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TEST TECHNOLOGY

PYROTECHNIC SHOCK STRUCTURAL RESPONSE

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Abstract. The following paper is the second of three that are based on presentations given at the 59th Shock and Vibration Symposium in a Plenary Session on Mechanical Shock Measurement. Hosted by Sandia National Laboratories and the Air Force Weapons Laboratory, the Symposium was held in Albuquerque, New Mexico on October 18-20, 1988. The first paper "State of the Art of Measuring Ground Shock and Cratering Phenomena," by E.J. Rinehart of the Defense Nuclear Agency was published in the September issue of the DIGEST. "Underwater Shock Measurement," by Henry C. Pusey, Consultant, Haymarket, Virginia, will follow. This presentation concerns the measurement of structural response on a structure subject to a pyrotechnic event.

The term "structural response" has been chosen for the title of this presentation when reference is made to the response of a dynamic mechanical structure in the 100- to 2,000-Hz range. This presentation explores what needs to be done in order to collect valid response data in that frequency regime as a result of a pyrotechnic event occurring on the structure.

The Naval Weapons Center was involved in an informal program related to the measurement of "structural response" under pyrotechnic shock in conjunction with a number of other organizations (McDonnell Douglas, General Dynamics, Astron and Endevco). The problem in measurement of "structural response" involved a need to obtain acceleration measurements close to the source of the pyrotechnic shock. Under these conditions, the signal-to-noise ratio, particularly in the 100- to 2,000-Hz range is, in general, very low.

In this presentation, some of what was learned during the course of the study about the collection, signal conditioning and processing of the data will be discussed. It is hoped that some of these experiences will provide a common ground for further reflection and discussion by other investigators.

WHAT IS PYROTECHNIC SHOCK?

The source of pyrotechnic shock is the detonation of an ordnance device on a structure. The shock that is produced is characterized by a near-instantaneous velocity change at the detonation point, with the acceleration momentarily approaching an infinite value. There is an intense stress wave propagation field throughout the structure, with accompanying stress wave reflection, amplification and eventual attenuation. Structural response to the shock measured in terms of acceleration at locations on the structure is of a high amplitude and a high frequency nature.

Figure 1 shows a typical pyrotechnic shock acceleration time history. This figure shows a valid piece of data about 4 milliseconds in duration. It has a two-sided character, and the time history trace decreases to the noise floor of the measurement system. In general, the pyrotechnic shocks that will be discussed in this paper are very modest events, with measured responses around 5,000 to 10,000 g and quite modest "grain per foot" pyrotechnic excitation inputs. Some of the work in the 1970s involved much higher g levels and much larger pyrotechnic excitation inputs.

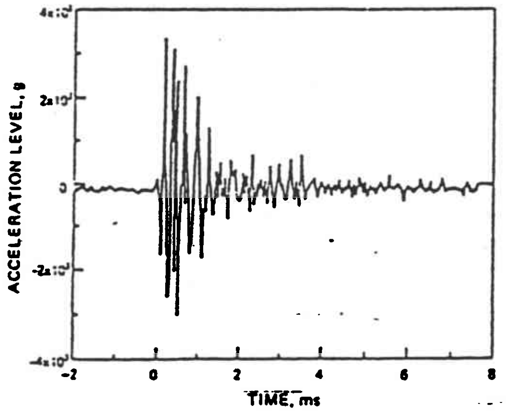

Figure 1. Typical Acceleration Time History for Pyroshock Event.

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MEASURING STRUCTURAL RESPONSE

There are four elements to a measurement system for structural response, as shown in Figure 2 [1]. First there is the transducer. Generally a high-frequency accelerometer is used. The signal from the accelerometer is fed into a signal conditioner, or amplifier, which usually includes a low-pass/high-pass filter combination. The voltage signal from the signal conditioning system is input to the recording system, which is either a tape recorder or a transient recorder. Finally, there is an analyzer with an anti-alias filter that processes the signal from the recording system.

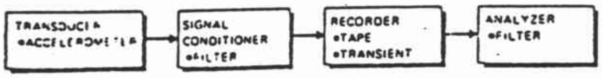


Figure 2. Measurement System for Structural Response.

In considering the problem of measuring structural response to pyrotechnic shock, it is important to understand the relationship between "material response" and structural response. Material response is the initial response of the material of the structural system to the pyrotechnic transient loading. It basically is characterized by the time interval required for the wave propagating in the structure to dissipate. During this time interval, the response of the free surfaces within the structure experience irregular steps in particle velocity, with sudden acceleration impulses of near infinite magnitude. In general, the material response is not measured, but its effects can be prevalent throughout the measurement system. Very broad band frequency devices such as strain gages could be used to measure the material response.

Because of its effect on the accelerometer and subsequently on the signal conditioner-amplifier system, the material response does affect measurement of the structural response. In particular, because of the material response, it becomes necessary to make a judgment as to whether the measured structural response is valid. In any case, if the measurement system is ranged high enough to prevent saturation of the accelerometer crystal or signal conditioner-amplifier system or both because of the material response, then the signal-to-noise ratio is very poor for structural response measurement.

Figure 3 is a sample of an amplitude time history illustrating three basic time-event regions. There is a material response region initiated by a sharp pulse. The transducer used for this particular time trace was a piezoelectric accelerometer, Endevco Model 2255B. The material response region, which lasts about 50 microseconds, initiates a very strong electrical pulse, probably caused by the wave propagating within the crystal of the accelerometer. This pulse is followed by a dead period, with no observable response, and finally by a structural response monitored by the accelerometer a few microseconds later. Here, the material response spike is "measured" at 80,000 g, even though physically it may not correlate at all with g measurement. The data in Figure 3 was sampled at 4 million samples per second. If twice the sampling rate were employed, that peak would be higher than 80,000. The peak reading is very dependent upon the sample rate.

Figure 3 clearly illustrates the preshock or the prepulse event, followed by the material response, the attenuation of the wave, and then the structure beginning to respond. It is the structural response that is the concern of this presentation and main concern with regard to measurement. If there is a need to set the signal conditioning so that it is not saturated by the early high level, the measurement system signal-to-noise ratio goes down. This is a big part of the problem.

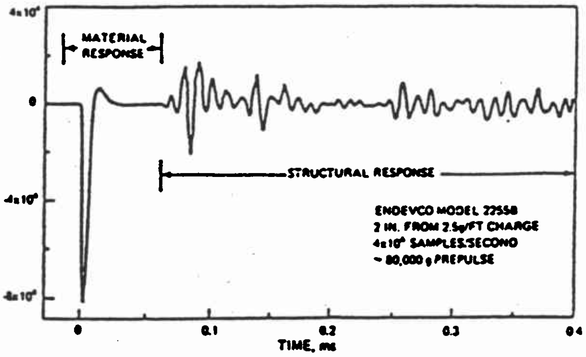
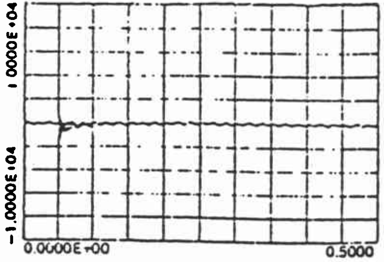


Figure 3. Pyroshock Acceleration Time History Showing Preshock Event.

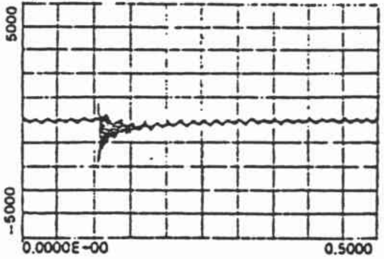
Figure 4 contains some typical acceleration time histories. Figure 4(a) shows an initial pulse with some noise contamination. Figure 4(b) shows a DC offset and a small initial pulse. Figure 4(c) shows a clear initial pulse with DC offset. In the latter case, there is either amplifier saturation or accelerometer crystal saturation. Figure 4(d) shows no offset but a decided one-sided initial pulse similar to that in Figure 4(a). These are some of the types of invalid measurements that may be experienced.

Additional observations on accelerometer measurement of pyrotechnic shock structural response are as follows:

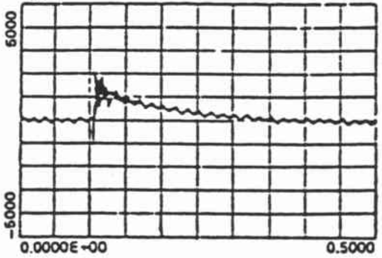
(a) INITIAL PULSE WITH NOISE



(b) DC OFFSET WITH NOISE



INITIAL PULSE WITH
(c) DC OFFSET AND NOISE



(d) INITIAL PULSE WITH NOISE

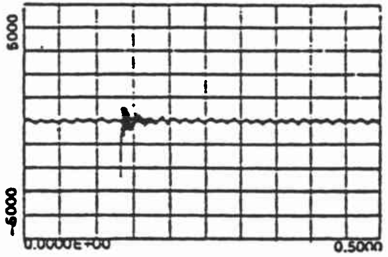


Figure 4. Typical Invalid Acceleration Time Histories.

- Mechanical accelerometers perform poorly in response to near-instantaneous velocity change, such as the sharp spike initiating the material response phase.
- It is difficult, if not virtually impossible, to measure "prepulse" associated with material response using an accelerometer.
- The "prepulse," in general, will cause excitation of the accelerometer resonant frequency.
- The "prepulse" may cause accelerometer "zero-shift" or "crystal saturation."
- Special care is required in electrical isolation and accelerometer mounting.
- Mechanical filtering at the accelerometer may be possible and desirable.

The second element in the schematic of Figure 2 is the amplifier, or signal conditioner, and its associated filter at the output stage. A test was conducted to examine the consistency of the amplifier/filter configuration and to attempt to collect low-frequency data (below 2,000 Hz) [2]. It is important to note that the amplifiers tested performed electrically exactly as amplifier manufacturers indicated they would.

The test setup consisted of a steel plate with 10 accelerometers. Five different amplifiers were tested. The findings were tape-recorded and results evaluated using the shock response spectra. It was determined that there were too many discrepancies to draw many conclusions about the amplifier/filter consistency.

Figure 5 shows the results for three different types of amplifiers involving a number of shocks. In general, there is fairly good consistency for a given amplifier. However, there are obviously significantly different shock response spectra for the different amplifiers.

Figure 6 shows the variation for the same amplifier and same accelerometer. The three different amplifiers and the mean of these shock response spectra (lower plot) are plotted. At some frequencies one may obtain up to 20 dB difference in the shock response spectra between the amplifiers. Again, the amplifier information was fairly inconsistent.

Figure 7 provides acceleration time history traces from two amplifiers that were low-pass filtered at 20 kHz during playback from the tape recorder. The signal was recorded on a tape recorder that had a frequency response level to 80 kHz.

Figure 8 shows some other cases illustrating amplifier filter differences. Figure 8(a) is for an amplifier with a 4-Hz high-pass filter, Figure 8(b) is for an amplifier with a 4- to 2-kHz band-pass filter and Figure 8(d) is for one with a 4-Hz high-pass and a 2-kHz low-pass mechanical filter. These three time histories show substantial differences. Figure 8(c) illustrates a second amplifier with a 2.5-kHz low-pass filter which for the same pyrotechnic input produced another form of time history trace.

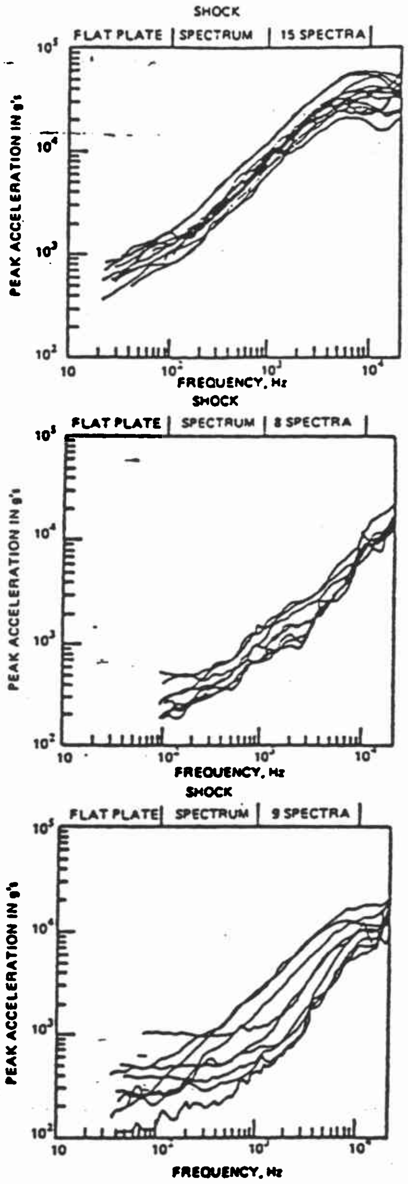


Figure 5. Variation with Amplifier

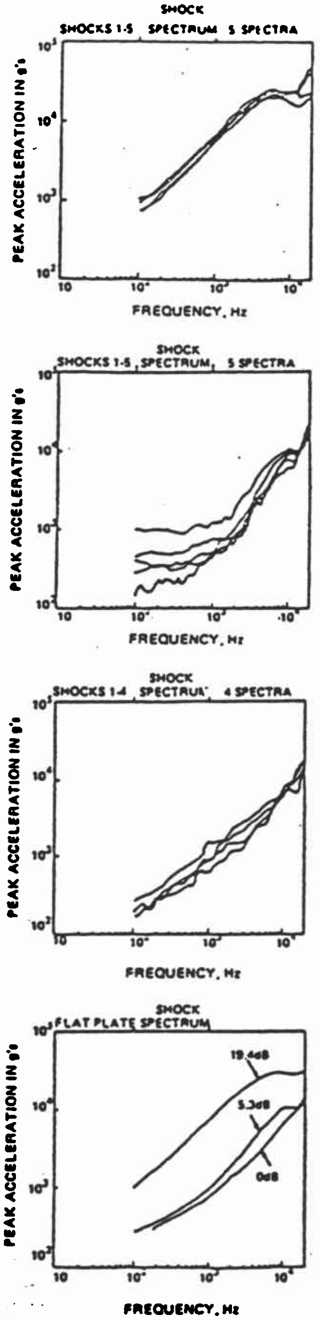


Figure 6. Variation for Same Accelerometer/Same Amplifier

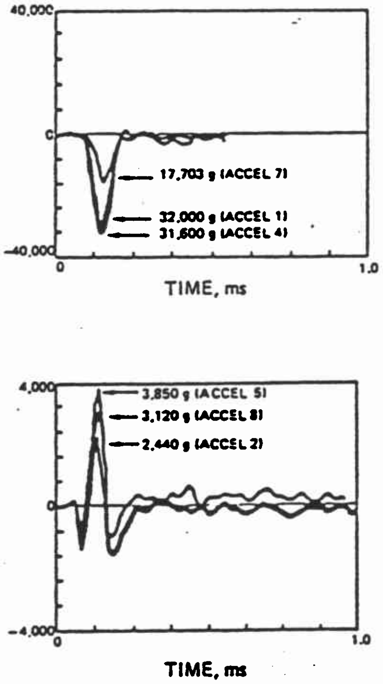


Figure 7. Variation Over Amplifier for 20 kHz Low-Pass Filter on Playback for Analysis

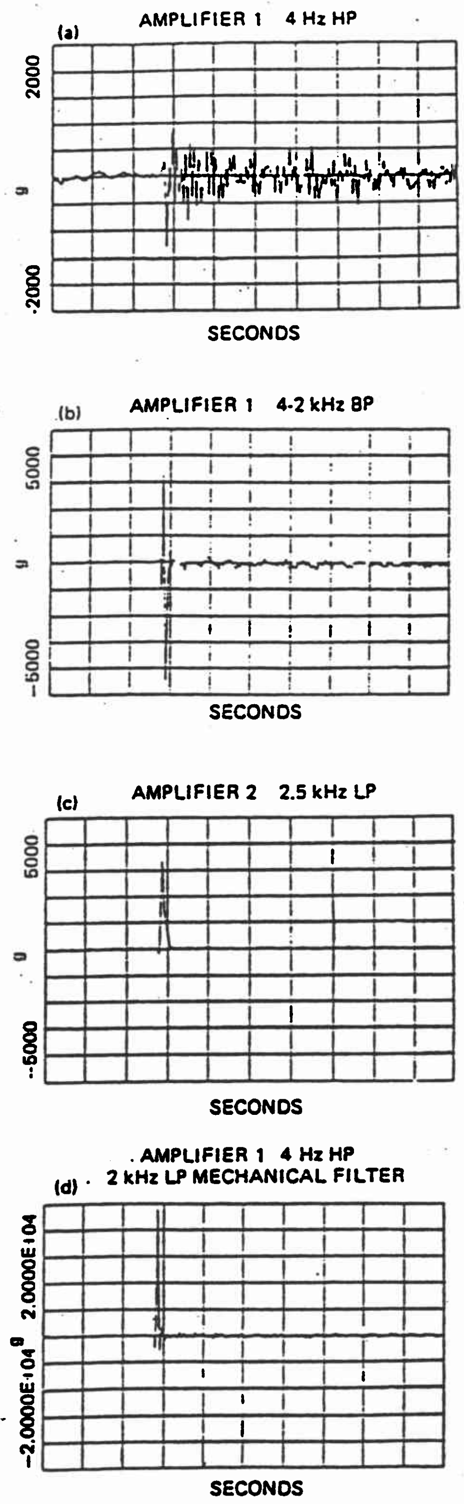


Figure 8. Amplifier/Filter Differences.

Figure 9 illustrates some other common accelerometer amplifier problems. From this study there are still a number of questions about amplifiers.

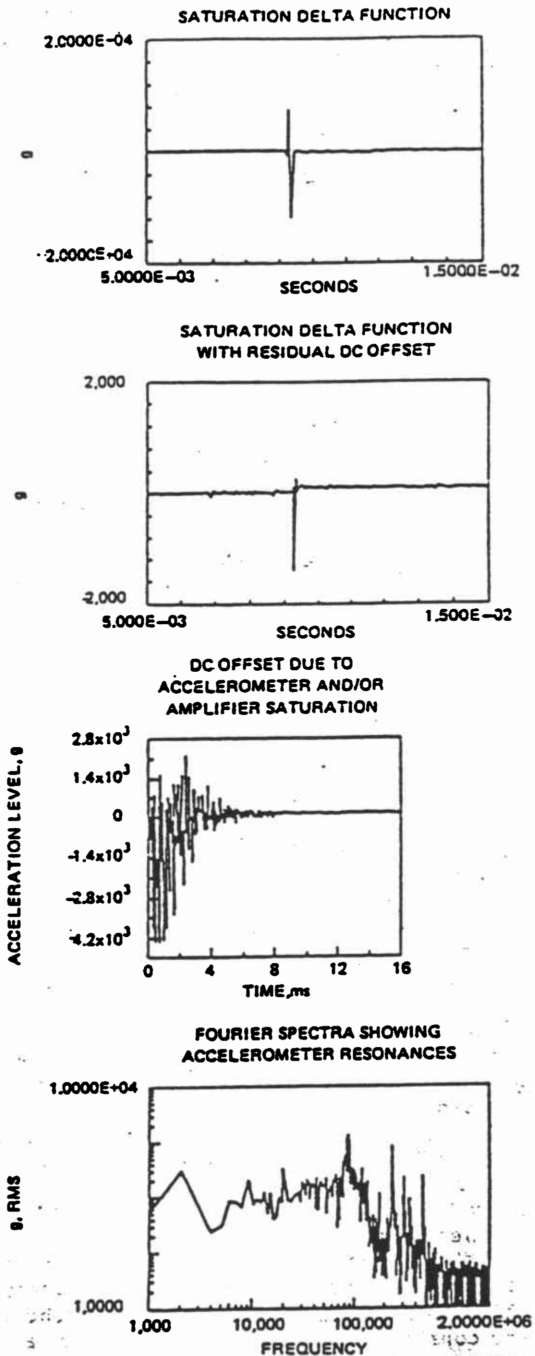


Figure 9. Illustration of Common Accelerometer/Amplifier Problems.

With respect to the recording system and, in particular, tape recorders and their associated problems, the key problem probably is the limited 30 to 40 dB signal-to-noise ratio. If only a few channels of data need to be recorded, the transient recorder provides better signal-to-noise ratio and provides a potential solution in this area.

The following observations may be drawn with respect to signal conditioning and recording:

- The "prepulse," or the effect of "prepulse," may cause the amplifier to "zero-shift" or to saturate, or it may cause slew-rate limiting.
- Electronic low-pass filtering below 20 kHz is questionable and probably should not be done on the output stage of the amplifier.
- Electronic high-pass filtering above 20 Hz appears to be acceptable.
- Use of transient recorders with 70+ dB signal-to-noise ratio is a potential recording system signal-to-noise ratio problem solution.
- Use of laboratory-quality, IRIG standard, 14-channel FM tape recorders is recommended if transient recorders are not available. However, it must be remembered that only a 30 to 40 dB signal-to-noise ratio is available.
- Use of a "standard tape" is recommended for azimuth, speed accuracy and tracking consideration.

Turning now to the processing of the data, Figure 10 illustrates a part of the problem of obtaining good structural response measurements. This figure shows a shock response spectrum (SRS) on a portion of the accelerometer output computed just before the shock. This is what is indicated by the noise spectrum, which "defines" the noise floor of the measurement system. A SRS on the shock is computed and overlayed on the plot. At 500 Hz and above the signal SRS is significantly above the noise SRS. This pattern confirms the need to check the signal-to-noise ratio by doing an SRS on the short portion of the signal before the shock and comparing it to the SRS of the shock. Another technique to assist in assessing the validity of acceleration data is what might be termed, "the velocity correction hypothesis," which is summarized in Table 1. The conditions are considered necessary conditions for a valid pyrotechnic shock acceleration measurement. Consider a shock that has a definite start time with a high signal-to-noise ratio, a statistically similar two-sided amplitude character, many zero crossings and a definite well-defined decay to the noise floor of the instrumentation system. If the acceleration is integrated, the velocity is essentially an additive random process with independent stationary increments. After the low-frequency "random walk" noise is filtered out, usually by visual inspection, the four characteristics listed in Table 1 should be present in the velocity time history.

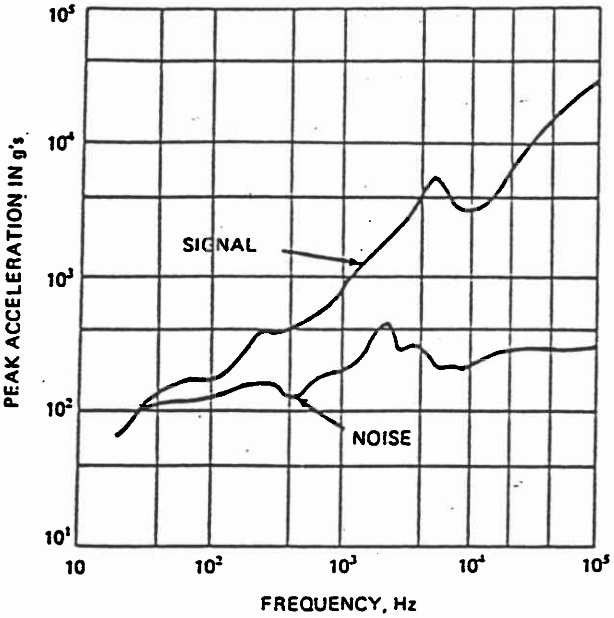


Figure 10. Shock Response Spectrum Illustrating Signal-to-Noise Problems at Low Frequencies.

Table 1. Velocity Correction Hypothesis.

Hypothesis ("Necessary Conditions")

For a valid pyrotechnic shock acceleration measurement $\ddot{x}(t)$ then $\ddot{x}(t)$ has

(1) definite start time (high signal-to-noise ratio
(2) statistically similar two-sided amplitude character
(3) many zero crossings
(4) definite well-defined decay to noise floor of instrumentation system then

$$\dot{x}(t) = \int_0^T X(u)du$$

is an additive random process with independent stationary increments and characteristics (1)-(4) after "random walk" low-frequency noise is removed

Table 2 summarizes implementation of the hypothesis. First, the period of time over which the shock occurs is selected, the mean acceleration is computed, the acceleration is constrained by subtracting the mean, and a constrained velocity is computed. Then, the constrained velocity is checked for character of pulse (one- or two-sided), number of zero crossings, overall amplitude and general appearance.

Table 2. Velocity Correction Application.

Application

For time interval T starting at <u>beginning</u> of shock compute

$$\bar{x} = \frac{1}{T}\int_0^T \ddot{x}(t)dt$$

Constrain $\ddot{x}(t)$ in this interval by computing

$$\ddot{x}_c(t) = \ddot{x}(t) - \bar{x}$$

Compute the "constrained velocity"

$$\dot{x}_c(t) = \int_0^t \ddot{x}_c(u)du$$

Examine $\dot{x}_c(t)$ for

- √two-sided character
  √number of zero crossings
  √overall amplitude
  (neglecting low-frequency random walk noise)

Figure 11(a) shows quite a long shock. Figure 11(c) is the velocity with a low frequency random walk. It certainly does have a two-sided character, and there is some attenuation. This looks like a valid shock. The shock response spectra, Figure 11(b), also shows characteristics of being valid in the sense of the slopes and the general shape. There is some art to interpreting the time history data along with the processed data for purposes of identifying valid pyrotechnic shock data.

Figure 12 is an example of an invalid pyroshock measurement. In this particular case the velocity proceeds to a large value and has no two-sided character.

Even though there have been quite a few improvements in the accelerometers, the signal conditioning and the tape recording, basically there are two types of analysis techniques: SRS and Fourier analysis, or some variant of the Fourier analysis. Table 3 summarizes some of the most significant characteristics of each technique. The parameters are: time, length of the shock, Q value (in the case of the SRS) and frequency spacing. In general, Q value and frequency spacing are powerful smoothers for shock response spectra.

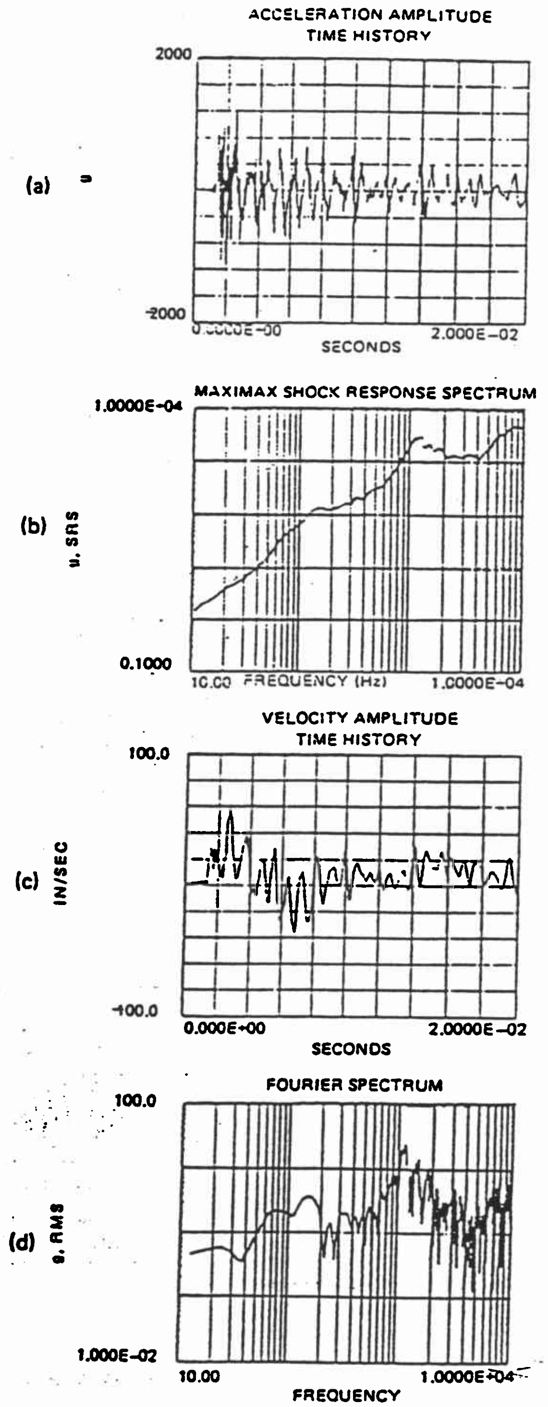


Figure 11. Valid Pyrotechnic Acceleration Measurement.

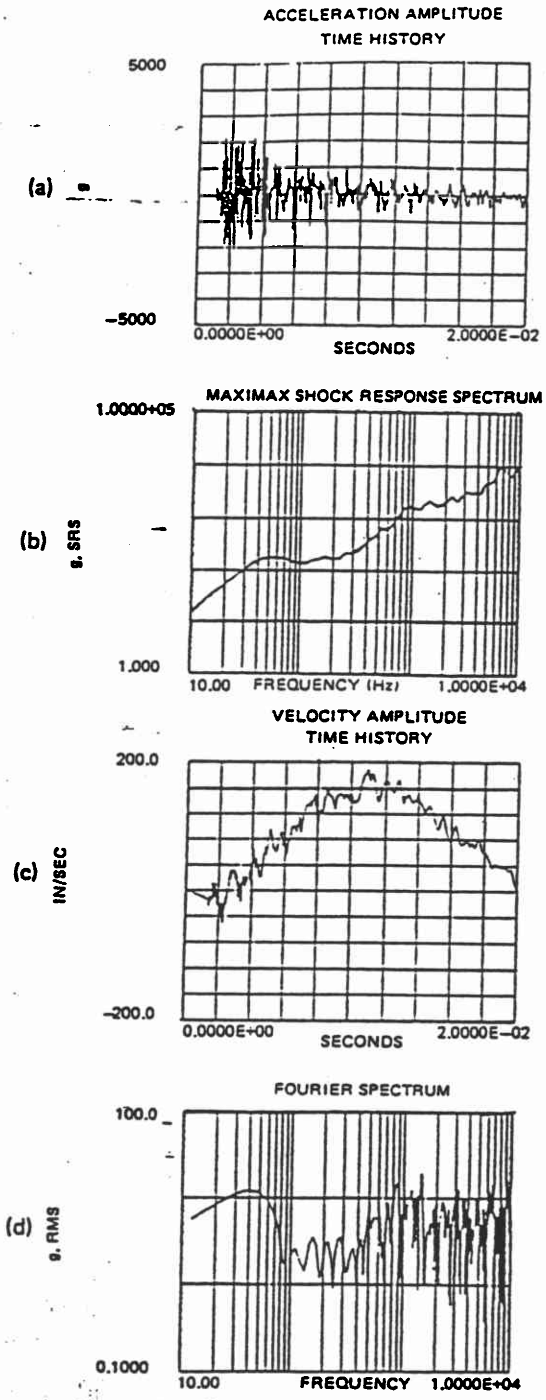


Figure 12. Invalid Pyrotechnic Acceleration Measurement.

Table 3. Analysis Considerations.

Maximax SRS	Fourier
Type	
Linear filtering (Nonlinear selection of maximums)	Linear transformation
Parameters over BW	
T-insensitive	T-insensitive (if selected properly)
Q-Smoothing	Δf-Same smoothing
Δ f-Smoothing	
Computation	
Intensive	Less intensive
Data Qualification	
Comparatively simple	Complex
Collective Analysis	
Single measurement	Single/multiple measurement
Ensemble average	Ensemble average
Neighborhood intensity weak	Neighborhood intensity strong
Some qualitative multichannel	Transfer/transmission with quantitative multichannel

The SRS technique is quite insensitive to the length of the record. The Fourier analysis requires analysis over length of the record, containing high signal-to-noise ratio, and there is very little smoothing through the selection of the frequency spacing (through zero padding or something of this sort). Data qualification is a bit more simply handled by the SRS; it is more complex with the Fourier analysis. In general, the SRS analysis is oriented toward single measurements. Ensemble averaging in the SRS case over several measurement locations is difficult with only qualitative multi-channel transfer characteristics; whereas, with the Fourier analysis, there is the option of being able to do quantitative transfer characteristics to help compare some of the data from various measurement locations.

To complete the discussion of measurement difficulties, observations related to data processing may be summarized as follows:

- An anti-aliasing filter should be set to the highest frequency of interest with a gentle roll-off.
- The data should be sampled at a frequency 10 times the highest frequency of interest.

- The noise in the record should be limited by editing the data to only capture the transient.

- The time history traces should be examined for obvious anomalies.

- In a transient, the data should be validated by examining the delta velocity for the transient.

- Use of Fourier techniques is important to assess the frequency character (potential accelerometer resonances and noise floor).

- If the SRS technique is used, correct the transient for the initial conditions ("Delta V = 0" correction). Remove the mean and constrain the velocity. Examine the noise floor. Make sure the noise SRS is at least 6 dB below the pyroshock SRS. Examine the slope of the SRS in the low-frequency domain between 100 to 500 Hz. This criterion is usually adequate for looking at noise within the data; display the SRS values only above 100 Hz. Consider everything below 100 Hz is probably not valid.

CONCLUSIONS

As a result of the independent examination of common problems by several organizations, the following may be concluded:

- Making structural response measurements in the vicinity of a pyrotechnic device is a formidable task, because of the material response/prepulse. The accelerometer either resonates, saturates or breaks, in the case of the piezoresistive accelerometers. The amplifier often saturates.

- Even under very good conditions, it is difficult to measure structural response at 100 to 2,000 Hz with only an analog tape recorder available, because of the limited recorder signal-to-noise ratio. The unreliability of amplifier filters and the limited experience with mechanical filtering at the accelerometer contributes to the problem.

- A classical analysis of a seismic mass device indicates that peak acceleration is very sensitive to pulse shape including initial slope.

- The pyrotechnics data of the 1970s should be reviewed and "proved" based on the knowledge today about the prepulse phenomenon, accelerometer behavior, amplifier/signal-conditioning behavior, recording techniques and analysis techniques.

- Multi-channel transient recorders should be used in lieu of tape recorders when a few channels of data are being examined.

- New methods of sensing structural response need to be developed and implemented, such as optically oriented devices.

ACKNOWLEDGEMENTS

I would like to express my sincere appreciation to Allen G. Piersol of Astron for much of the information on processing in this paper, Dan R. Powers of McDonnell Douglas for his data on amplifiers and filtering, Anthony Chu of Endevco, Harry Riead of General Dynamics, Ned Jones, Brian Veit and Luke Rynda of the Naval Weapons Center for their support. Without these contributions this presentation would not have been possible.

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1. Piersol, A.G., "Pyroshock Data Acquisition and Analysis of U/RGM-109D Payload Cover Ejection Tests," Astron Rept. 7141-01 (Mar 17, 1988).

2. Powers, D.R., "Charge Amplifier Characteristics When Subjected to Pyrotechnic Shock," McDonnell Douglas Astronautics Co., Lab. Tech. Memo. TM-TMHK-ENV-R7484 (Jan 14, 1987).

The following discussion followed Ronald Merritt's presentation of this paper at the 59th Shock and Vibration Symposium. It is included because of the pertinent information that it contains.

<u>Robert Smith, Motorola</u>: In your discussion, you talked about a prepulse. The question is, were you using explosives to generate the shock, and how was the explosive ignited?

<u>Merritt</u>: It was just a standard, so many grains per foot, type of pyrotechnic device. I think it was an electrical initiator. I am not that familiar with that particular setup.

<u>Smith</u>: I was wondering if anyone had considered the possibility than an electrical noise was actually that prepulse, and that you were getting some response to the ignition pulse?

<u>Merritt</u>: I think there is a general feeling that the high voltage that one gets out of the accelerometer is probably due to the wave traveling within the accelerometer itself, producing that voltage. That has been seen several times before. This is one of the cases in which we were able to capture it and look at it.

Smith: I have done a lot of mechanically generated shock and I have never seen that prepulse. Maybe I am not sampling at a high enough frequency. I have sampled it at 250 kHz.

Merritt: At the time, we were using a transient recorder. It is one of the first prepulses that we have seen also, but the phenomena has been quite well documented. I think Pat Walters talked about it and Arnold Galef wrote a paper that talked about it as well. In looking at the data, our conclusion was that it actually did come out of the accelerometer. I believe that Anthony Chu of Endevco has also looked into this. He claims that he can sometimes get a voltage pulse on the order of 40 dB or so higher than signal, just from the piezoelectric crystal responding to the wave. And, of course, in the initial phase, the accelerometer really becomes a part of the structure itself. The waves could bounce back and forth within the accelerometer and the compression of the crystal provide high voltage levels.

Allen Curtis, Hughes Aircraft: I listened to Ron's paper and would like to compliment him. Clearly, it is a picture of a process and an enterprise that requires some elegance, knowledge, and finesse. Yet, if I am going to build a black box for a spacecraft, I will get a specification which has a very easily interpreted plot of an SRS up to several thousands of g. It is expected that I will go down to the laboratory and rather casually ask the guys to create this shock spectrum as best they know how, either on a shaker or some kind of an anvil. It should be done on a sort of "in by 10" and "out by 5" kind of thing. Clearly, we cannot possibly do such testing on a routine basis, and yet our customers are surprised when we do not think this is the way that it can be done. Then they wonder why we object to these pyroshock spectra, which do not really describe what is going on in the usage environment. How do we improve the way that we are doing business in this area?

Merritt: We have learned a lot in this study. A couple of years ago at the Naval Weapons Center, I do not think we really knew how to properly process this pyrotechnic shock data. We have learned a lot just by this particular exercise and we have come under a lot of pressure because of the need, etc. We have more questions than we have answers at this point, certainly in the area of signal conditioning and the accelerometers. There is currently some work on mechanical filters going on. Some of this has been successful and some not. The whole area is really in a developmental stage. It would be nice, as I mentioned in my final comment, if we had an optically oriented device that would not be subject to some of the limitations that we see on the mechanical accelerometers. That would certainly help clear up many of the problems. I think Allen's comment is appropriate. We are in an exploratory stage and we are not sure we totally understand.

S. Dyne: Often, as a consultant, I have found that people have tried to avoid anti-alias filters. It is important to point out that any anti-alias filtering must be done before any digital sampling. That is absolutely vital. Quite often people fail to realize that. Secondly, you implied that you got different results using different manufacturers, I presume for filters. I wonder if you would recommend any sort of calibration technique before one goes out on a trial and actually starts data acquisition?

Merritt: Let me also emphasize the absolutely essential need to use a good anti-alias filter before putting the analog waveform in a digital form. I guess our recommendation is that you do not do any low-pass type filtering at the output stage of your amplifier, just because of the inconsistencies we have seen. If you are using an amplifier, you should check it out very carefully. There may be some amplifiers built today that do a better job than the three we were looking at. But, you really need to know what the characteristics of that amplifier are.

Dyne: Do you have any recommendations as to how we should find that out?

Merritt: I would imagine that you could establish some sort of an electronic type of test, sending a signal into the amplifier and examining the output. Use of a known input signal and examination of output signals looking at various filter combinations, that sort of thing. That is what I would suggest.

Dan Powers, McDonnell Douglas: Ron, some of the spectra that you showed earlier were from a study that I did 2 years ago on amplifier characteristics. In clarification, for the benefit of the audience, I would like to point out a few things. Electrically, each one of these charge amplifiers did exactly what the manufacturer said it would do. It was only when subjected to an ordnance shock that they differed greatly. Each amplifier, on its own, was always plus or minus 3 dB, which is the normal tolerance band. It is only when we compare one amplifier with respect to another amplifier that we end up with drastic differences. Of course, this is a real problem because, when you go from company to company, it depends upon the amplifier that you are using and there are drastic differences between the amplifiers. In connection with Allen's comment, I do see a lot of specs that are being generated that show shock response spectra all the way out to 50,000 Hz. There is no way in the laboratory that we can adequately simulate this, especially on shaker shock. So, I think one of the areas that we have to address is how we can adequately write the specification so that we can give a test to the laboratory that they can really perform.

Voice: How important is the preshock, as you described it, to understanding the later time structural response?

Merritt: If you need to range your amplifier so that it does not saturate because of the preshock, then you decrease your signal-to-noise ratio in your structural response. The preshock is important because you need to make some ranging decisions at that point.