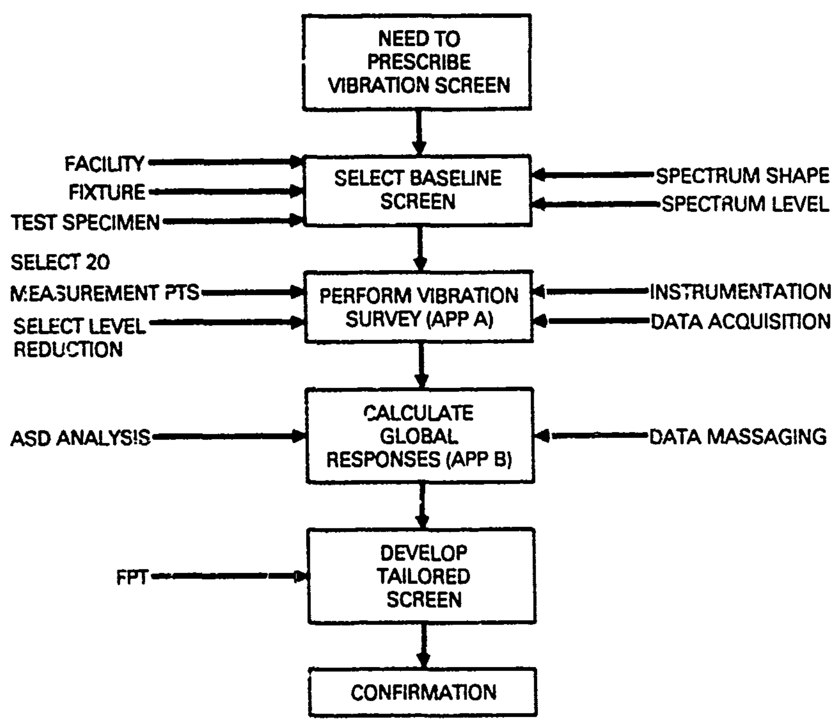


Figure B-1 Flowchart of vibration screen derivation

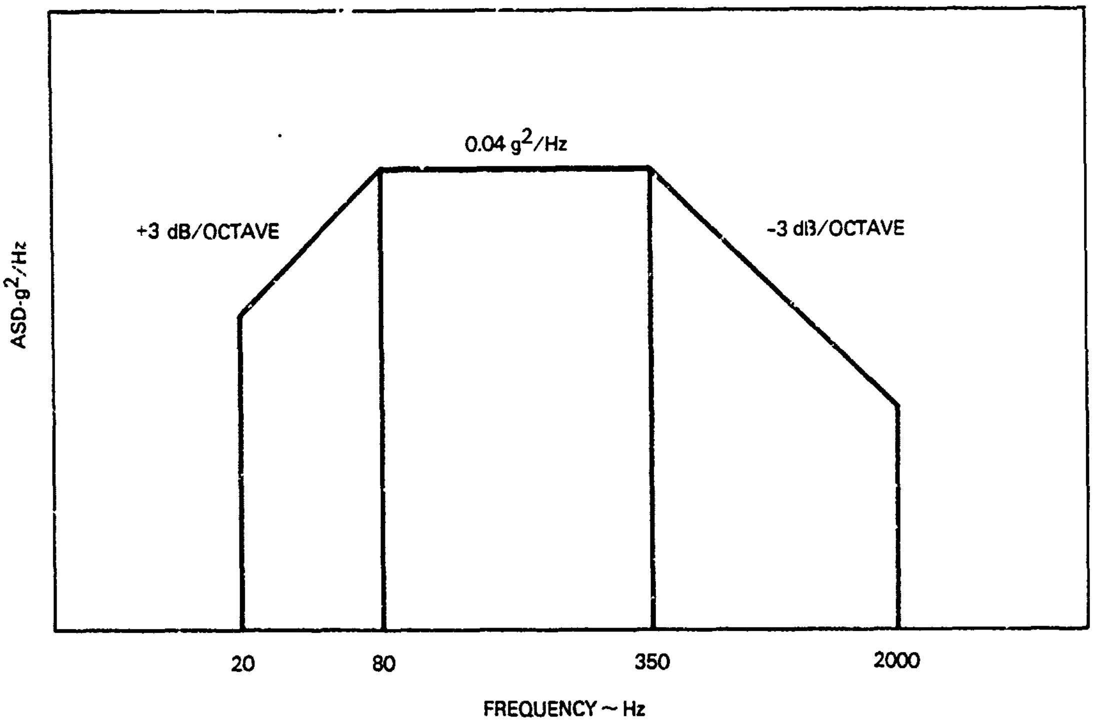


Figure B-2. Random vibration spectrum.

6. The hardware design is sufficiently mature that vibration screening is appropriate, i.e., the screening process will not be inhibited by unsolved design problems. Further, major design changes, which would obviate the screen, are not anticipated, e.g., the design qualification is complete.

The next step is to select approximately twenty vibration measurement locations and perform the vibration survey in accordance with the guidelines of Appendix A. After performing the vibration survey, calculate the global responses within the equipment as follows:

1. Calculate ASDs for each accelerometer signal.
2. Verify input ASD was as specified.
3. Calculate Sum-ASD for each measurement location, i.e., the sum of the three spectra for three orthogonal axes at that location.
4. Calculate mean of Sum-ASDs. Smooth to approximately 10 percent bandwidth (i.e, $\approx 1/7$ octave) if convenient.
5. Calculate grms versus frequency for each Sum-ASD and for the mean Sum-ASD.
6. Tabulate grms values at 100, 300, 500, 1000, 1500 and 2000 Hz for each Sum-ASD and for the mean Sum-ASD.
7. Tabulate grms versus cutoff frequency for the 90th percentile and 50th percentile. (For 20 measurements, 90th and 50th percentiles are the second from highest and eleventh from highest values at each cutoff frequency, respectively.)

8. Scale up mean Sum-ASD by reduction factor employed during vibration survey and compare to Figure B-3.
9. Scale up 50 percent, 90 percent and mean grms values by survey reduction factor. Compare mean grms to Figure B-4 or Table B-1. Check that 90 percent and 50 percent values are within 3 to 6 dB of the mean value.
10. Scale overall level, notch and/or boost input spectrum as needed to obtain reasonable match of mean Sum-ASD and grms values to Figures B-3 and B-4 respectively. This is the tailored screen.
11. If resources are available, repeat some or all measurements using tailored spectrum at full level to validate the desired responses within the equipment.

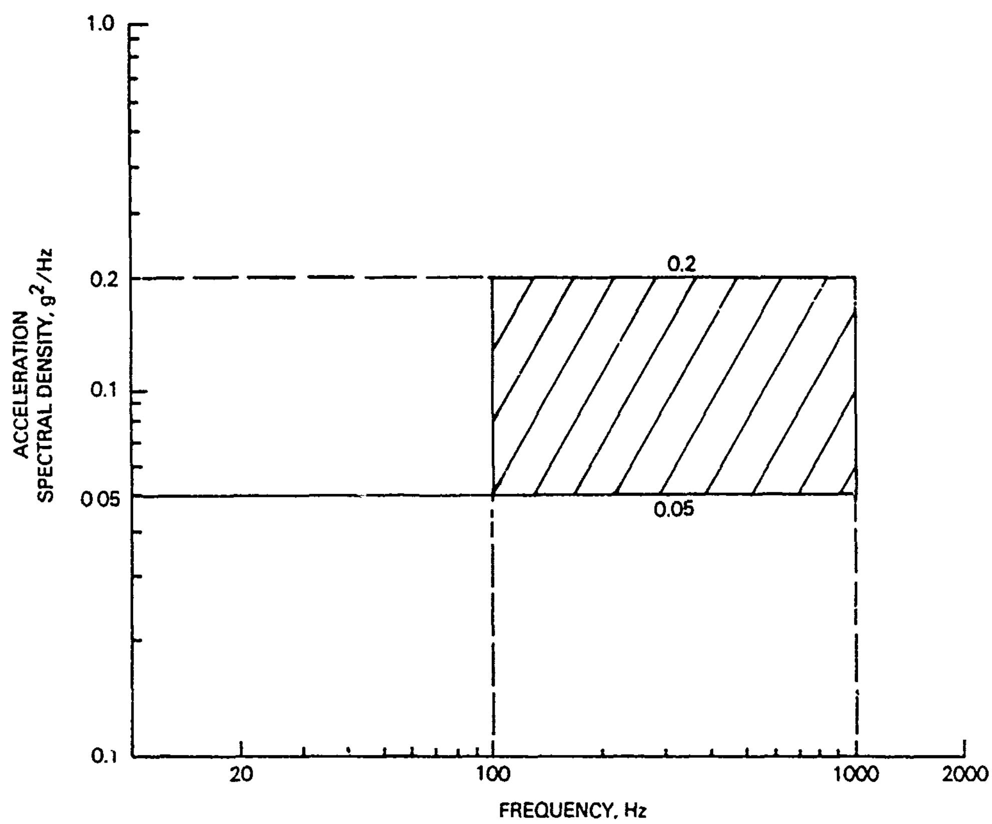


Figure B-3. Range of mean response Sum-ASD.

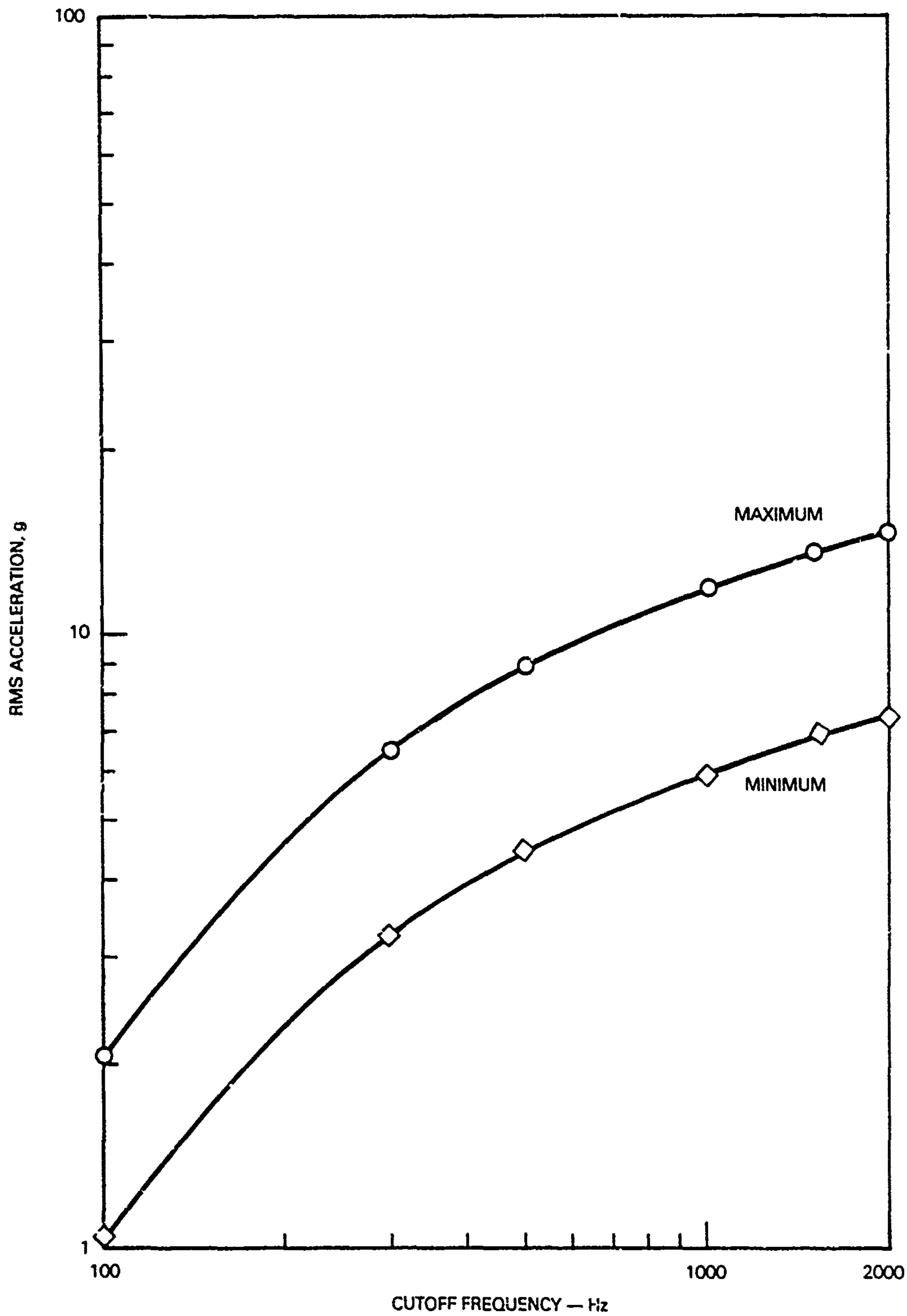


Figure B-4. RMS acceleration vs frequency range for mean Sum-ASD.

TABLE B–1. FLAW PRECIPITATION THRESHOLD RMS ACCELERATION VS CUTOFF FREQUENCY

Cutoff Frequency (Hz)	Lower Limit (grms)	Upper Limit (grms)
100	1.0	2.0
300	3.3	6.6
500	4.5	9.0
1000	6.0	12.0
1500	7.0	14.0
2000	7.5	15.0

APPENDIX C
EXAMPLE TAILORING OF A VIBRATION SCREEN

APPENDIX C
EXAMPLE TAILORING OF A VIBRATION SCREEN

INTRODUCTION

An example of tailoring a screen to a specific equipment, using the methods of Appendix B, is presented. The example equipment is an electro-optical package approximately 6 by 12 by 12 inches in size, weighing approximately 30 pounds. The package is composed of two modules, one containing optical and electronic components and the other housing printed circuit boards.

The 6 grms NAVMAT P-9492 specifications (Figure C-1) was proposed as the input spectrum for screening. The excitation was provided by a two-axis electrodynamic shaker. The input was applied to both axes simultaneously and to the individual axes serially. Revised input spectra were calculated for each excitation case: X axis individually, Y axis individually, X and Y axes simultaneously.

TEST PERFORMANCE

Sixteen measurement locations were selected. The survey guidelines of Appendix A were used to choose measurement locations throughout the equipment that would result in a good estimate of global structural response. With strategic placement of accelerometers, it was possible to acquire valid triaxial response at 16 locations using 32 accelerometers.

For each excitation, response data from all accelerometers were recorded on a 28 channel tape recorder. Two runs per excitation were necessary to record all of the data. The test duration was 2 minutes per run.

The duration is governed by the length of data necessary to calculate acceleration spectral density (ASD) functions with 50 averages and a 5 Hz bandwidth over a 20 to 2000 Hz frequency range.

The NAVMAT P-9492 spectrum was selected as the trial input. The recommended excitation level for a screening vibration survey is 6 to 10 dB below the proposed input spectrum. For this particular test item, it was deemed satisfactory to perform the vibration survey at the full level 6 grms NAVMAT P-9492 specification.

DATA REDUCTION AND PROCESSING

ASDs were computed from the recorded response accelerations using the previously stated processing parameters. The ASDs for each triaxial measurement location were added to form the Sum-ASD for each location. The Sum-ASDs were then smoothed by performing a continuous 10 percent bandwidth approximation. (Data processing can be decreased by smoothing only the mean Sum-ASD after it is obtained.) The smoothed Sum-ASDs were then averaged to obtain the mean Sum-ASD. The mean Sum-ASDs for the X axis, Y axis, and X-Y axes are shown in Figures C-2, C-3, and C-4, respectively.

To summarize, the data massaging for each excitation resulted in a set of 16 smoothed Sum-ASDs and one smoothed mean Sum-ASD. Each of these functions was then integrated over six frequency ranges: 20 to 100 Hz, 20 to 300 Hz, 20 to 500 Hz, 20 to 1000 Hz, 20 to 1500 Hz, and 20 to 2000 Hz. Tables C-1A, C-1B, and C-1C list the grms values from the integration process. [The data from location 4 was suspect and not used.] For each column of the tables, the values representing the 50th percentile (median) and 90th percentile were selected. To illustrate the selection of the 50th and 90th percentile values, refer to column 4 of Table C-1A. These are the 20 to 1000 Hz grms values from X-axis excitation. The 15 values from the Sum-ASD functions were ranked by magnitude in ascending order. The 50th percentile value is the 8th highest, 18.31 grms at location 6. The 90th percentile value is the 14th highest, 26.96 grms at location 10.

If the test had been performed at a reduced level, it would have been necessary to scale the mean Sum-ASDs and the 50th percentile, 90th percentile, and mean sum grms values to the proposed screening input level. However, for this particular test, the survey was performed at the proposed input level, obviating the scaling process.

For each excitation, the 50th percentile, 90th percentile, and mean Sum-ASD rms acceleration values were plotted as a function of cutoff frequency. These curves are shown in Figures C-5 through C-7.

REVISED INPUT SPECTRA CALCULATION

Comparing grms versus cutoff frequency curves for the X, Y, and X-Y excitations (Figures C-5, C-6, and C-7, respectively) against the FPT curves of Figures C-8 and C-9, it was observed that the overall response from all three excitations was much higher than the FPT. It was also observed that a disproportionate amount of response occurred in the 100 to 300 Hz range. Therefore, to tailor each of the three screens so that the responses would be within the FPT, the overall input level should be reduced, and the input spectrum should be notched in the 100 to 300 Hz range. This conclusion was also evident by comparison of the mean Sum-ASDs (Figures C-2 through C-4) with the recommended mean Sum-ASD range (Figure C-10).

The amount of input level reduction and spectrum notching was calculated using the mean Sum-ASD. In Figure C-11, the mean Sum-ASD from X axis excitation is plotted along with the recommended mean Sum-ASD response range (lower cross-hatched rectangle). To get most of the mean Sum-ASD within the recommended range, the curve was lowered 6 dB. (For ease of illustration, the cross-hatched rectangle was raised 6 dB.) The region of mean Sum-ASD above the +6 dB rectangle (140 to 300 Hz) was inverted to become a notch in the input spectrum. The resulting X axis input spectrum is shown in Figure C-14. Note that the overall level has been reduced 6 dB and the spectrum is notched from 140 to 300 Hz. The input level from 20 to 2000 Hz was reduced to 2.92 grms from the original 6 grms. For synthesis in a digital controller, this input spectrum was approximated by the frequency and magnitude breakpoints listed in column 2 of Table C-2. Referring to Figure C-11, it is seen that the 6 dB overall reduction mandates boosting of the input ASD over a small interval at each end of the FPT frequency range. However, this added complexity to the spectrum was not considered essential to achieve an effective screen.

The same calculation process was repeated for the Y axis and X-Y axes excitations. For the Y axis, the overall level reduction was 3 dB. Spectrum notching was necessary, as seen in Figures C-12 and C-15. The revised input spectrum is 4.11 grms and is approximated by the breakpoints in Table C-2, column 3. The X-Y input spectrum was lowered 7 dB and notched (Figure C-13), resulting in a tailored input of 2.50 grms (Figure C-16). The breakpoint approximation to Figure C-16 is given in Table C-2, column 4.

Development of these three (X, Y and X-Y) screening spectra was performed to examine the relative merits of single and dual axis excitation. All three have been included in this report as examples of the tailoring process.

TABLE C–1A. SUM–ASD AND MEAN SUM–ASD RMS ACCELERATIONS

X–Excitation

Identification	Frequency Range – Hertz					
	20-100	20-300	20-500	20-1K	20-1.5K	20-2K
Loc1	1.68	4.45	6.96	8.54	9.88	10.74
Loc2	1.68	4.45	6.71	8.55	10.20	10.99
Loc3	1.67	4.45	6.67	8.27	9.64	10.45
Loc4*	4.66	5.56	5.57	5.58	5.58	5.58
Loc5	1.77	4.99	7.97	14.54	16.91	17.26
Loc6	1.63	5.78	17.24	18.31	18.54	18.66
Loc8	2.18	13.74	15.86	17.37	17.68	17.79
Loc9	2.32	14.07	17.99	20.48	21.52	21.72
Loc10	2.88	25.78	26.96	27.91	28.58	28.34
Loc11	1.72	16.42	19.78	21.22	21.73	21.85
Loc12	2.26	28.96	29.67	34.49	34.96	35.55
Loc13	2.86	21.87	24.00	29.03	30.42	30.61
Loc14	1.68	7.97	8.92	14.48	15.41	15.72
Loc15	1.99	9.53	11.29	16.07	16.94	17.31
Loc16	1.74	23.18	24.05	31.93	43.83	44.70
Loc17	1.98	13.70	15.20	34.53	35.24	35.48
Mean-Sum	2.06	15.55	17.74	22.56	24.61	24.96

*Data from this location was suspect and eliminated from input spectrum calculations.

TABLE C–1B. SUM–ASD AND MEAN SUM–ASD RMS ACCELERATIONS

Y–Excitation

Identification	Frequency Range – Hertz					
	20-100	20-300	20-500	20-1K	20-1.5K	20-2K
Loc1	2.07	5.24	7.10	10.33	11.03	11.43
Loc2	2.07	5.07	6.91	10.14	10.90	11.27
Loc3	2.07	5.00	6.82	10.09	10.76	11.12
Loc4*	3.69	9.02	9.06	9.06	9.06	9.06
Loc5	2.00	4.99	7.44	16.48	22.95	23.12
Loc6	2.18	31.53	32.99	33.30	33.54	33.58
Loc8	2.23	7.12	10.01	14.76	15.13	15.21
Loc9	1.83	9.40	11.21	15.71	16.80	17.01
Loc10	1.84	17.94	18.84	20.54	21.54	21.60
Loc11	1.80	6.66	9.82	15.80	17.00	17.08
Loc12	1.89	10.35	11.52	16.38	17.50	17.85
Loc13	1.92	14.16	16.20	21.34	22.24	22.46
Loc14	1.88	5.27	7.21	12.07	13.26	13.52
Loc15	1.90	5.35	7.69	13.57	14.58	14.80
Loc16	1.59	9.58	11.05	16.23	30.86	31.18
Loc17	1.60	6.06	8.08	15.15	16.36	16.46
Mean-Sum	1.92	12.13	13.63	17.31	19.81	19.98

*Data from this location was suspect and eliminated from input spectrum calculations.

TABLE C–1C. SUM–ASD AND MEAN SUM–ASD RMS ACCELERATIONS

X–Y Excitation

Identification	Frequency Range -- Hertz					
	20-100	20-300	20-500	20-1K	20-1.5K	20-2K
Loc1	2.75	6.49	9.69	13.15	14.59	15.49
Loc2	2.75	6.35	9.42	13.02	14.70	15.55
Loc3	2.75	6.30	9.32	12.81	14.25	15.10
Loc4*	5.92	9.72	9.75	9.75	9.75	9.75
Loc5	2.70	6.61	10.61	21.73	28.49	28.81
Loc6	2.69	30.66	35.95	36.66	36.98	37.06
Loc8	3.24	15.70	18.79	22.80	23.24	23.36
Loc9	3.05	16.44	20.52	24.76	26.30	26.50
Loc10	3.60	26.58	28.20	30.02	30.92	31.00
Loc11	2.53	18.84	22.75	26.65	27.68	27.76
Loc12	3.09	28.17	29.28	35.77	36.55	37.19
Loc13	3.48	24.56	27.32	34.90	36.63	36.87
Loc14	2.57	8.53	10.37	18.00	19.36	19.70
Loc15	2.75	10.19	12.70	20.13	21.41	21.77
Loc16	2.53	24.65	26.22	36.33	54.96	55.91
Loc17	2.85	14.78	17.15	37.53	38.63	38.87
Mean-Sum	2.89	18.44	21.10	27.32	30.70	31.09

*Data from this location was suspect and eliminated from input spectrum calculations.

TABLE C–2. REVISED SCREENING INPUT SPECTRA

Frequency (Hz)	Magnitude (g^2/Hz)			
	6 grms NAVMAT	X	Y	X-Y
20	0.0100	0.0025	0.0050	0.0020
80	0.0400	0.0100	0.0200	0.0080
140		0.0100		0.0080
155			0.0200	
160		0.0055		
165				0.0043
180			0.0050	
190		0.0080		
205				0.0055
210			0.0200	
225				0.0062
240			0.0200	
260		0.0040		
265			0.0040	
270				0.0022
280			0.0040	0.0022
310		0.0100		
320				0.0080
325			0.0200	
350	0.0400	0.0100	0.0200	0.0080
2000	0.0070	0.0018	0.0035	0.0014

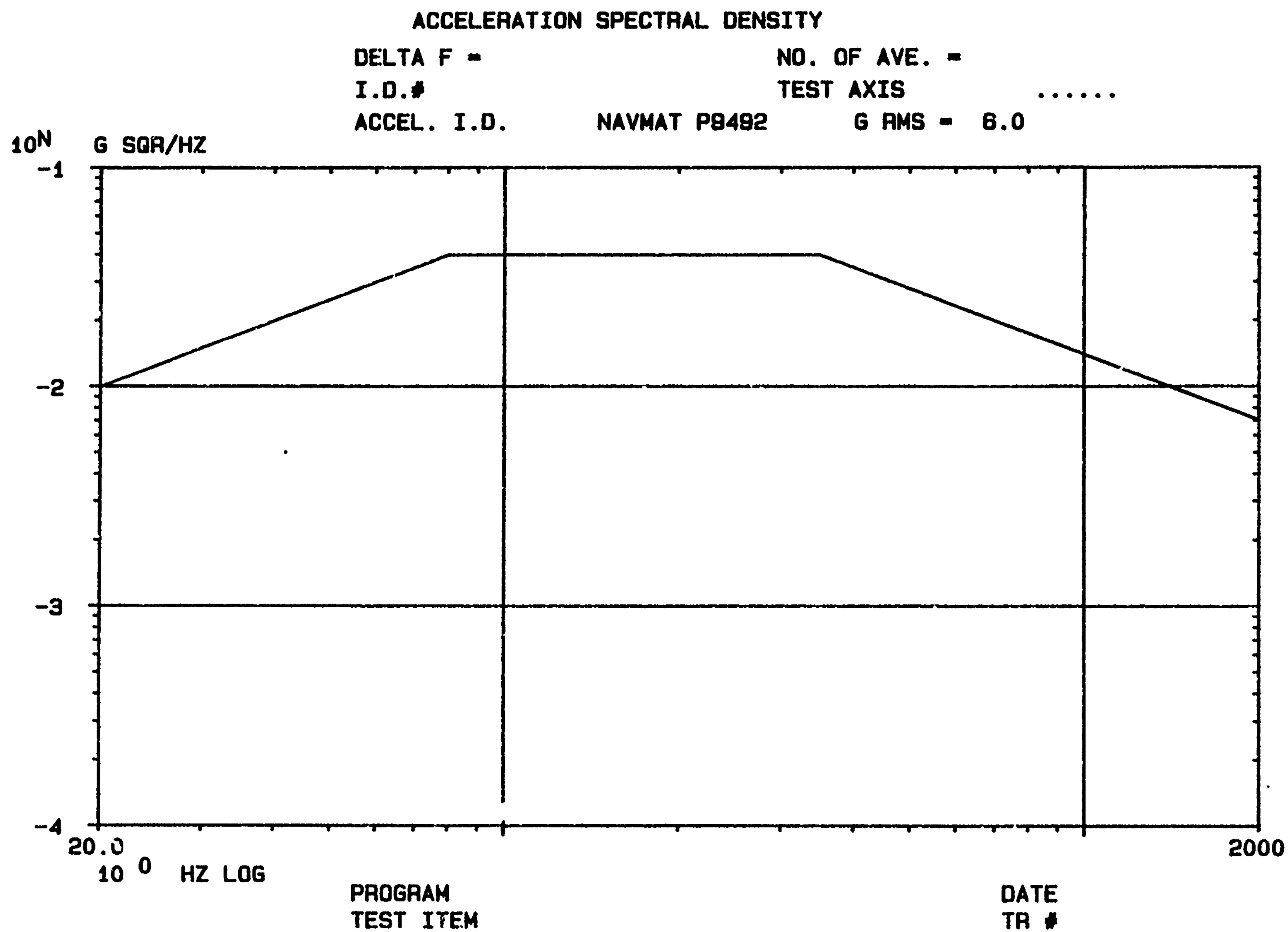

ACCELERATION SPECTRAL DENSITY
DELTA F =
NO. OF AVE. =
I.D.#
TEST AXIS ......
ACCEL. I.D.
NAVMAT P9492
G RMS = 6.0
10N G SQR/HZ
-1
-2
-3
-4
20.0
10 0 HZ LOG
2000
PROGRAM
TEST ITEM
DATE
TR #

Figure C-1.

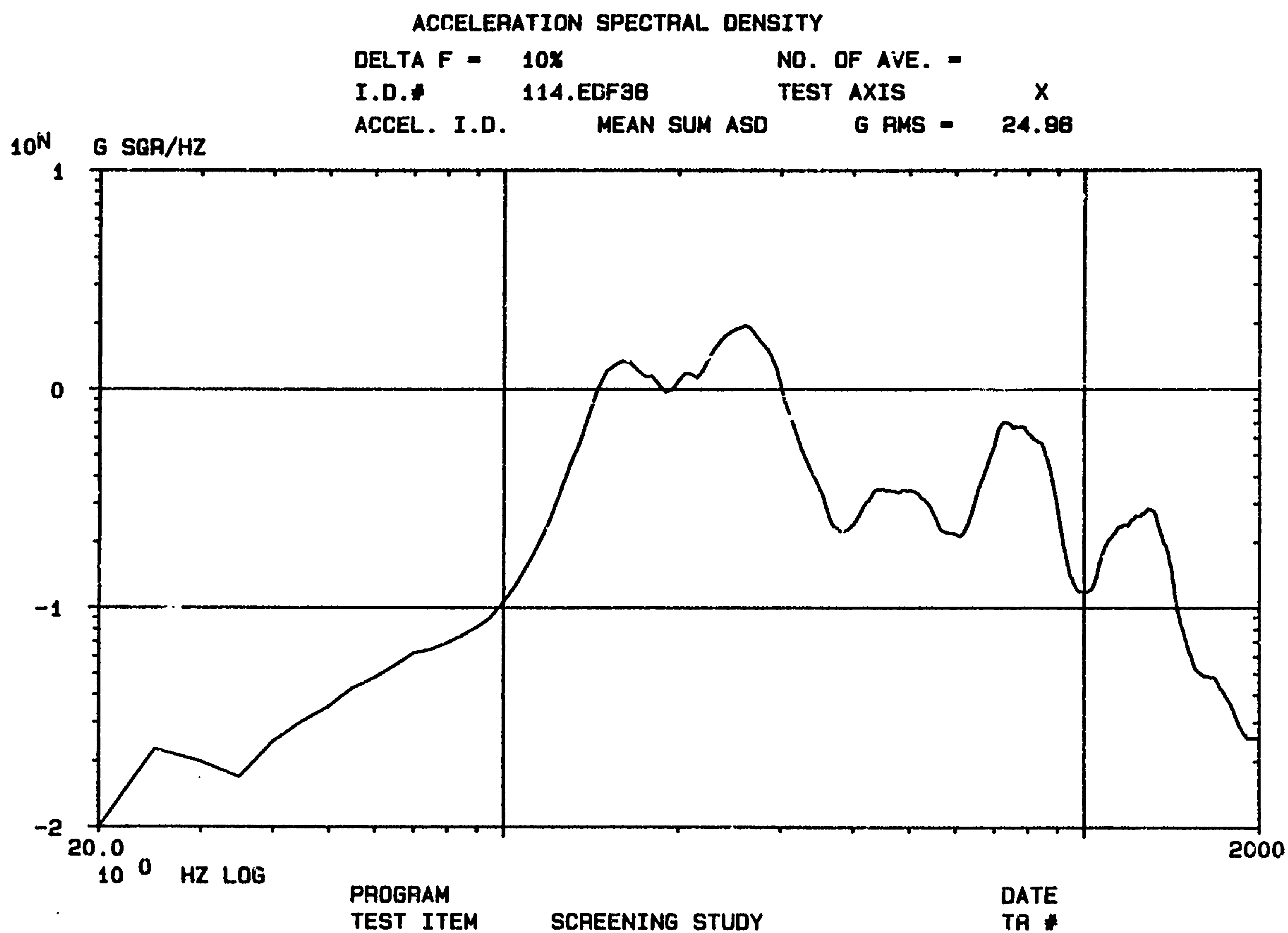
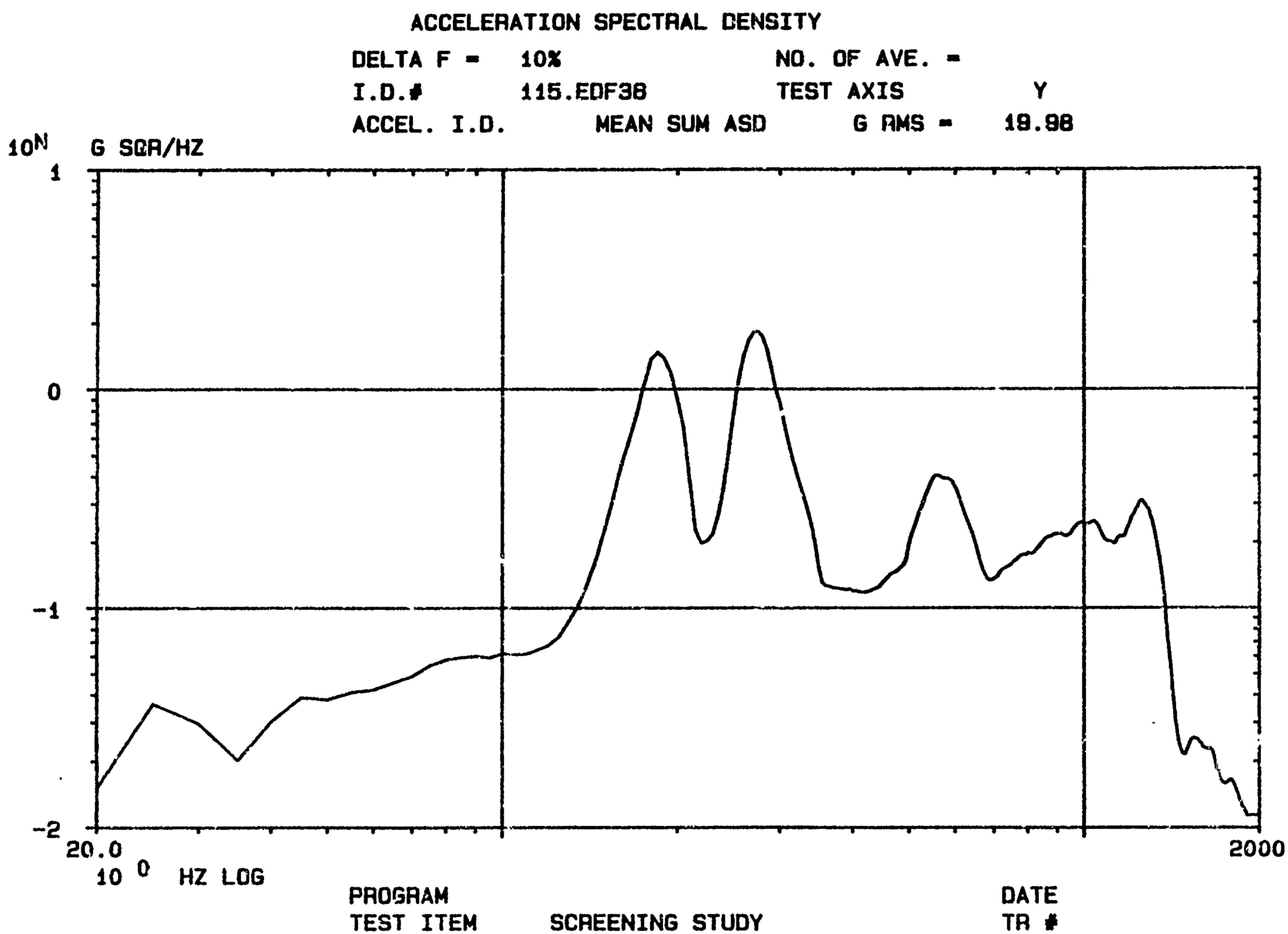

ACCELERATION SPECTRAL DENSITY
DELTA F = 10%
NO. OF AVE. =
I.D.# 114.EDF38
TEST AXIS X
ACCEL. I.D. MEAN SUM ASD
G RMS = 24.98
10^N G SQR/HZ
1
0
-1
-2
20.0
10^0 HZ LOG
2000
PROGRAM
TEST ITEM SCREENING STUDY
DATE
TR #

Figure C-2



ACCELERATION SPECTRAL DENSITY
DELTA F = 10%
NO. OF AVE. =
I.D.# 115.EDF38
TEST AXIS Y
ACCEL. I.D.
MEAN SUM ASD
G RMS = 19.98
10N G SQR/HZ
1
0
-1
-2
20.0
10 0 HZ LOG
2000
PROGRAM
TEST ITEM
SCREENING STUDY
DATE
TR #

Figure C-3

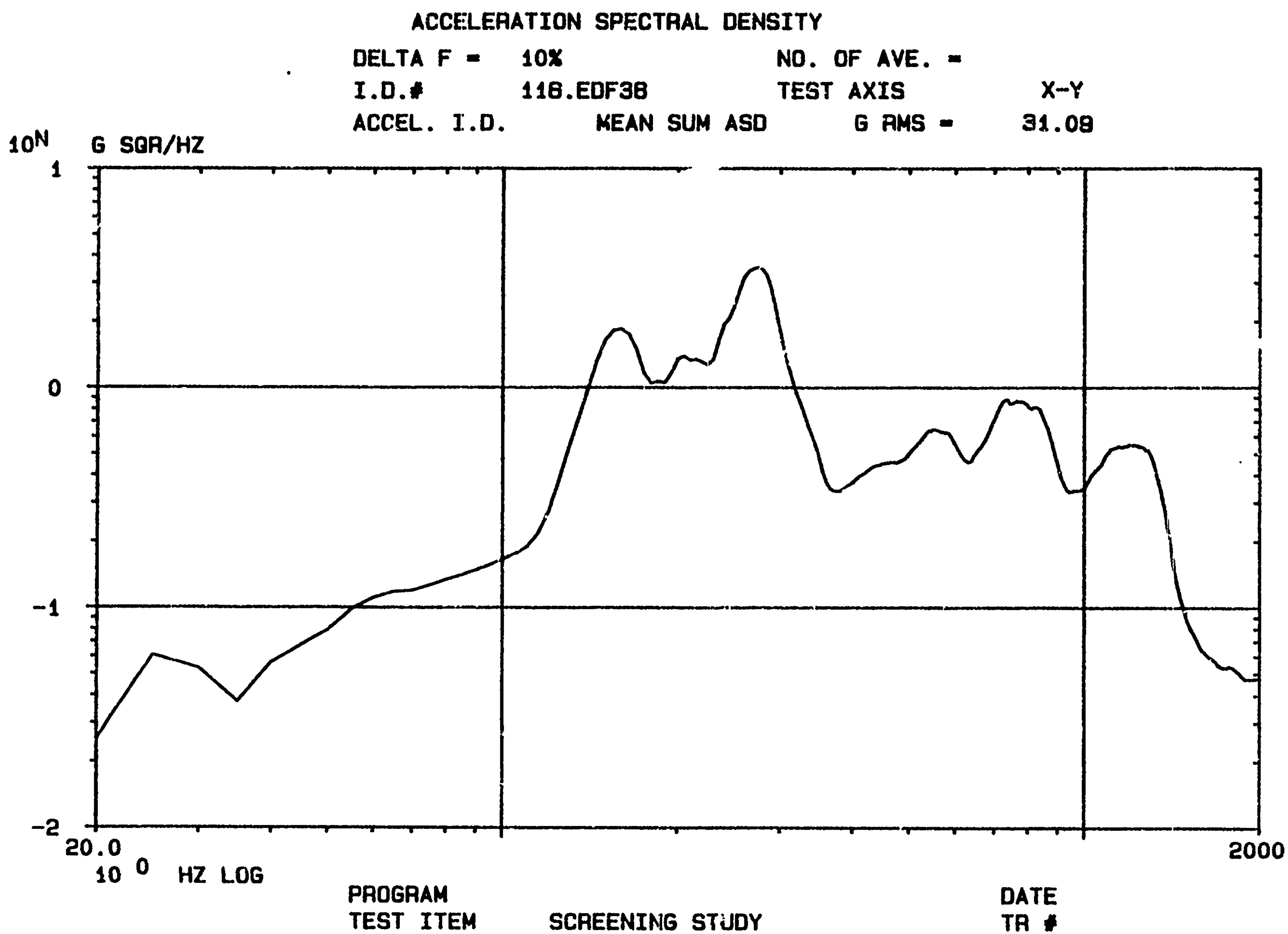

ACCELERATION SPECTRAL DENSITY
DELTA F = 10%
NO. OF AVE. =
I.D.# 116.EDF38
TEST AXIS X-Y
ACCEL. I.D. MEAN SUM ASD
G RMS = 31.09
10^N G SQR/HZ
1
0
-1
-2
20.0
2000
10^0 HZ LOG
PROGRAM
TEST ITEM SCREENING STUDY
DATE
TR #

Figure C-4

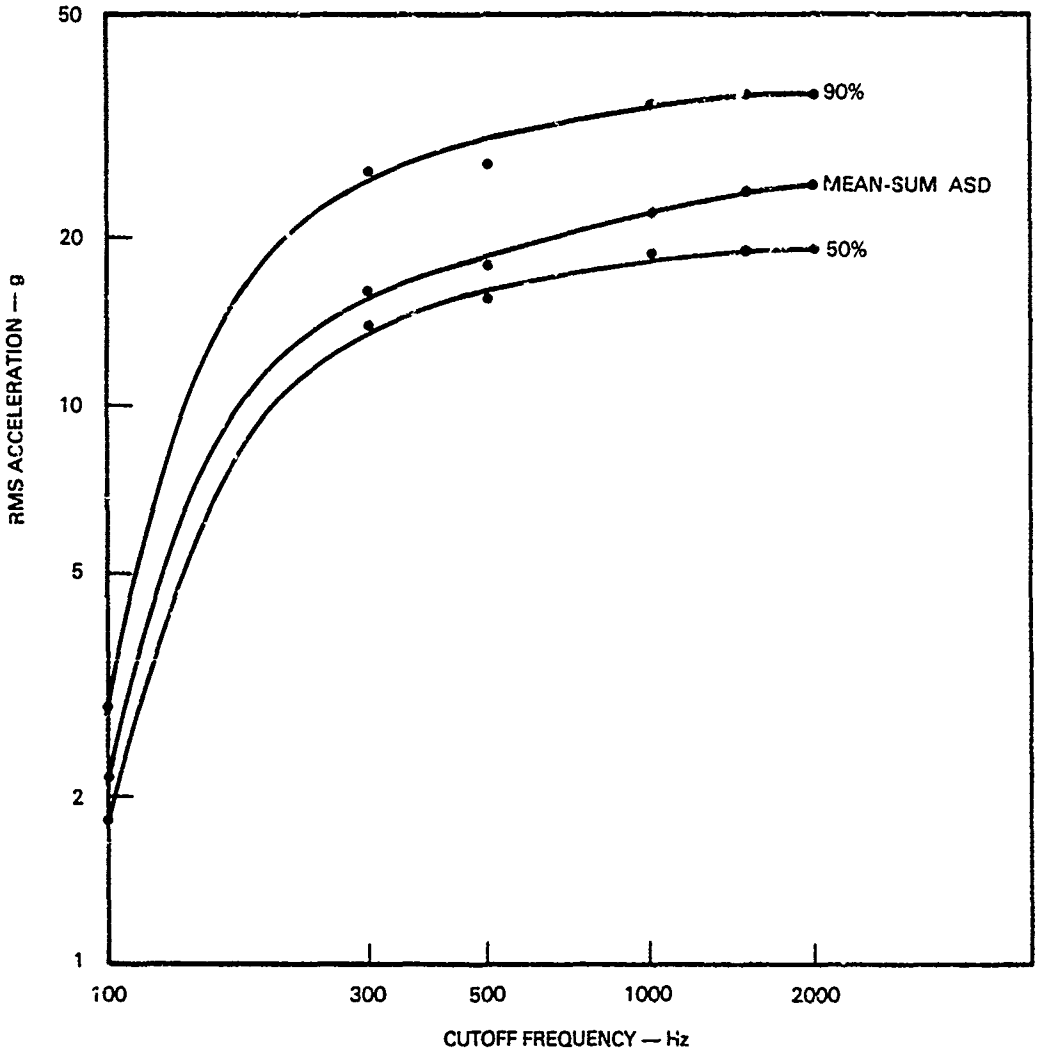


Figure C-5. RMS acceleration vs frequency range, X axis.

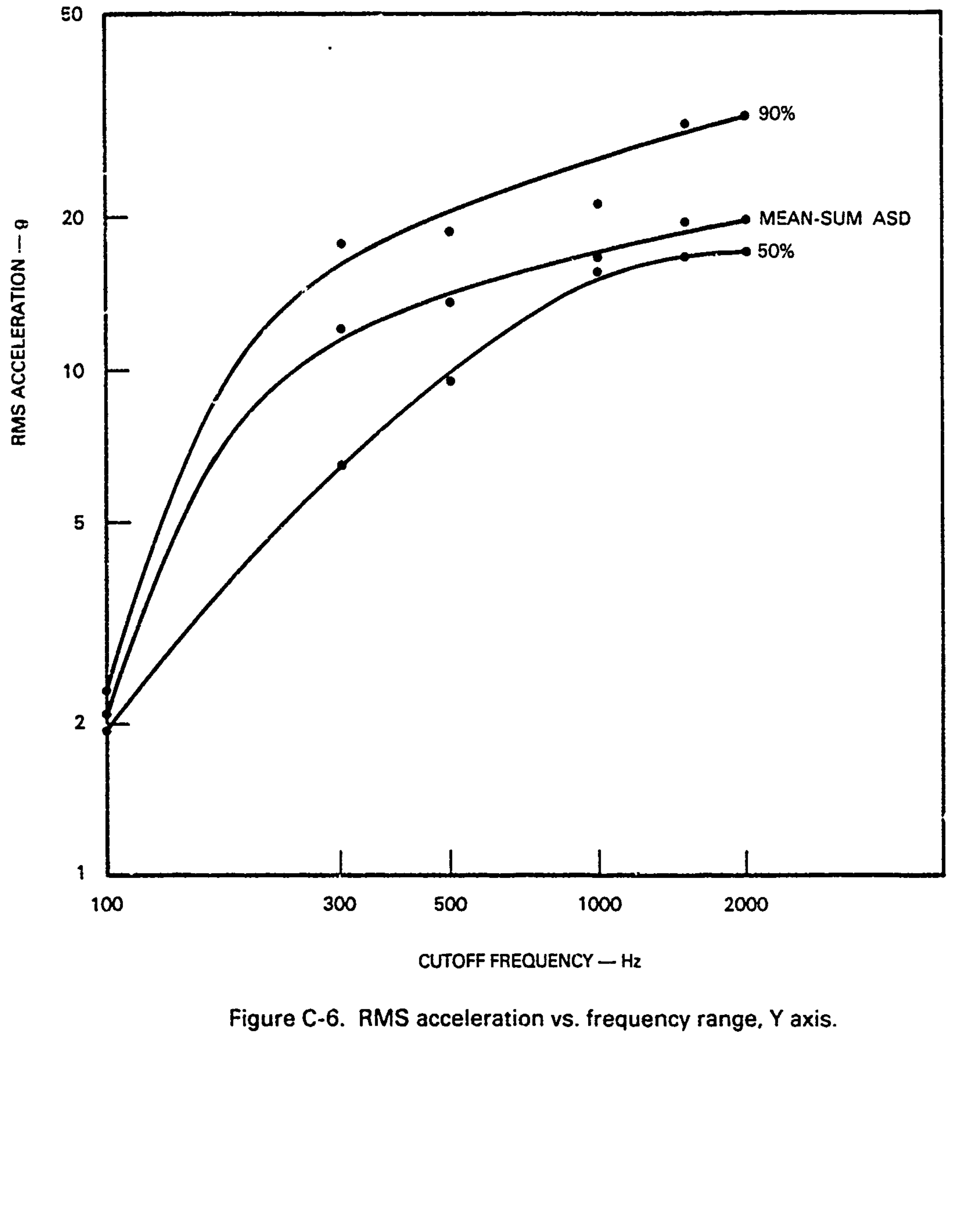


Figure C-6. RMS acceleration vs. frequency range, Y axis.

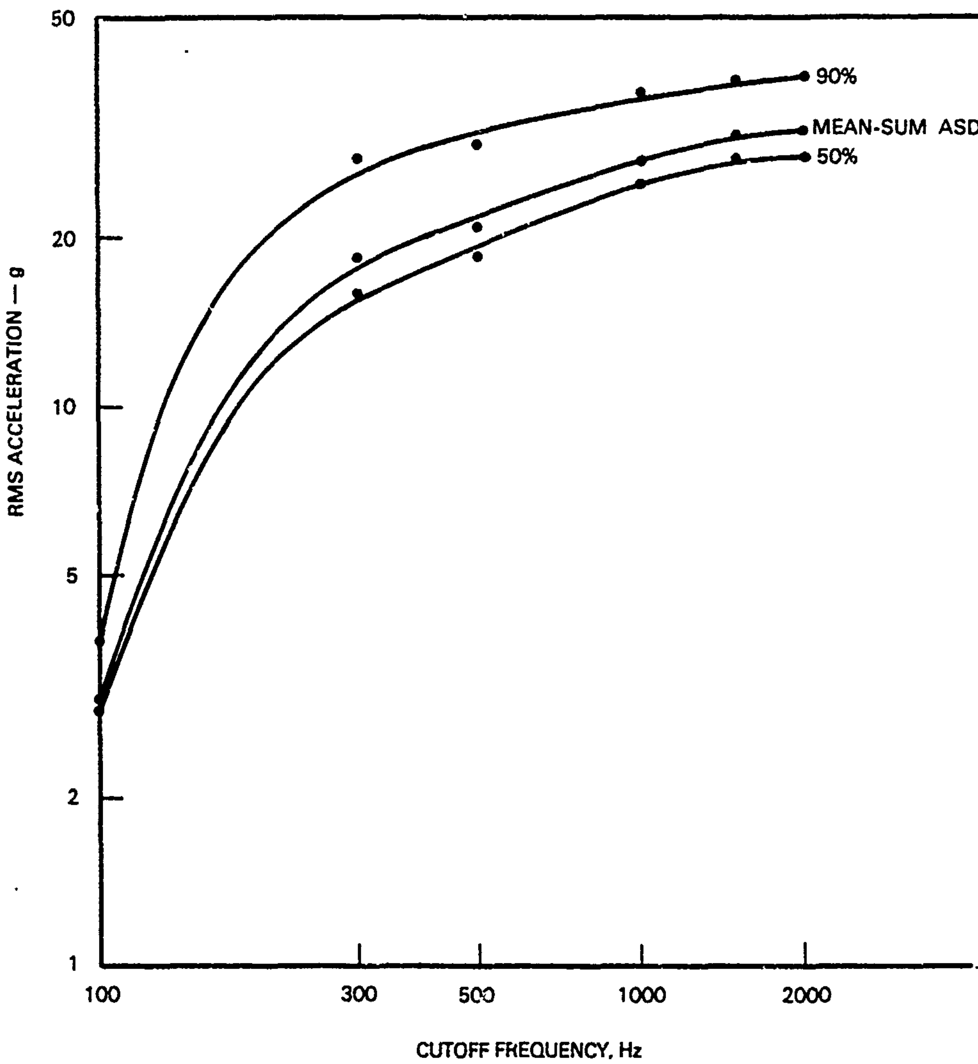


Figure C-7. RMS acceleration vs frequency range, X-Y axes.

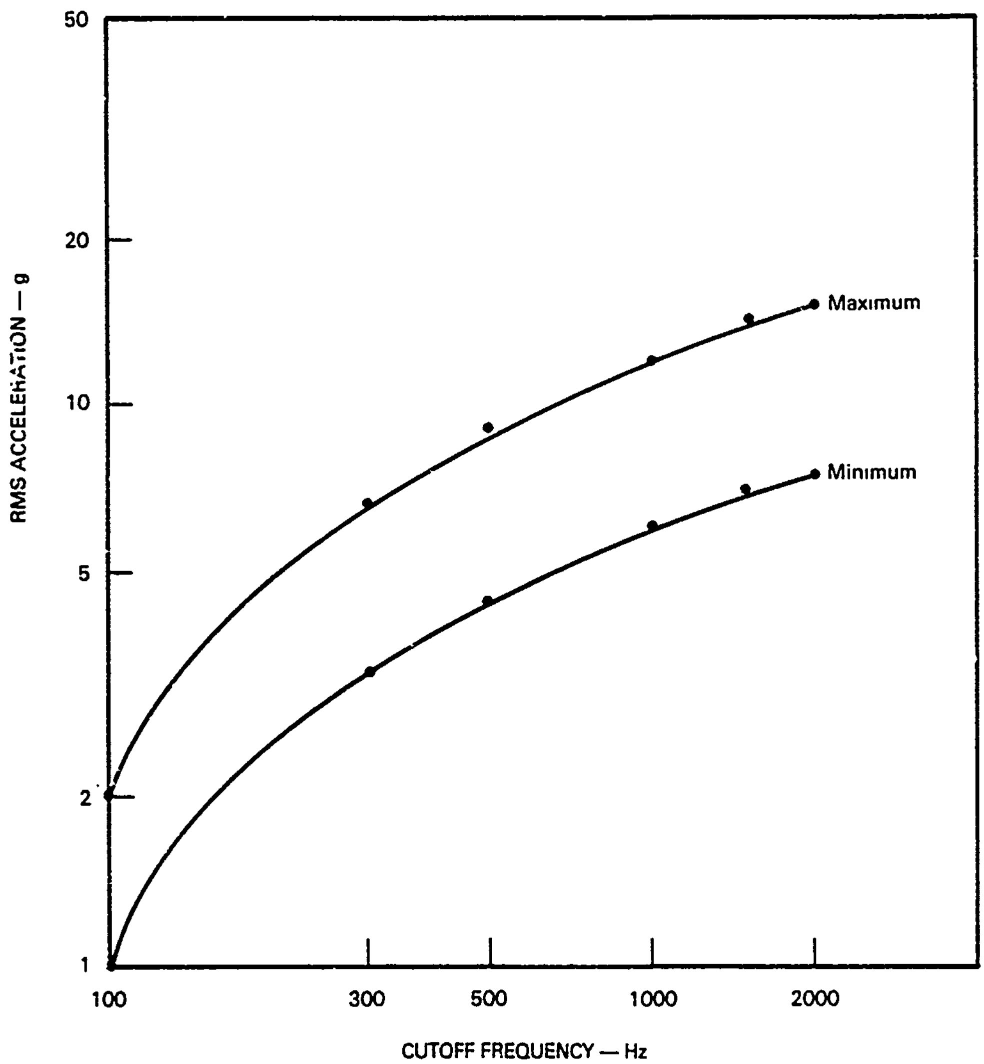


Figure C-8. RMS acceleration vs. frequency range, flaw precipitation threshold.

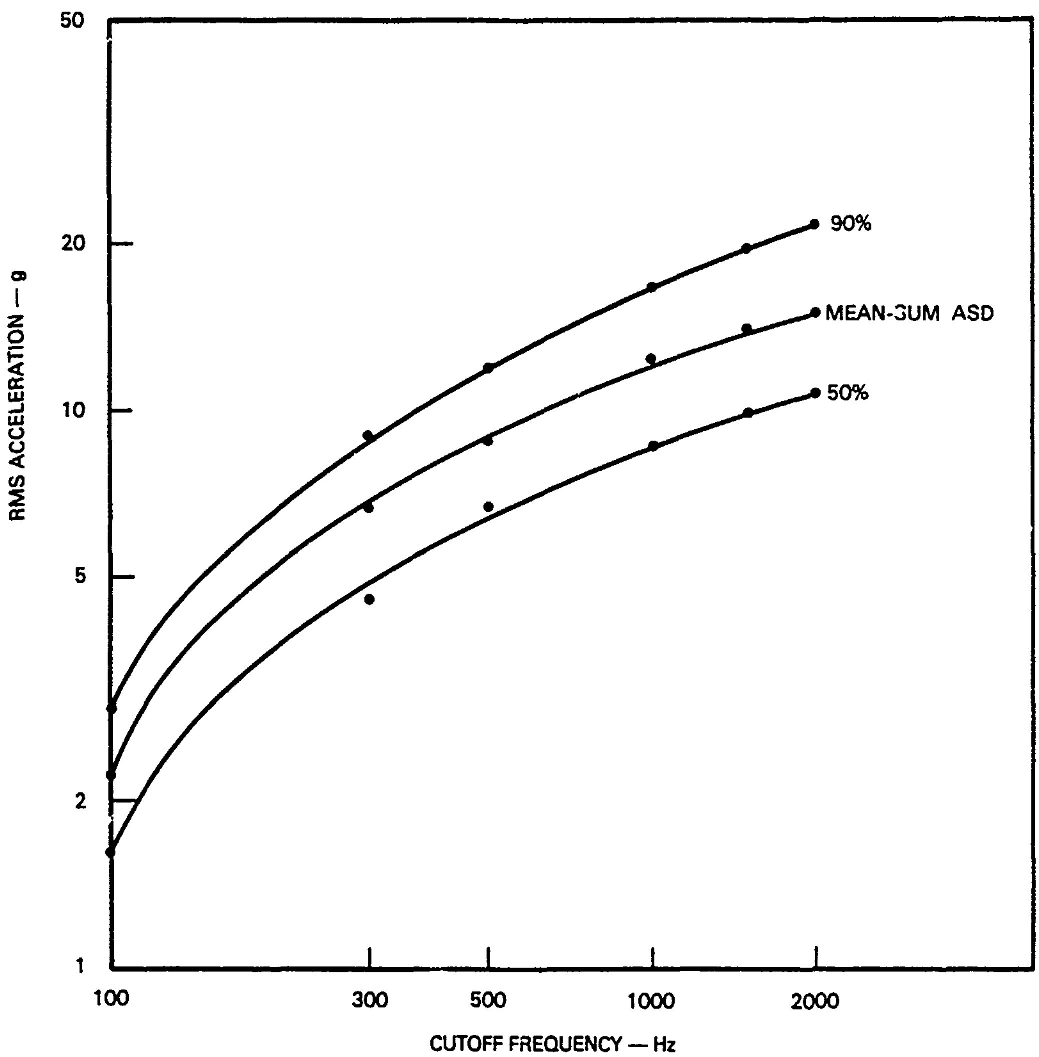


Figure C-9. RMS acceleration vs. frequency range, flaw precipitation threshold.

ACCELERATION SPECTRAL DENSITY

Range of Mean Response

Sum-ASD

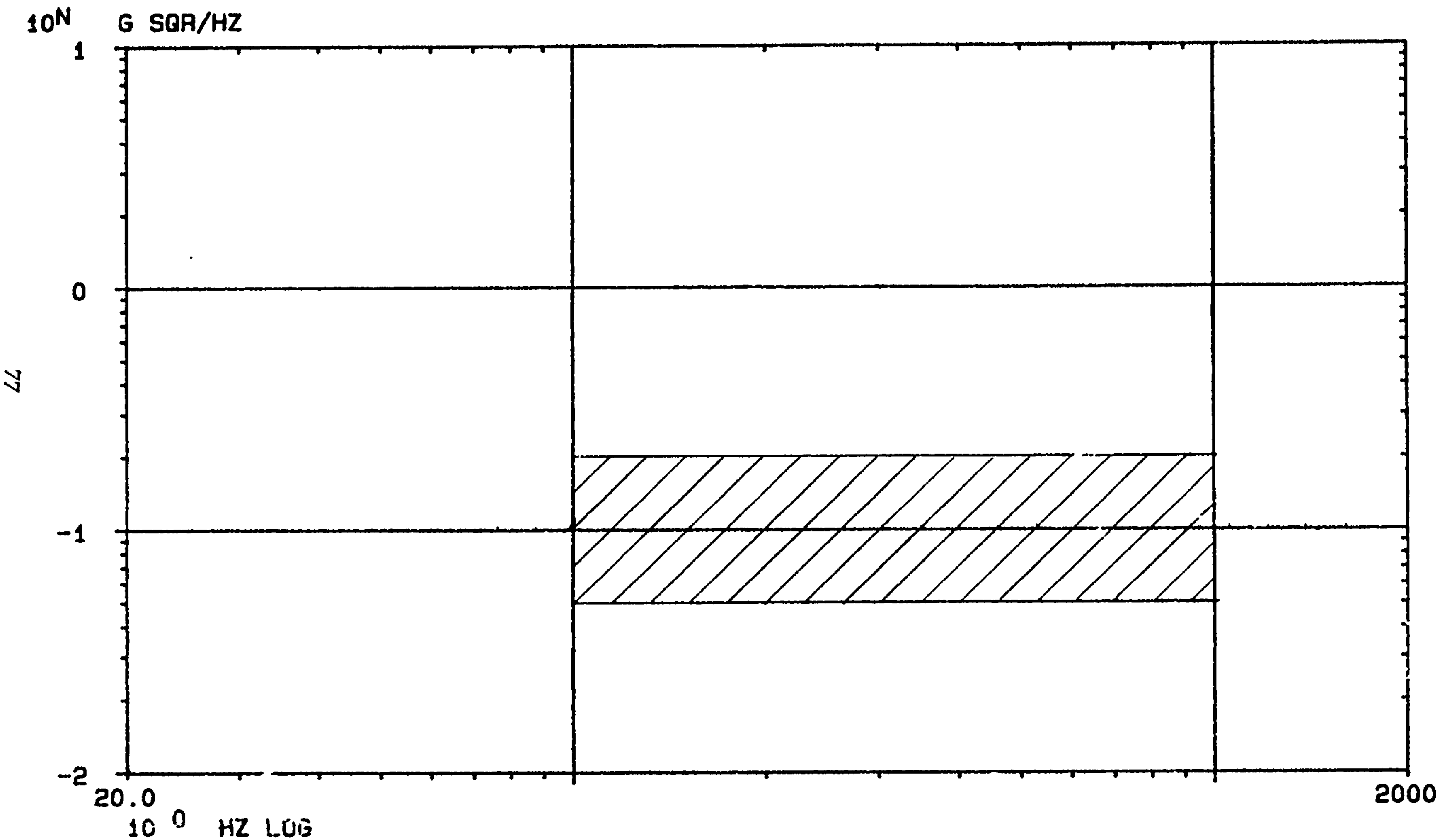


Figure C-10

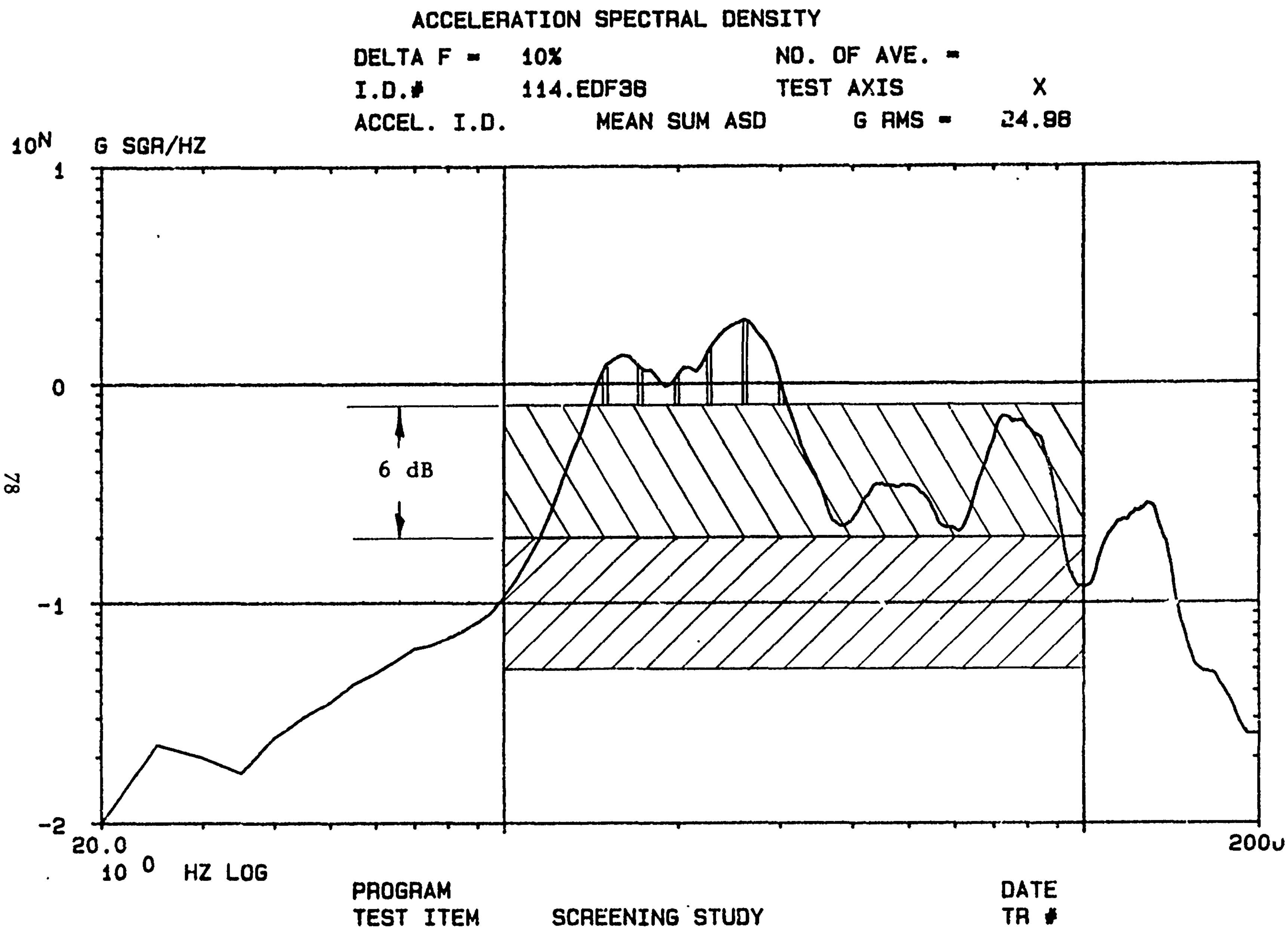

ACCELERATION SPECTRAL DENSITY
DELTA F = 10%
NO. OF AVE. =
I.D.# 114.EDF38
TEST AXIS X
ACCEL. I.D.
MEAN SUM ASD
G RMS = 24.98
10N G SQR/HZ
1
0
-1
-2
6 dB
20.0
10 0 HZ LOG
2000
PROGRAM
TEST ITEM SCREENING STUDY
DATE
TR #

Figure C-11

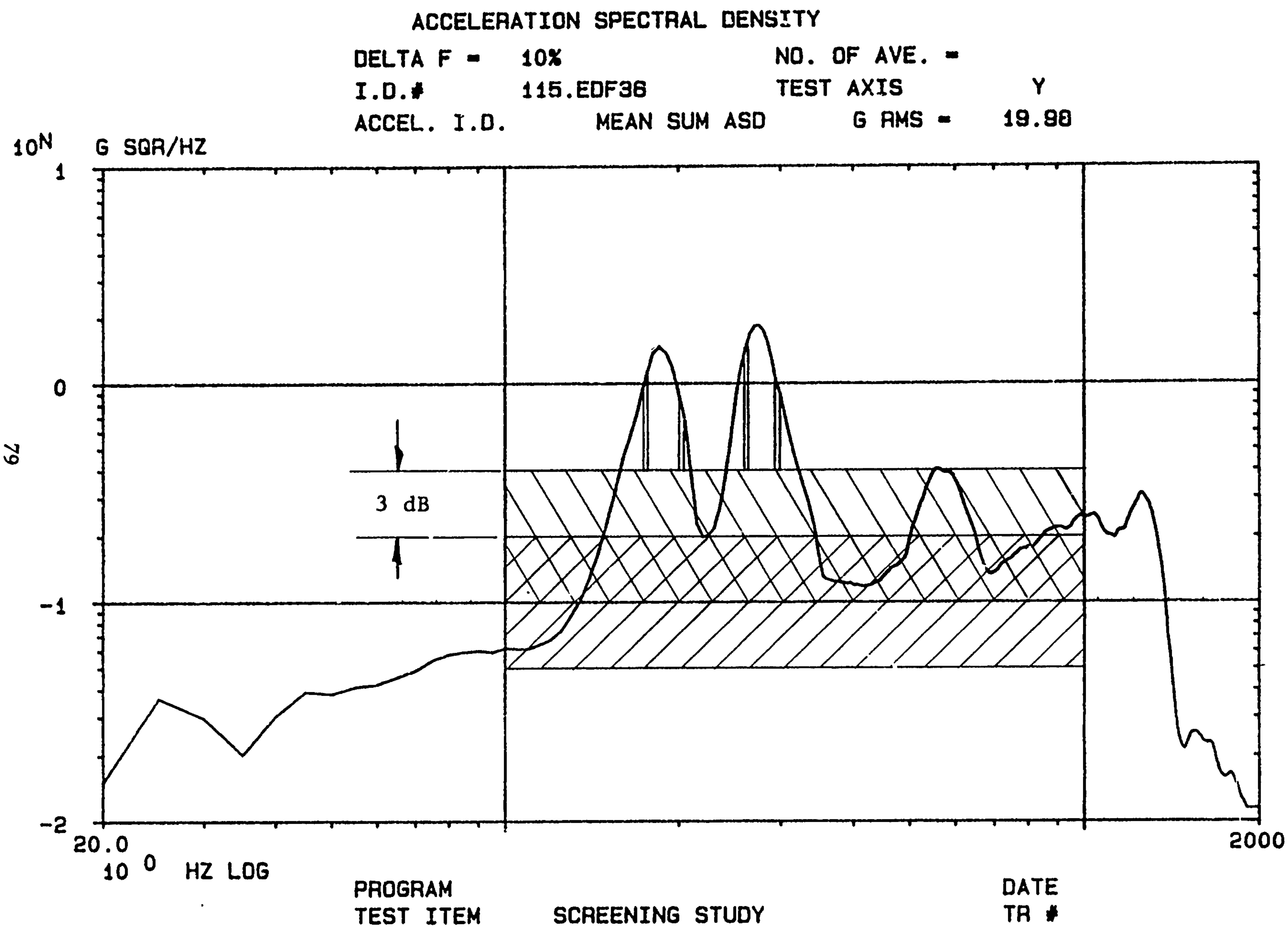

ACCELERATION SPECTRAL DENSITY
DELTA F = 10%
NO. OF AVE. =
I.D.# 115.EDF36
TEST AXIS Y
ACCEL. I.D. MEAN SUM ASD
G RMS = 19.98
10N G SQR/HZ
1
0
-1
-2
3 dB
20.0
10 0 HZ LOG
2000
PROGRAM
TEST ITEM SCREENING STUDY
DATE
TR #

Figure C-12

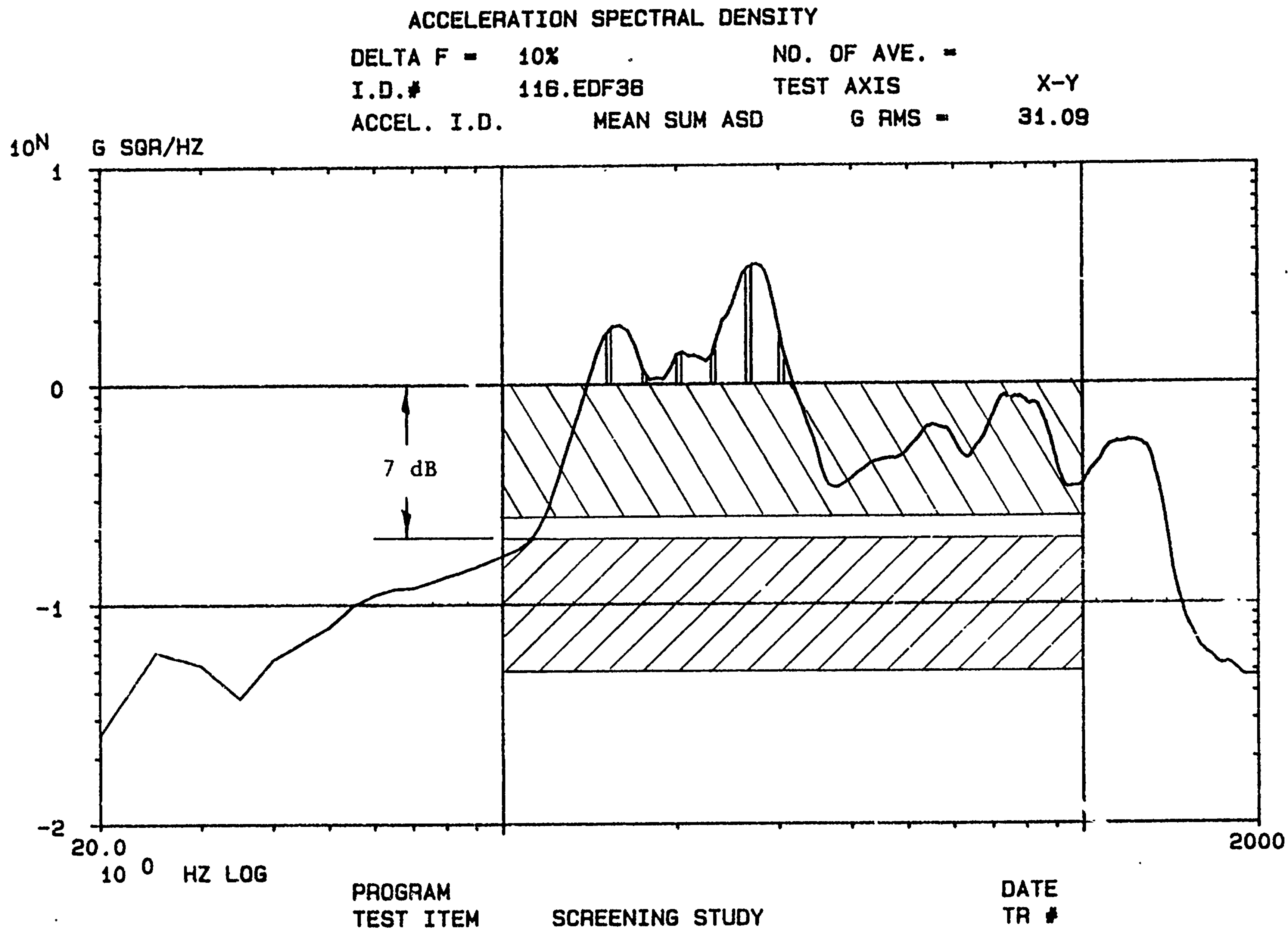

ACCELERATION SPECTRAL DENSITY
DELTA F = 10%
NO. OF AVE. =
I.D.# 116.EDF38
TEST AXIS X-Y
ACCEL. I.D. MEAN SUM ASD
G RMS = 31.09
10N G SQR/HZ
1
0
-1
-2
7 dB
20.0
10 0 HZ LOG
2000
PROGRAM
TEST ITEM SCREENING STUDY
DATE
TR #

Figure C-13

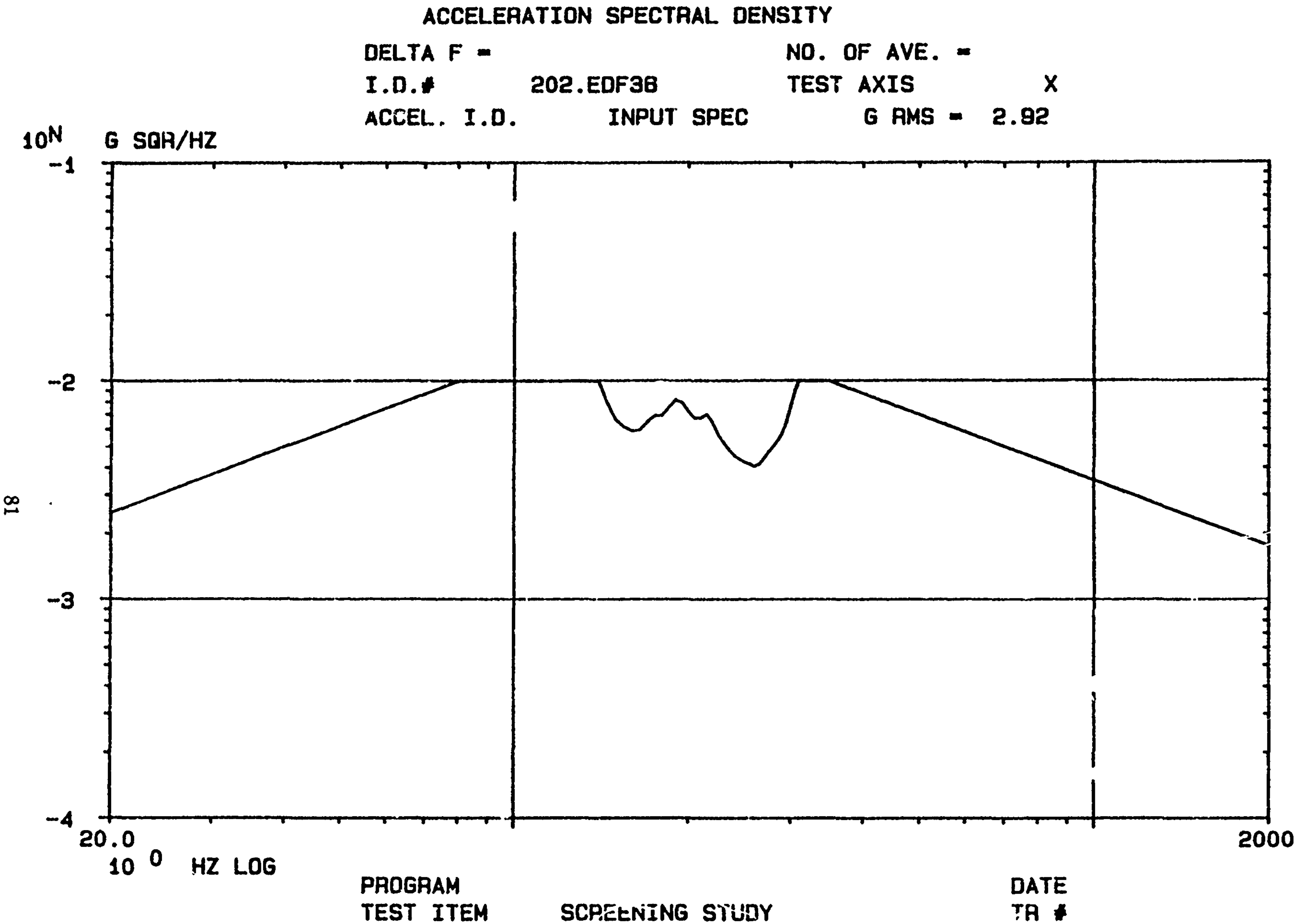

ACCELERATION SPECTRAL DENSITY
DELTA F =
NO. OF AVE. =
I.D.# 202.EDF38
TEST AXIS X
ACCEL. I.D. INPUT SPEC
G RMS = 2.92
10N G SQR/HZ
-1
-2
-3
-4
20.0
10 0 HZ LOG
2000
PROGRAM
TEST ITEM SCREENING STUDY
DATE
TR #

Figure C-14

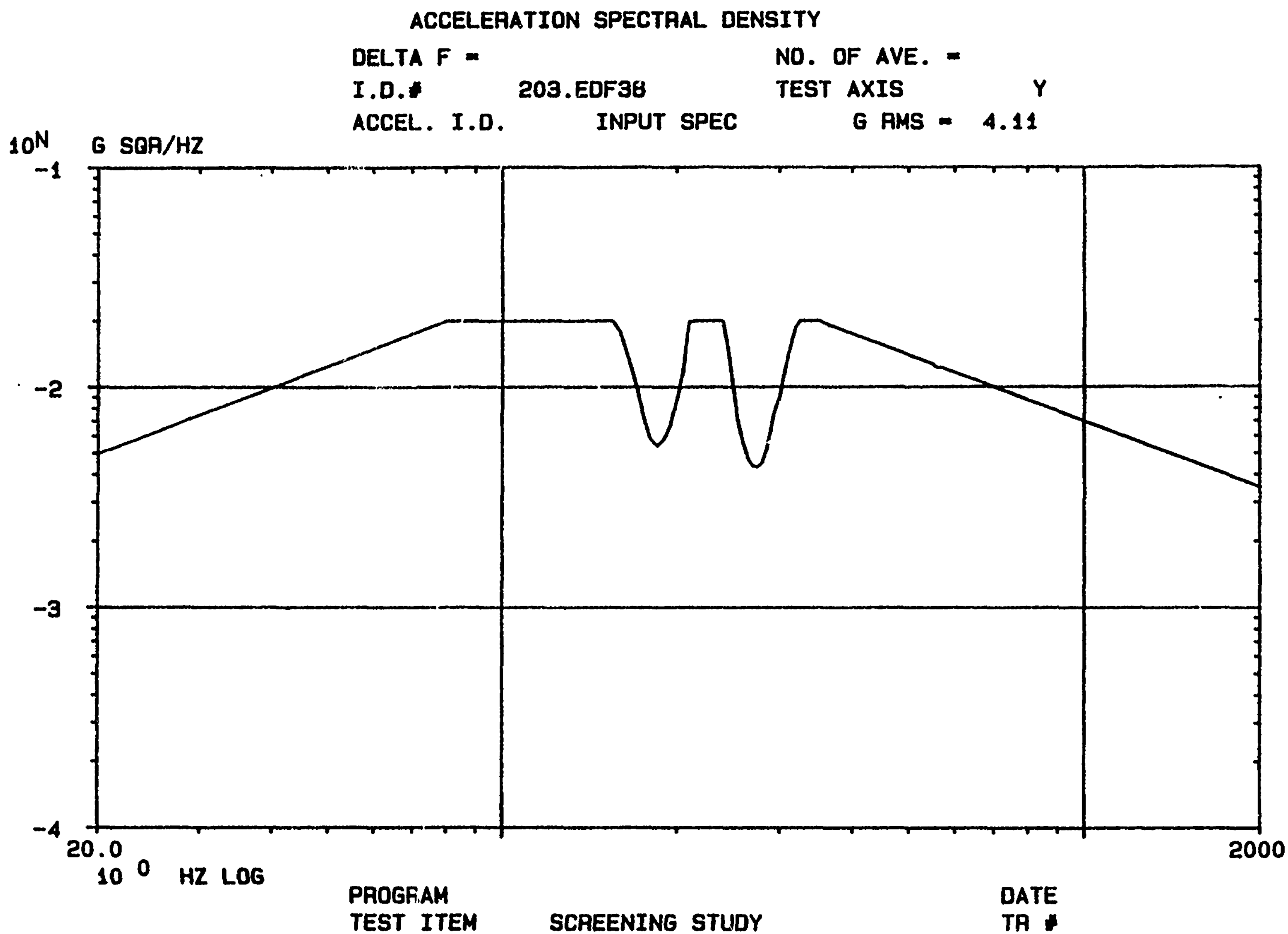

ACCELERATION SPECTRAL DENSITY
DELTA F =
NO. OF AVE. =
I.D.# 203.EDF38
TEST AXIS Y
ACCEL. I.D. INPUT SPEC
G RMS = 4.11
10N G SQR/HZ
-1
-2
-3
-4
20.0
10 0 HZ LOG
2000
PROGRAM
TEST ITEM SCREENING STUDY
DATE
TR #

Figure C-15

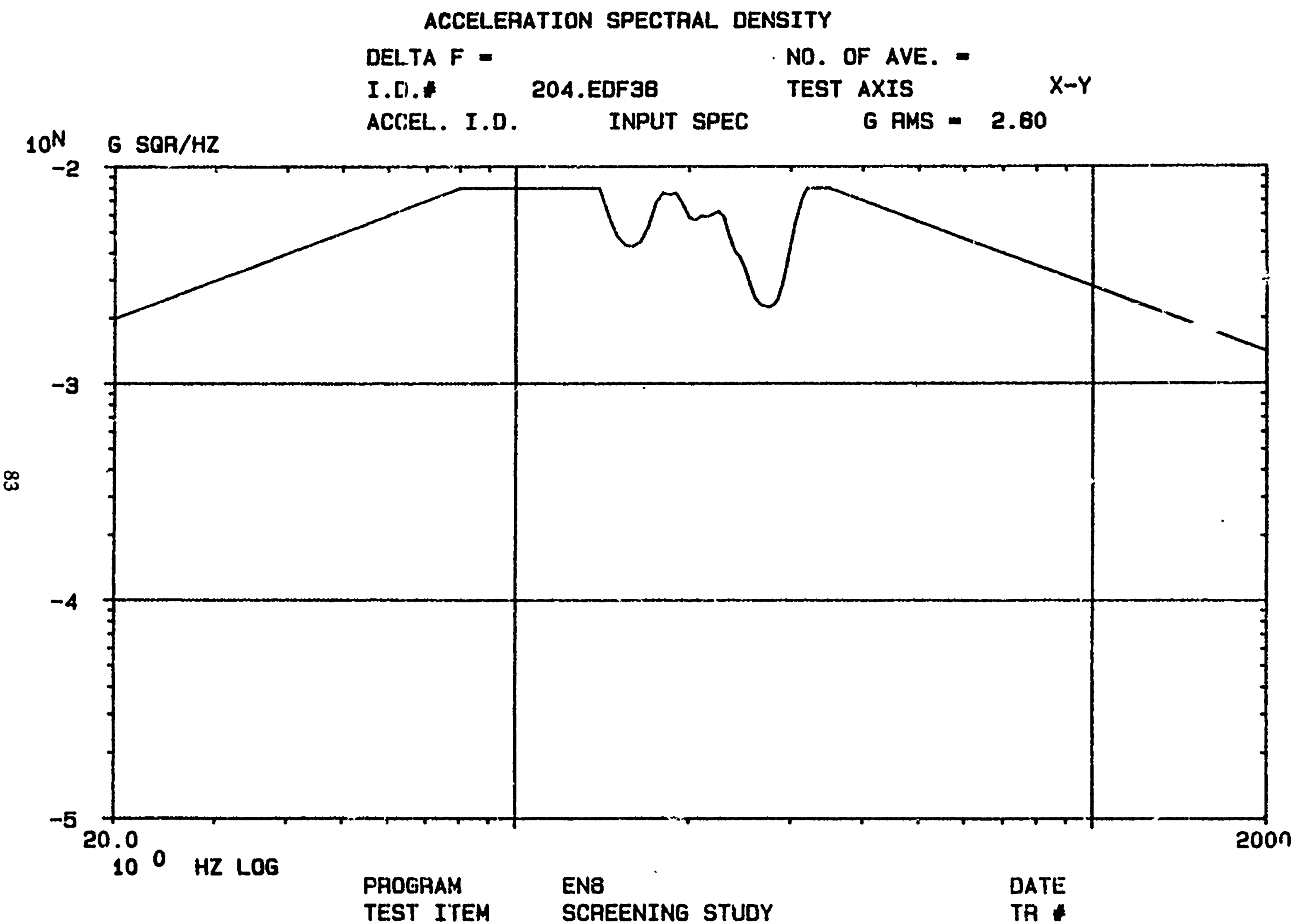

ACCELERATION SPECTRAL DENSITY
DELTA F =
NO. OF AVE. =
I.D.# 204.EDF38
TEST AXIS X-Y
ACCEL. I.D. INPUT SPEC
G RMS = 2.80
10N G SQR/HZ
-2
-3
-4
-5
20.0
2000
10 0 HZ LOG
PROGRAM ENS
TEST ITEM SCREENING STUDY
DATE
TR #

Figure C-16