LABORATORY SIMULATION OF RESPONSE TO A DISTRIBUTED PRESSURE LOAD

Todd Simmermacher
twsimme@sandia.gov

Randy Mayes
rlmayes@sandia.gov

Sandia National Laboratories
PO Box 1800
Albuquerque, NM 87111-0557

ABSTRACT: Responses to a distributed pressure load are typically predicted through the use of a finite-element model. This procedure depends on the model to represent the actual structure accurately. Another technique that is developed in this work is to predict the response based upon an experimentally derived model. This model consists of frequency response functions. The pressure distribution is assumed to be known. In this work, the pressure load will be a blast load.

The focus of this work will be to simulate a harsh, shock-like environment. Data from a reverse Hopkinson bar (RHB) test is used to generate the response to a symmetric, distributed load. The reverse Hopkinson bar generates a high amplitude, high frequency content pulse that excites components at near-blast levels. The frequency response functions generated from 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. This result can then be used with a model correlation technique to adjust a finite element model such that data from a true blast test can be used to only fine tune the model. This work details the estimation of the response due to the blast.

Nomenclature

-\( y \) ............ Response in the time domain
-\( Y \) ............ Response in the frequency domain
-\( p \) ............ Pressure loading in the time domain
-\( P \) ............ Pressure loading in the frequency domain
-\( g \) ............ Green's Function
-\( G \) ............ Frequency domain Green's Function
-\( N \) ............ Shape functions
-\( H \) ............ Experimental frequency response function
-\( \lambda, \xi \) ........ Response and input vectors

Introduction

Qualifying a system to perform the task for which it was developed necessitates reasonably accurate testing or simulation of the 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 input 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, an RHB testing technique is used. The analysis technique used with the RHB data is described here, while the test itself is presented in a companion paper, Simmermacher et. al [1]. The analysis technique given here provides a rich set of data that modelers can use to improve their model's predictive capability. The idea is to develop a highly refined model and use the relatively expensive field testing to confirm or "proof test" the end result.

The hardware described in this paper was a mock system that consisted of a large cylinder and a component connected through a bolted interface (Figure 1). The load to be simulated was a blast load that was applied to the large cylinder through a blast tube. Component response was of interest. The acceleration responses were both predicted from an experimental model using the RHB technique and measured through an actual blast test.

The response against which the RHB predictions were to be compared was generated by a blast test. The setup is shown in Figure 1. The blast was designed to provide enough impulse to exercise the nonlinearity in the system's only joint, yet not cause 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 smallest quantity of explosive necessary to achieve the low-impulse level. The blast thus designed still had too short of rise time which would tend to excite the accelerometers resonance,
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possibly affecting the data. To increase the rise time of the blast wave, a light-weight foam pad was placed on the surface of the test unit as a programming material. 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 was placed a small (0.25") distance 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 1 Test setup

Theory

To predict the response of a structure at a point due to a surface pressure load, as an impulse will appear to the structure, the Green's function is typically used. This function describes the response at any point on the structure due to an impulsive loading at any point on the structure. Analytically these functions are impossible to determine explicitly for all but a few extremely simple shapes.

The test structure is shown in Figure 2 to demonstrate the use of the Green's function. The pressure load is arbitrarily distributed over the circular region. The response of interest is on the component. Assuming the Green's function between the response vector, $\mathbf{x}$, and the input vector, $\mathbf{u}$, is defined as $g(\mathbf{x}, \mathbf{u}, t)$, and the distribution of the pressure loading $p(\mathbf{u}, t)$ are known, the response can be predicted through

$$y(t) = \int d\mathbf{x} \int g(\mathbf{x}, \mathbf{u}, t - \tau) p(\mathbf{u}, \tau) d\tau.$$  \hspace{1cm} (1)

This expression for the response is useful if the Green's function for the structure is known. However, as was alluded to earlier, the Green's function for complex shapes is rarely known. However, the Green's function between two points can be estimated experimentally and is known as the frequency response function (FRF). These FRFs were measured in this work using the RHB as an input. This will be discussed further in the Discussion of Procedure section of this paper.

The FRF is measured between the desired response location and the anticipated area that the pressure loading will occur. Since the structure is assumed to be linear and reciprocity should apply, whether the force is located at the response location and the accelerations are measured in the pressure-loaded region, or vice versa, should not matter. However, due to the harsh nature of the blast load, it is desirable to apply the force in the pressure region. This may adversely affect Eq. (1), as there is an assumption of linearity inherent in the equation. For this analysis it will be assumed that there are slowly varying, weak nonlinearities that allow us to use a linear assumption. This will be discussed in detail later.

To describe the proposed technique, consider a simple region as shown in Figure 3 with the input locations highlighted. The location of the response points are immaterial. As Figure 3 shows, the forcing locations can be connected into a mesh to define surface elements. Shape functions can be used to interpolate the FRFs between grid points to form an approximation to the Fourier transform with respect to time Green's function valid over the circular region. This approximation is defined as

$$\{G(\mathbf{x}, \mathbf{u}, \omega)\} = \{H(\mathbf{x}, \mathbf{u}, \omega)\}\{N(\mathbf{u})\},$$  \hspace{1cm} (2)

where $\{G(\omega)\}$ is the Fourier transform with respect to time Green's Function, $\{N\}$ is the matrix of shape functions, and $\{H(\omega)\}$ is the FRF matrix. The subscripts indicate discrete quantities. Using a similar notation the pressure can also be interpolated using shape functions as

$$P(\mathbf{u}, \omega) = \{N(\mathbf{u})\}^T \{P(\mathbf{u}, \omega)\}.$$  \hspace{1cm} (3)

Now the integral in Eq (1) can be written in the frequency domain as

$$y(\omega) = \{N(\mathbf{u})\}^T \{P(\mathbf{u}, \omega)\}.$$  \hspace{1cm} (4)
The result of Eq (4) can now be transformed into the time domain to obtain the desired response. Had all the above calculations been performed in the time domain, the convolution would have to be performed instead of the simple multiplication in the frequency domain.

Note that once the discrete Green's function is known (Eq. 3) the response due to any loading within the applicability of Eq. (3) can be calculated.

The hardware tested consisted of three 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 4. 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.

Discussion of Procedure

The RHB is used to apply high frequency and high amplitude inputs to a structure. This test has been used in the past on smaller objects, such as material samples. Recently, Mayes, [2], used the RHB to provide high level inputs into a large structure. He developed a more portable version of the Hopkinson bar test that can be used much like an input from a modal test. The setup used in this work is shown in Figure 5. 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 impact locations were arbitrarily chosen to cover the blast area (Figure 6). 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 5 Reverse Hopkinson bar setup

Once the FRFs from the RHB test were collected, the predicted accelerations were generated using Eq (4). As a check on the validity of the method, the columns can be summed in the matrix defined by Eq. (5) before the post multiplication of the FRFs. By summing across the columns (or rows, since it is symmetric), a lumped, area weighting can be calculated. These lumped weightings can be used as an intuitive check to see if the allocation of area is consistent with what the analyst thinks would be a reasonable distribution. In this case, the distribution seemed reasonable.

Results

The main response of interest was the acceleration response at the base of the component. Measures of this response are shown in Figure 7. The location is referenced in Figure 4. The shock spectrum is the main comparison function. The shock spectrum tends to be the function most often used when a performance specification is written. Note that at the base of the component, the prediction appears too low. The trends are about the same, but the prediction is low over the entire bandwidth. At low frequency, the power spectral density (PSD) is higher than the predicted (note that only one average was used). The phenomenon between about 500 - 1800 Hz is not typical of a structural response and could be due to accelerometer problems. A post-test calibration, however revealed no problems with the acceleration.
The prediction at the tip of the component is much better, as can be seen in Figure 8. The shock spectrum and the PSD both show good agreement between the actual blast data and the prediction. The frequencies of the first and second bending modes (peaks at about 400 and 2500 Hz) are a little lower in the actual data than in the prediction. The mounting of the accelerometers in the blast test required a significant amount of very heavy putty to support the cables. 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.

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 points behind the region where the pressure was applied (Figure 4) on the main body is shown in Figure 9. The shock spectrum once again shows a fairly good match between the actual blast data and the prediction. The PSD reflects many more system modes in this response. These modes are the "can" modes of the body. The damping is higher in the actual blast data, as was seen in Figure 8. Some modes that appear in the prediction are not excited in the actual test. One explanation for this disappearance is that since the damping has increased in the system, the modes that do not appear may have been completely damped out. Another, more probable explanation is that the symmetric nature of the blast did not excite these modes and the impact points chosen were not sufficient to accurately cancel these modes.

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 that affect the results. For the prediction, the assumption of linearity could cause deviations from the actual results. 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 in the results of the RHB test 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 FRFs 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. The pressure was measured at the impact locations. A poor choice of impact locations would give an inaccurate view of the pressure distribution. In this setup, the pressure at the edge of the blast tube is unknown and highly complex. This analysis assumed that the pressure was zero at the edges.

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 technique was described that can be used to efficiently estimate the response of a system to a distributed pressure load. The pressure input in this work was a blast load. A Reverse Hopkinson Bar was used to estimate high force level, high frequency content transfer functions. These transfer functions were combined using a weighted sum technique 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 of the two responses that compared well required the stress waves to travel through a joint that introduces a mild nonlinearity.

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References

[1] Simmermacher, T., Mayes, R. L., Benham, R.A., and

