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Laboratory Simulation of Response to a Shock Environment

Todd Simmermacher
Randy Mayes
Robert Benham
Benjamin Duggins

Sandia National Laboratories
PO Box 5800
Albuquerque NM 87185-0557
(505) 844 - 0096

The focus of this work will be to simulate a harsh, blast environment on a space structure. Data from a reverse Hopkinson bar (RHB) test is used to generate the response to a symmetric, distributed load. The RHB generates a high-amplitude, high-frequency content, concentrated pulse that excites components at near-blast levels. The transfer functions generated at discrete points, with the RHB, are used to generate an experimental model of the structure, which is then used in conjunction with the known pressure distribution, to estimate the component response to a blast. The shock spectrum of the predicted response and the actual response compared well in two of the three cases presented.

INTRODUCTION

Qualifying a system to its environment necessitates reasonably accurate testing or simulation of those various environments that the system will experience. Through tests in these representative environments, component response can be determined, and the component capability for survival can be assessed. Developing a representative test environment can at times be difficult. The focus of this work will be to simulate a harsh, shock-like environment. This shock is typically seen by a large area of the surface of the system in test. Simulating this environment is not perfect; these tests are costly and require much planning to ensure that the test will be a success.

To generate response data at a much higher response level than a standard modal test, a reverse Hopkinson bar (RHB) testing technique is used. The experiments, including the RHB test and the blast tests are described here, whereas the analysis procedure itself is presented in a companion paper, Simmermacher et al. [1]. The analysis involves a weighted sum of the transfer functions measured using the RHB as an input, producing an experimental model. This model can then be used to generate predictions to any distributed, applied load. The objective is to develop a highly refined model and use the relatively expensive field testing to confirm or "proof test" the end result.

It was observed in previous tests performed on space structures performed at Sandia National Laboratories that the response data were nonlinearly dependent on force levels. To a certain input level, the system would remain linear. When the threshold was reached, damping would increase, modes would shift, and modes would appear and disappear. When the force level was high enough, the system would seem to settle to a new linear system. These systems typically have many bolted interfaces, and it was conjectured that the linearity regimes of the structures occurred due to the joints either overcoming the stiction (high levels) or not breaking free (low levels). At the intermediate levels the response would consist of a combination of the two systems producing a nonlinear system. In the simple system presented here, the response was not linear but changed slowly with input level. For this technique to be applicable, the structure must be excited with the RHB at a level that is near that expected from the blast. This will ensure that the linearization is appropriate.

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SYSTEM DESCRIPTION

The hardware tested consisted of three connected pieces. The main design consideration was for the unit to have a large main body, a small component, and a ring between them. The bolted interfaces between the body and ring and the ring and component introduce the most significant nonlinearities into the structure. A schematic of the assembled unit is shown in Figure 1. The component was made of solid aluminum and the body was a hollow cylinder made of aluminum with a wall thickness of 0.25 inches. A ring was used as a mount to connect the component to the body. The ring was about 0.5 inches thick. The three pieces were fastened together with seven bolts.

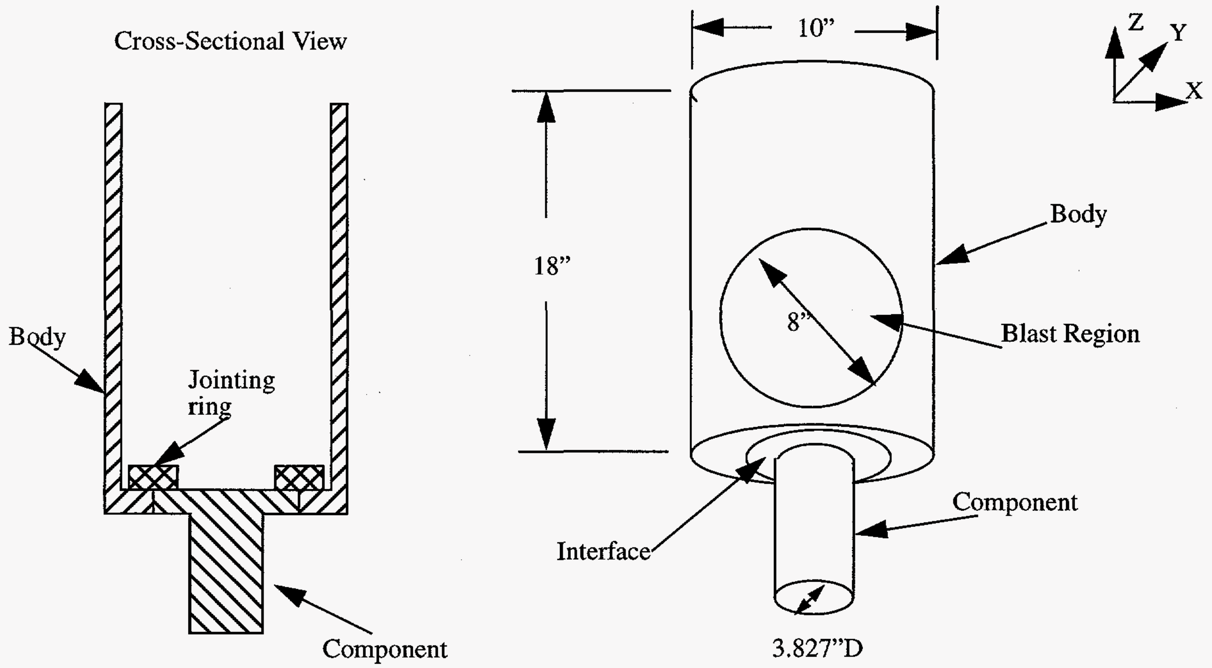

Figure 1 Experimental unit

OVERVIEW OF EXPERIMENTS

The main objective of the project was to predict a component response to a distributed blast load using data generated with the RHB technique. The blast was generated at the end of a tube that directed the wave to the structure. The acceleration response was measured on both the top and bottom of the component as well as some locations on the body.

There were two parts to the experiments. The first consisted of the RHB test. From the RHB test, transfer functions would be measured between the input location and the positions on the structure where the response to a shock load is to be predicted. It was desired to get the level of the RBH input to be consistent with the levels expected from the blast test. This was critical in order to excite the structure to respond as the high level linear structure.

The second set of experiments consisted of applying an actual blast load to the structure and measuring the response. It was these blast responses that were compared to the predicted response generated by the RHB test and subsequent analysis. Much effort went into designing the blast load to obtain as large of response as possible without damaging the structure or ringing the accelerometers.

REVERSE HOPKINSON BAR TEST

The RHB is used to apply high frequency and high amplitude inputs to a structure. This test is typically used on small objects, such as material samples. Recently, Mayes, [2], used the RHB to provide high level inputs into a large structure. He developed a portable version of the Hopkinson bar test that can be used much like an input for a modal test. The setup used in this work is shown in Figure 2. The input is measured by a force transducer on the impact end of the RHB. The force transducer has proven to provide a signal with a higher signal-to-noise ratio in the configuration used in this work than the strain gauge that is typically used on a RHB test.

The unit was instrumented with nine accelerometers and a total of nine input locations were used. The important response was the motion of the component in the overall direction of the applied pressure load (Y direction). There were bi-axial accelerometers placed at the top and bottom of the component. The remaining accelerometers were placed in a diamond pattern on the back side of the body in Fig. 1 (opposite the applied load). At the impact locations, a heat-treated steel pad was placed radially to prevent the RHB from pitting the surface of the unit. The pads and the accelerometers were attached with epoxy and tended to loosen during the test due to the high levels of input. The bonds were checked during the test although there was an obvious degradation in signal from an accelerometer whose bond had started to fail. The input pads either were attached securely or fell off, simplifying the diagnostic of the bond.

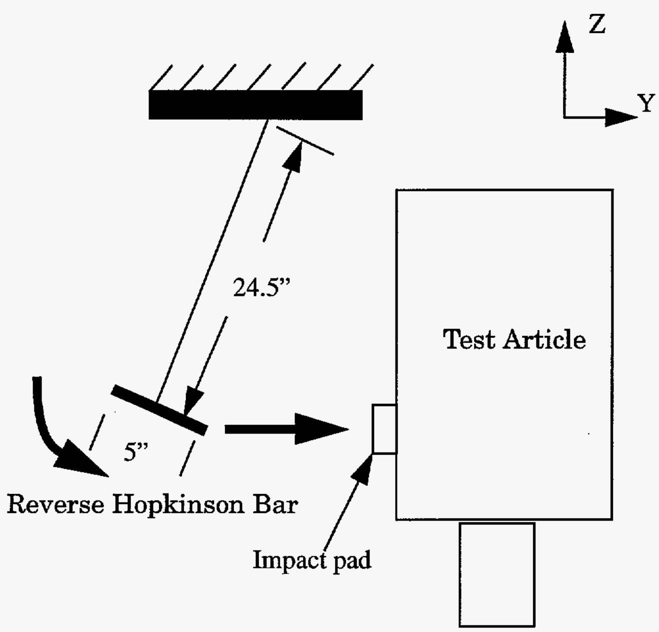

Figure 2 Reverse Hopkinson bar setup

The impact locations were chosen in an ad-hoc manner to cover the blast area (Figure 3). Ideally, impact locations would be chosen so they excite the structural modes in the way that the blast does. No optimization of impact locations was performed here, but a finite element model could conceivably be useful for choosing the locations.

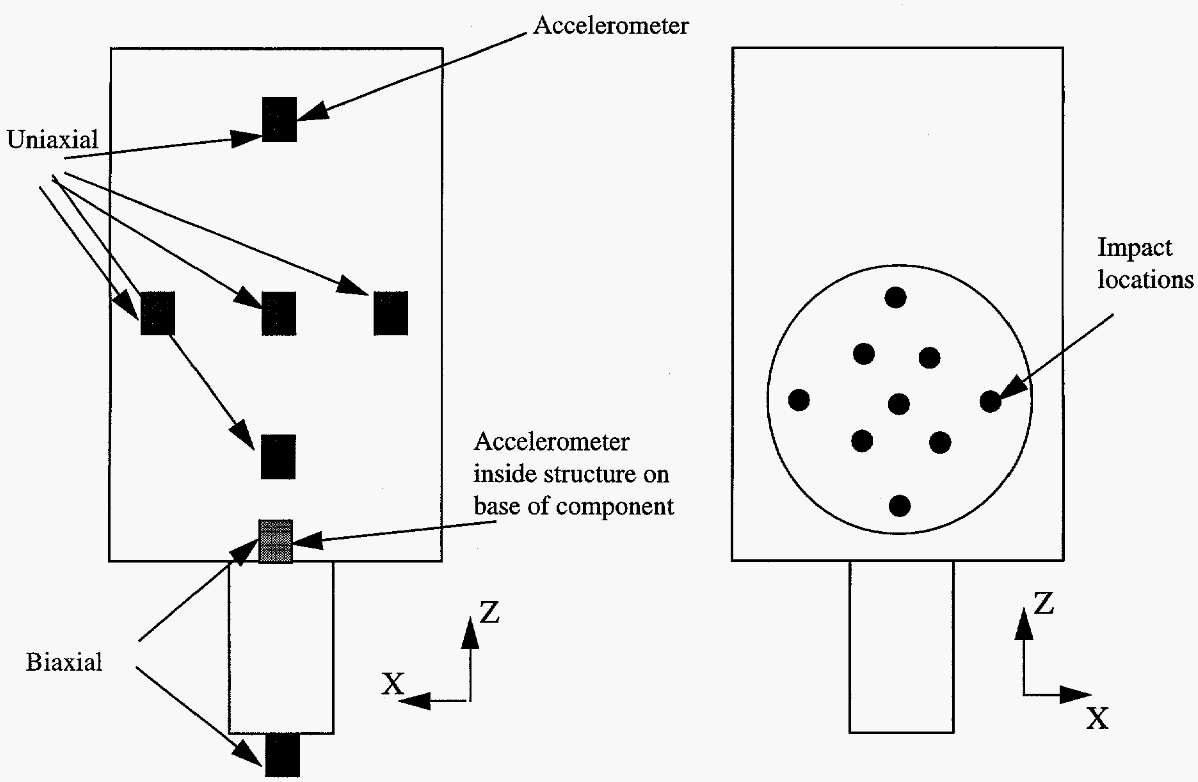

Figure 3 Instrumentation for RHB test

A problem that was encountered during the RHB testing was that double hits of the bar were difficult to prevent. When the RHB hits the structure twice in quick succession, a large number of dropouts occur in the autospectrum of the impact (Figure 4). These dropouts represent frequencies where little energy is being input to the structure. If these dropouts occur at a resonance, the resonance may not be excited. In the case the RHB test, the frequencies at which the dropouts occur do not have the desired high level of input which is necessary to exercise the non-linearities. More work is required to determine how to avoid the double hits.

Another problem was the frequency content of the force signal. For this test, the maximum frequency of interest was set at 6 kHz. The autospectrum shown in Figure 4 shows diminishing energy past about 4 kHz. Achieving energy out past the bandwidth is critical in this application. The joints need to be exercised in order to excite the non-linearities. With so little energy out at the edge of the bandwidth, it is questionable that the joint is being sufficiently worked. The bandwidth achieved by the RHB system is dependent on the flexibility of the target structure. In this system, the structure is fairly soft, and therefore obtaining a high bandwidth was difficult.

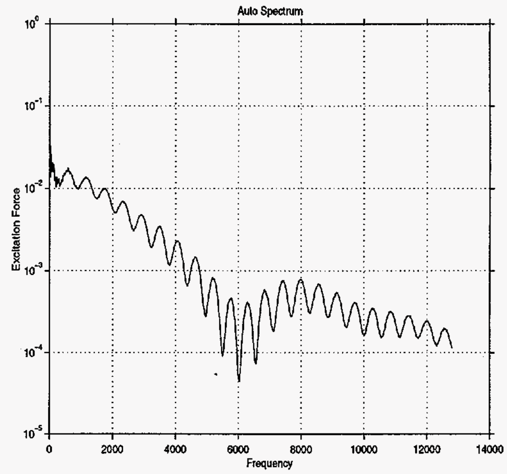

Figure 4 Autospectrum of representative RHB impact location

BLAST TESTS

The response to which the RHB predictions were to be compared against were generated by a blast test. The setup is shown in Figure 5. The blast was designed to provide enough impulse to exercise the non-linearity in the joint, yet not enough force to damage any part of the test unit. The layout of the explosives was chosen to provide the most uniform distribution of pressure using the small quantity of explosive necessary to achieve the desired impulse level. The blast thus designed still had too short of rise time which tended to excite the accelerometers resonance which adversely affected the data. To soften the blast wave, a light weight foam pad was used as a programming material which was placed on the surface of the test unit. This had the effect of increasing the rise time with no effect on the total impulse developed. The final consideration was that the blast tube end was placed a small distance (0.25") away from the structure to prevent it from impacting the test unit. If the tube impacted the test unit, an unmeasured input would be provided that could not be accounted for in the prediction.

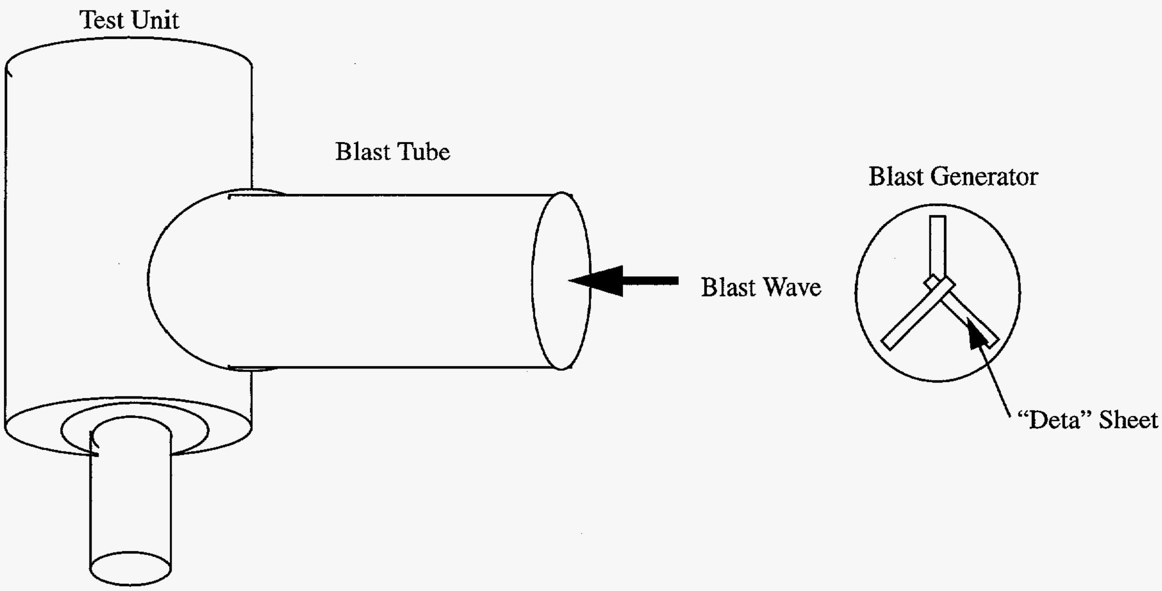

Figure 5 Blast test setup

The instrumentation for the blast test is show in Figure 6. The pressure gauges were thin film carbon pressure gauges, which turned out to be very base-strain sensitive for the low levels that were used in this series of tests. The gauges are typically used at very high levels for very short durations (1-2 μs) where the base-strain response is small compared to the pressure. This turned out to be a problem which is still being addressed. Note that the pressure gauges are located at the same locations as the impact points of the RHB. The pressure load was assumed to be symmetrical and therefore only half of the impact circle was instrumented. The accelerometers were piezo-resistive gauges. The locations are similar to the RHB test, although there are fewer gauges due to availability issues.

The base-strain sensitivity of the pressure gauges turned out to be a bigger problem than first expected. The gauge is biaxially sensitive to strain. The impulse level was known and very repeatable. Many tests were performed using a flat plate and a Kulite pressure gauge which is insensitive to base strain. The Kulite gauge was not used for the actual tests because a hole must be drilled into the structure to mount it. For the last blast test, a Kulite gauge was mounted and compared with the output of an adjacent carbon gauge (Figure 7). This comparison does show that the carbon gauge was measuring mostly strain response. Consequently, to extrapolate the pressure distribution on the shell, we must make some assumptions. To determine the relative pressure magnitudes at each of the gauge locations, it was assumed that the rise and fall time of the pulse was consistent at each location with only the maximum amplitude changing from one location to the next. The amplitude was determined by assuming that the relative magnitudes of the pressure pulses were the same as the relative magnitudes of the combined strain and pressure pulses. The pressure for the center point was determined by assuming that the pulse at that location always had the same impulse. This last assumption should be pretty accurate as the same amount of explosive was used in each test. The resulting pressure distribution for the last test (with the Kulite gauge) is shown in Table 1.

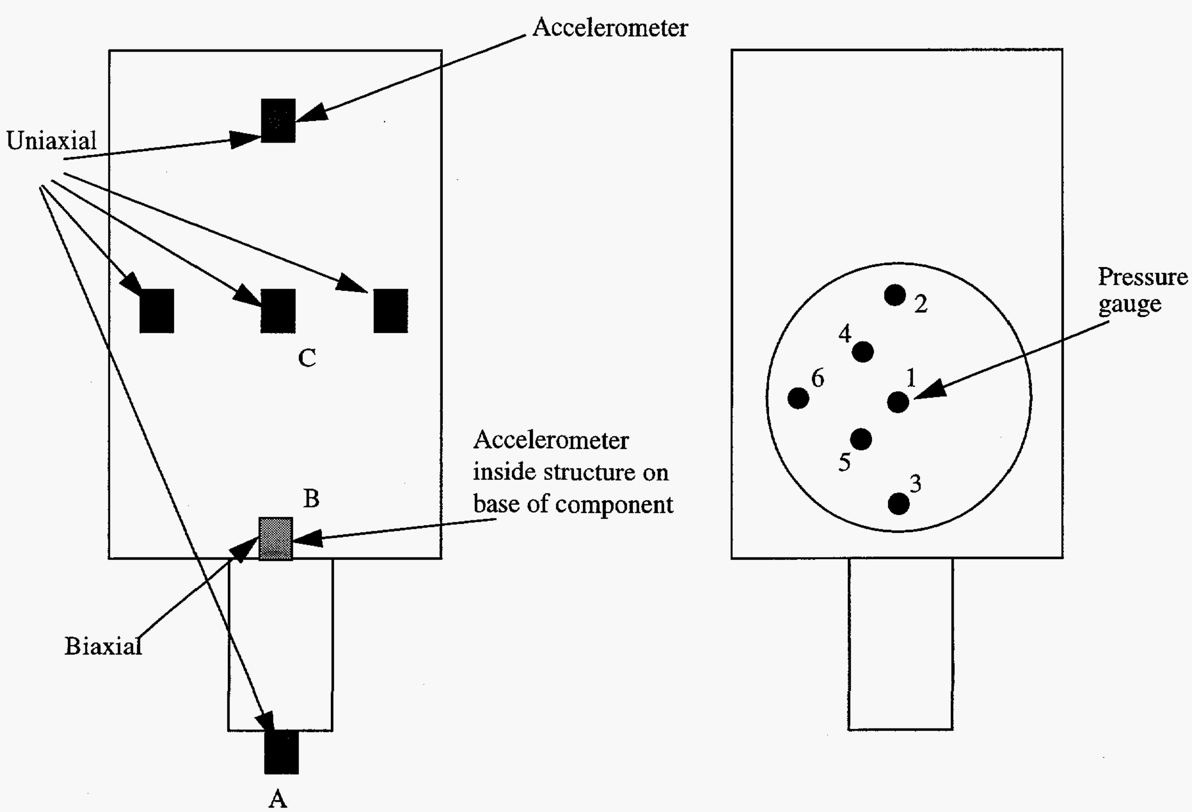

Figure 6 Instrumentation for the blast test

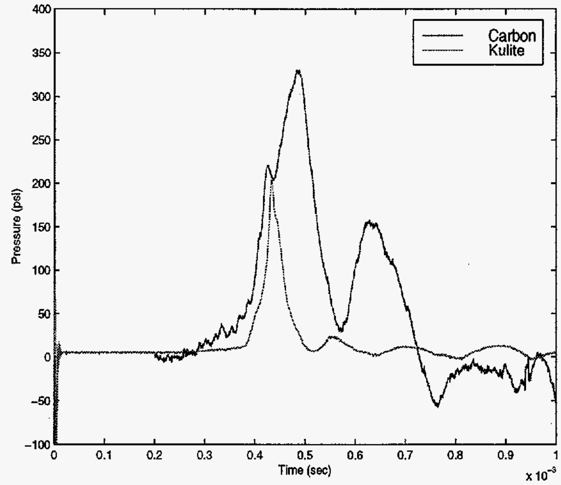

Figure 7 Carbon gauge and Kulite gauge comparison (Test set 7_22e)

Table 1: Measured/Expected Pressure Characteristics at Indicated Positions

Position	1*	2**	3**	4**	5**	6**
Peak Pressure (psi)	200	150	143	155	155	153
Rise Time (μs)	40	40	40	40	40	40
Impulse (Taps†)	700	525	499	540	540	538
Duration (μs)	100	100	100	100	100	100
* Values measured in flat plate tests and test unit with Kulite gauge						
** Values estimated from local carbon gauge measurement						
† 1 Tap = 1 dyne-sec/cm2 or 1 psi-sec = 69,000 Taps						

RESULTS

The procedure to predict the response of the structure to a distributed load from the RHB data is detailed in [1]. The method is based upon a discrete approximation to a Green's function. By using linear interpolation between impact points, a continuous function can be approximated. Then, knowing the pressure distribution, the prediction can be calculated using linear superposition, thus, this method assumes that the structure behaves linearly. Recall that the basis of this technique is rooted in the observation that at high levels, these systems behave as a near-linear system.

The main response of interest was the acceleration response at the base of the component. Measures of this response are shown in Figure 8. The location is referenced in Figure 3. The shock spectrum is the most common comparison function. The shock spectrum is the function most often used when a performance specification is written. Note that at the base of the component is low over the entire bandwidth. At low frequency, the predicted autospectrum is also low (note that only one average was used).

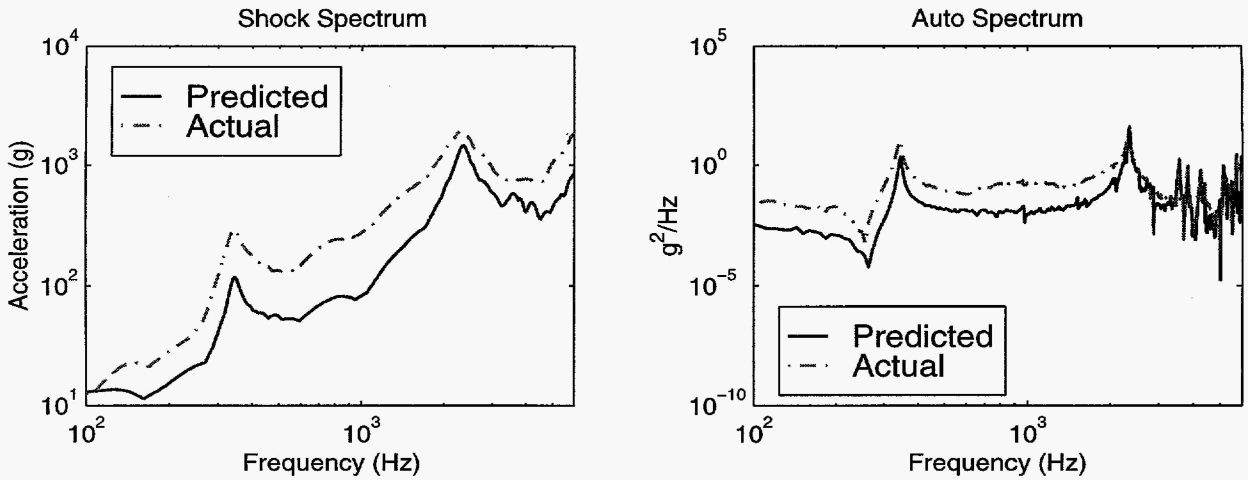

Figure 8 Base of component response (location B)

The prediction at the tip of the component is much better, as can be seen in Figure 9. The shock spectrum and the autospectrum both show good agreement between the actual blast data and the prediction. The frequencies of the first and second bending modes (peaks at about 320 and 2200 Hz) are a little lower in the actual data than in the prediction. This may be explained by the mounting of the accelerometers in the blast test. Each accelerometer required a significant amount of very heavy putty to support the cables to the shell. The added mass would tend to lower the frequency. The damping is higher in the actual blast data. The addition of the putty and the programming foam both could have affected the damping. Otherwise, the prediction gives a good representation of the actual test data.

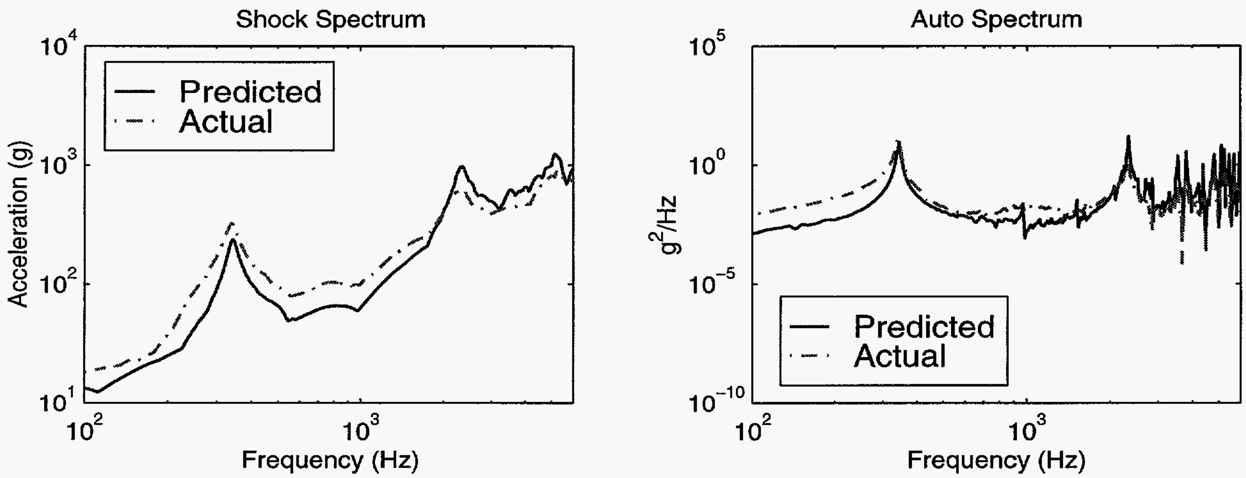

Figure 9 Tip of component response (location A)

The easiest responses to predict using this technique are at points on the body. The stress waves produced by the blast do not have to travel through any joints and the response should be very linear. Measures of the response at a point behind the region where the pressure was applied (Figure 3) on the main body is shown in Figure 10. The shock spectrum once again shows a fairly good match between the actual blast data and the prediction. The autospectrum reflects many more system modes in this response. These modes are the "can" modes of the body. The damping is again higher in the actual blast data. Some modes that appear in the prediction are not excited in the actual test. A probable explanation is that due to the symmetric nature of the blast, it did not excite these modes while the impact points chosen for the RHB test where not sufficient to cancel these modes due to symmetry.

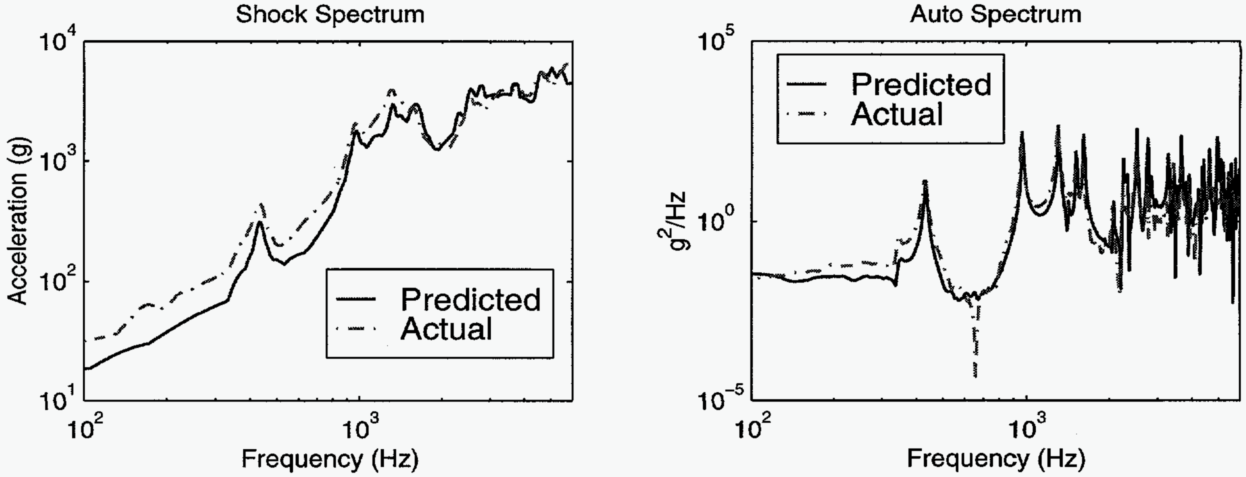

Figure 10 Center of body response (location C)

DISCUSSION OF UNCERTAINTY

As with any experimental technique, there are sources of errors that affect the results. In the technique described in this paper there are two experiments (the RHB test and the blast test) that could affect the results. For the prediction of the blast response, the assumption of linearity is required, and that may not be a good approximation. Care was taken to insure that the system tested exhibited near linear characteristics near the blast level of the load.

Another source of potential uncertainty is the difference in instrumentation setup between the RHB test and the actual blast. The actual blast test used a heavy putty to support the cables; the RHB test did not require the cables to be supported. The putty had the effect of adding mass and damping to the system.

The last major source of uncertainty in the RHB test was the analysis procedure itself. It was assumed that the frequency response functions and the pressure loads vary linearly over the blast region. This is similar to the assumption used in a finite element simulation. Also, the points to impact were chosen in an ad-hoc manner. An optimal criterion would reduce the error caused by a poor choice in excitation location.

The prediction technique relies on an accurate representation of the pressure distribution. As was shown, the pressure distribution estimated was based upon some assumptions that could be unreasonable, but necessary due to unforeseen limitations in instrumentation.

Bounding these systematic errors would be necessary to quantify their affects on response predictions. A complete uncertainty analysis would include consideration of randomness in the estimation of the FRFs and the specification of the applied pressure. The distribution of the response would be evaluated based on knowledge of the system behavior.

CONCLUSIONS

In this paper, a series of experiments were described which were used to develop a technique to inexpensively estimate the response of a system to a distributed shock load. A Reverse Hopkinson Bar was used to measure high force level, high frequency content transfer functions. These transfer functions were combined using a weighted sum to produce a predicted response. This response was then compared to an actual blast test. The predicted response represented the actual response quite well in two of the three cases presented. One response (base of the component) showed the correct trend in the shock spectrum but the level was off. One of the two responses that compared well required the stress waves to travel through a joint which introduces a nonlinearity.

There were some problems with the RHB technique as implemented in this work. First, the bar tended to impact the structure multiple times resulting in large dropouts in the autospectrum. This produces frequencies where not much energy is being added. Another problem was the bandwidth achieved with the bar. The maximum frequency desired was 6.0 kHz while energy was limited above 4.0 kHz. The bandwidth of the input force is very dependent on the flexibility of the test structure. The structure used was fairly flexible and the flexibility could have affected the bandwidth.

ACKNOWLEDGMENTS

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