# Modeling of Ordnance-Induced Pyrotechnic Shock Testing

**WHITE PAPER**

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Design of an ordnance-induced pyrotechnic shock test to meet a specific acceleration based Shock Response Spectrum (SRS) test requirement for a given test article has traditionally been an empirical process. Based on experience, the test engineer will determine a potential test configuration and then, through a trial-and-error process, modify the test parameters and configuration until acceptable SRS levels have been achieved. As a complement to this approach, Element U.S. Space & Defense (EUSSD) has developed an explicit finite element based modeling approach to simulate an ordnance-induced pyrotechnic shock test. This tool may be used to assist with test configuration design for particularly challenging test requirements or to streamline the process of arriving at acceptable test levels during the calibration phase of a test program.

While others have recognized the value of modeling ordnance-induced pyrotechnic shock, the majority of these efforts have utilized more traditional linear implicit finite element based approaches. The implicit approach suffers from two major challenges: 1. determining a suitable spatio-temporal force/pressure distribution on the resonating plate induced by the explosive charge detonation; and 2. accounting for non-linear material response such as plastic deformation in the primary resonating plate which commonly occurs during an ordnance-induced pyrotechnic shock event. The explicit approach inherently overcomes both of these challenges.

The EUSSD-developed explicit finite element modeling approach for ordnance-induced pyrotechnic shock testing will be presented along with model predictions for specific test configurations. Predicted results will include the acceleration-time history and corresponding SRS levels for a given location on the mounting shelf. Test data for these test configurations will be presented for comparison with model predictions. Post-processing of the model results in order to facilitate comparison with measured test data will also be discussed.

## INTRODUCTION

Ordnance-induced pyrotechnic shock testing uses the detonation energy of a high explosive (HE) material to expose a test article to an acceleration environment that typically exhibits both high amplitude and high frequency content. The test starts with selection of a suitable resonating structure, often a metal beam or plate. The explosive material is located on one side of the resonating structure and the test article is typically located on the opposite side; either mounted directly to the resonating structure or through an intermediate mounting structure. The impulsive shock to the resonating structure caused by the detonation event generates stress waves that propagate through the structure and ultimately into the test article.

Due to the complexity of the acceleration waveform generated by a pyrotechnic shock, both the test specification and the test results are typically characterized using the absolute acceleration Shock Response Spectrum (SRS) [1]. A detailed discussion of the SRS along with various calculation algorithms can be found in references [2-4]. All SRS curves presented in this work are calculated using the Smallwood algorithm [4] with a Q-value of 10. Several representative pyrotechnic shock SRS test specifications are presented in Figure 1. As indicated in the figure, pyrotechnic shock test requirements are usually specified over a range of natural frequencies from 100Hz up to 10kHz or 20kHz. While there is clearly a large variation in the SRS amplitude among the test requirements, roughly a factor of ten across the entire spectrum, there is a consistent shape. Each curve starts with relatively low amplitude at 100Hz, increases steadily up to an intermediate frequency, and then plateaus. The point at which the SRS curve reaches the plateau is often referred to as the "knee" in the SRS curve and is a common characteristic of mid-field pyrotechnic shock. Along with the nominal test specification, several other criteria are often specified in order for SRS levels achieved during a test to be considered acceptable. These include tolerance bands which should envelope the test SRS, typically -3dB to +6dB, and the requirement that at least 50 percent of the SRS curve exceed the nominal test specification [1]. Finally, it is often desirable to subject the test article to a single pyrotechnic shock which meets the test requirements simultaneously in having reviewed the desired results, or output, of an ordnance-induced pyrotechnic shock test, it is instructive to investigate the input energy in order to appreciate the challenge of designing an appropriate test fixture. The detonation velocity of most HE materials is between 5 and 9 millimeters per microsecond [5]. Using a radius of 50 millimeters as a reasonable size for the explosive charge yields a detonation event with a duration of roughly 5-10 microseconds.
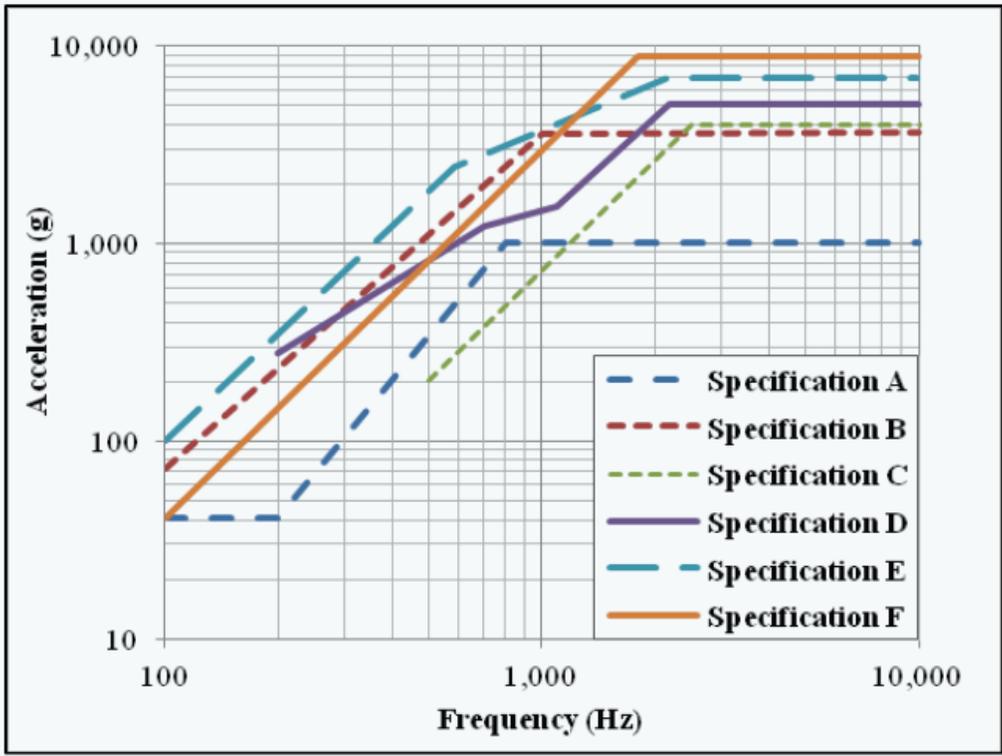
Figure 1. Example of the variation within different test specifications

Assuming a half-sine shape for the resulting force from the detonation, and scaling the resultant local acceleration to a value of one produces the hypothetical acceleration profile shown in Figure 2 (left). The maximax SRS of this acceleration profile is also shown in Figure 2 (right). A pulse with this short duration is essentially equivalent to a delta function, producing uniform frequency content over the 100Hz to 10kHz frequency range. The SRS of a pulse with uniform frequency content is a straight line with a slope of +6dB/octave, as can be seen in Figure 2 (right). Thus, for ordnance-induced pyrotechnic shock, the goal is to design a test fixture which will have a dynamic structural response capable of transforming input energy with uniform frequency content into an environment which matches the spectral content of the test specification.
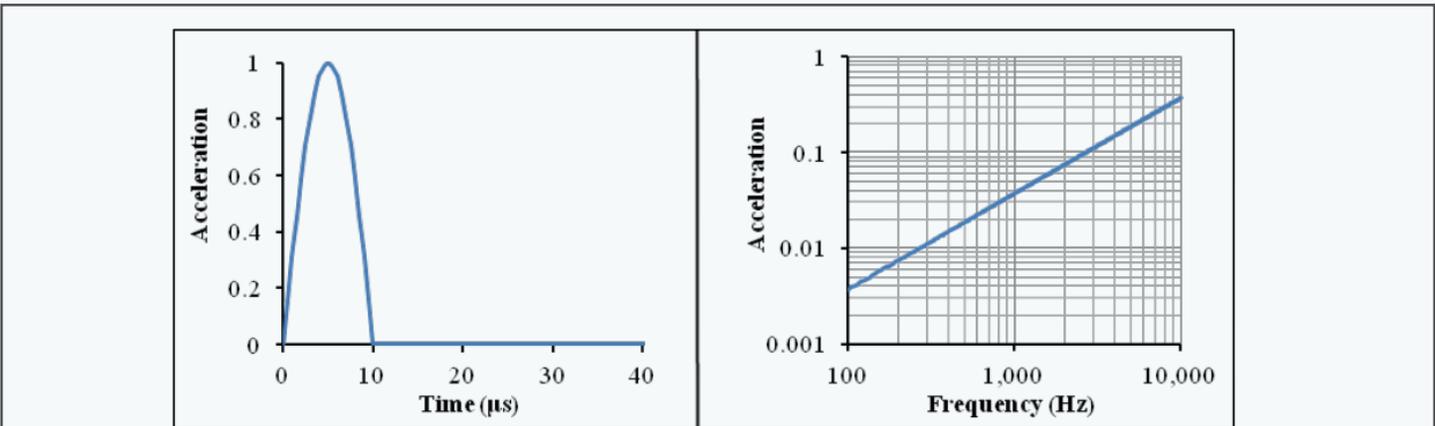


Figure 2. Hypothetical local acceleration profile generated by a detonation event (left) and the maximax SRS calculated from the hypothetical acceleration (right)
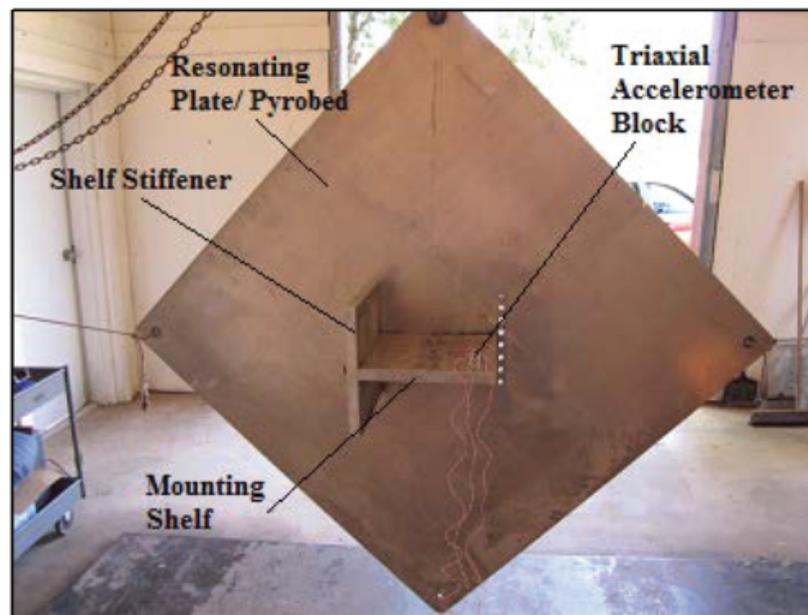
*Figure 3. Representative pyrotechnic shock test configuration*

An example of a pyrotechnic shock test fixture is show in Figure 3. In this configuration, the resonating structure is a large square aluminum plate suspended from one corner. Perpendicular to the resonating plate there is mounting shelf where the test article would be located. The dynamic response of the fixture is tailored by including a vertical shelf stiffener on one side of the mounting shelf. Based on this somewhat generic test fixture, the following items may be considered as a list of parameters which create the design space for a pyrotechnic shock test fixture:

- General configuration and geometry
- Ordnance type, amount, and location
- Test article location, orientation, and attachment method

The first bullet point, general configuration and geometry, encompasses a significant design space by itself including decisions regarding use of a mounting shelf (as opposed to mounting directly to the resonating structure), location and orientation of any stiffening structures or lumped masses, as well as the size, thickness, material and attachment method of each of these structures. In order to design a pyrotechnic shock test fixture to meet a specific test requirement for a given test article, a test engineer has traditionally had to rely on personal past experience and/or an empirical database built from cumulative experience. Based on the available information, the engineer will design a test fixture and then, through a trial-and-error process, modify the test parameters and configuration until acceptable SRS levels are achieved.

Unfortunately, once an initial test configuration is fabricated and testing has started it becomes expensive and time consuming to transition to a completely different configuration. Therefore, subsequent iterations in the trial-and-error process are often limited to varying the parameters covered by the second and third bullet points: ordnance type, amount, and location as well as the test article location, orientation and attachment method. This severely limits the ability of the test engineer to tailor the resulting test SRS to the specification. This limitation becomes even more severe if the test article or test requirements are outside of the available empirical database; for example a large or unwieldy test article or particularly high SRS levels. In this case, the likelihood of the initial configuration producing acceptable results is significantly reduced.

It is clear that the pyrotechnic shock testing community would benefit from a modeling approach with the ability to predict the SRS levels which would be achieved in any arbitrary test configuration. Such a model could be utilized by the test engineer as an alternate approach to test fixture design which would permit the engineer to explore the entire test fixture design space prior to fabrication, thereby streamlining the process of arriving at acceptable test levels even in situations where the desired test is outside of the empirical database. While others have previously developed modeling approaches for ordnance-induced pyrotechnic shock, their methods have suffered from several significant limitations. Both Wattiaux et.al. [6] and Heyd et.al. [7] utilize a linear implicit finite element methodology which is unable to capture the non-linear phenomena which occur during the ordnance detonation event such as localized plastic deformation of the resonating plate. The second significant limitation is how the input energy from the detonation event is derived. Wattiaux et.al. model the input energy as a triangular pulse characterized by a duration and amplitude. The values of duration and amplitude are determined through an optimization process with a goal of minimizing the error between the SRS calculated from test results and the SRS calculated from the modeling results. Heyd et.al. use a rectangular pulse wave-

form and calculate the duration based on the detonation velocity and extent of the charge, but similar to Wattiaux et.al., they tailor the amplitude of the pulse to achieve the best match to their experimental results.

Therefore, in both cases, the input excitation to the model must be tuned using existing experimental results. This effectively eliminates variation of ordnance type or substantial changes to the ordnance amount from the design space.

In this work, an EUSSD-developed explicit finite element model is presented which overcomes the limitations of previous modeling work. The explicit methodology allows for implementation of non-linear phenomena, and plastic deformation is incorporated in the model. The HE material is also directly modeled, incorporating the calculation of pressure loading on the resonating plate as part of the simulation. Therefore the effects of variation in the explosive type, amount, and geometry are captured without the need for an ad hoc tuning approach. This model is implemented using the commercial code LS-DYNA, from Livermore Software Technology Corporation.

## MODEL DEVELOPMENT

### Objective

Ultimately, in order for any modeling tool to be useful for design of a pyrotechnic shock test it must meet two requirements: 1) the ability to accurately predict the SRS which would be realized during the actual test, and, 2) have a simulation run time which is allows for significant savings in time and money over the traditional empirical approach. Unfortunately, in the realm of modeling and simulation, accuracy and speed are often conflicting goals. Nevertheless, significant effort in this work has been devoted to development of a modeling approach which would provide acceptable accuracy within a relatively short simulation run time. As a benchmark, a test facility may be able to execute between four and six ordnance-induced pyrotechnic shocks on a specific piece of test hardware in one work day. Therefore a simulation time of one hour would save significant time and also reduce the cost associated with fabrication and the use of consumable materials.

### Modeling Approach

One of the first decisions which must be made when developing a modeling tool for prediction of the dynamic structural response of a system is how the equations of motion (EOM) will be solved. The approaches which are typically used in structural dynamics fall into two broad categories: modal superposition and direct numerical integration. In modal superposition, which is the approach utilized in the previous modeling efforts for pyrotechnic shock [6,7], the free vibration modes of the structure are utilized to uncouple the EOM by transforming into modal coordinates. The transient response of each mode to the input excitation is then solved independently, and finally the results are summed to calculate the overall transient system response. This solution depends on linearity in the system response, otherwise superposition of the modal responses would not be valid.

Within the direct numerical integration category, solution techniques can be characterized as either implicit or explicit. Implicit approaches discretize the time domain by casting the unknown displacement vector $u_{n+1}$ as a function of the current displacement, velocity, and acceleration vectors ($u_n, v_n, a_n$) and of itself. In other words, the location of each node $v$ at the next time step will depend on both its current state as well as the next location of all of the nodes in its vicinity. Since the resulting equations are coupled, the system of equations must be solved simultaneously. Non-linearity can be handled using the implicit approach, but the computational expense can be significant as convergence at each time step now requires iteratively solving the simultaneous equations. In the explicit approach, the nodal displacement vector $u_{n+1}$ is a function of only current displacement, velocity, and acceleration vectors ($u_n, v_n, a_n$). Since all of these values are known, the new displacement vector can be calculated directly, typically making the calculation time per time step much shorter for the explicit approach. However the reduced calculation time comes with a penalty in the form of stability. The explicit approach is conditionally stable with respect to time with a maximum time step limitation specified by the Courant-Friedrichs-Lewy condition. The implicit approach is unconditionally stable and therefore the time step is not inherently limited by the technique. Due to the ability to utilize larger time steps, the implicit approach tends to be preferable for longer duration events, on the order of seconds, while the explicit approach tends to be preferable for events with a duration on the order of milliseconds. An ordnance-induced pyrotechnic shock event typically lasts between 15 and 20 milliseconds.

In this work, our goal is to replicate the measured results of an ordnance-induced pyrotechnic shock test. Due to the high frequency content of the input energy of the pyrotechnic event, there is always a concern that the accelerometer resonance might become excited and the high amplitude out-of-band energy may be aliased into the sampled data. To avoid this, there are often strict requirements on the amount of attenuation required by the analog anti-aliasing (AAA) filter at the Nyquist frequency [1]. In order to ensure sufficient attenuation, pyroshock data is typically oversampled and then the AAA filter cutoff frequency is set several octaves below the Nyquist frequency. At Element U.S. Space & Defense, ordnance-induced pyrotechnic shock data is always acquired using a sampling rate of at least 1MHz with an AAA filter cutoff frequency of 20 kHz. The sampling rate of 1MHz sets the upper limit on the time step size in the simulation to 1 microsecond if we are to output simulation results with the same frequency as the acquired data. A time step on the order of 1 microsecond or less is also required in order to resolve the shape of the impulse imparted to the resonating plate due to the detonation event (see Figure 2, left).

Finally, the combination of short computational time required per time step, and therefore the ability/requirement to utilize extremely small time steps, coupled with the ease of handling non-linear material models makes the explicit approach the natural choice for modeling detonation of HE materials. In fact, most commercial explicit codes have built-in material models for explosives, typically using a Jones-Wilkins-Lee equation of state to model the detonation

product behavior. The ability to directly simulate the explosive type and geometry in order to determine the spatial and temporal variation of the impulsive load imparted to the resonating plate is a significant advantage.

To summarize, there are several key aspects of this modeling problem which favor an explicit modeling approach, namely:

- The relatively short duration of the ordnance-induced pyrotechnic shock event, ~20ms
- The small time step requirement driven by the desire to capture the transient impulse imparted to the plate during the detonation event and by the need to write model results at 1MHz to match experimental sampling rate
- The ability to directly model the detonation and subsequent behavior of the HE material

Based on this analysis, the decision was made to pursue an explicit technique for modeling of ordnance-induced pyrotechnic shock.

## MODEL SETUP

As a test bed for the modeling methodology, a finite element model of the test configuration shown in Figure 3 and Figure 4 was developed. The test fixture consists of a 48" x 48" x 1" aluminum resonating plate, 12" x 12" x 1" horizontal aluminum shelf, and a 12" x 12" x 1" vertical aluminum stiffener. The shelf and the stiffener are attached to the resonating plate using bolts (eight each), which pass through the resonating plate and into threaded holes along each edge. The shelf is connected to the stiffener using the same approach. The aluminum plates in the test fixture were modeled using Belytschko-Tsay shell elements, the default formulation in LS-DYNA [8]. The plates were connected by merging the nodes along the common edges. An elastic-plastic material model was used for the resonating plate in order to capture the local plastic deformation caused by the HE detonation while a purely elastic model was utilized for the shelf and the stiffener. The mesh size for all three plates was based on the desire to capture sufficient frequency content in the model. For a semi-infinite rectangular plate, the bending wavelength as a function of frequency is given by,

$$\lambda = \sqrt{\frac{2\pi}{f}} \left( \frac{Et^2}{12(1-v^2)\rho} \right)^{0.25}$$

where E is Young's Modulus, t is the plate thickness, f is frequency, v is Poisson's ratio, and p is density [9]. For a 1" thick 6061-T6 aluminum plate, the bending wavelength at a frequency of 20 kHz is 4.37". The maximum element size utilized in the aluminum plate mesh was set at 0.27" to ensure greater than 16 elements per bending wavelength up to 20 kHz. No damping was incorporated into the model.

One type of high explosive commonly used at Element U.S. Space & Defense is pentaerythritol tetranitrate (PETN) detonating cord. In order to localize the energy imparted to the resonating plate, the cord is coiled into a disk configuration. For the simulation, the coil of detonating cord was modeled as a homogeneous solid disk of PETN with a diameter equivalent to the diameter of the coiled cord. In order to ensure that the total explosive weight was consistent with the coiled cord, the density of the PETN material in the solid disk model was reduced. Detonation was initiated in the center of the disk and propagated using a programmed burn model, and the detonation product behavior was modeled using the Jones-Wilkins-Lee (JWL) equation of state for high explosives

$$p = A\left(1 - \frac{\omega}{R_1 V}\right)e^{-R_1 V} + B\left(1 - \frac{\omega}{R_2 V}\right)e^{-R_2 V} + \frac{\omega E}{V}$$

where pressure (p) is defined as a function of relative volume (V), internal energy per initial volume (E), and A, B, R1, R2, w are equation of state parameters unique to each high explosive material. The equation of state parameter values used in this work were taken from reference [5].

In order to validate the model, simulation results and test data were acquired for several different test configurations achieved by varying two parameters: ordnance location and amount. Two ordnance locations were utilized, as shown in Figure 4 (right). Location 1 was 9" above center and 12" to the right; location 2 was on the horizontal symmetry plane but 18" to the left. Three different amounts of explosive were utilized: 2ft, 5 ft, and 10 ft of 15 grain/ft detonating cord. The finite element model is shown in Figure 5, with the PETN disk visible at Location 1 on the back of the resonating plate.

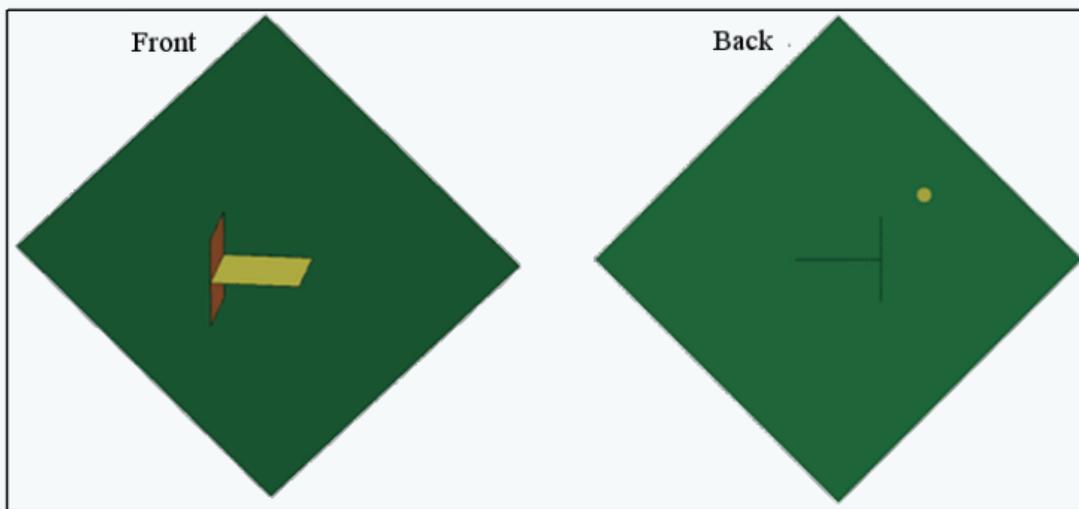Figure 4. Test configuration (left) and ordnance locations (right) used to validate the model



Figure 5. Finite element model of ordnance-induced pyrotechnic shock test configuration shown in Figure 4

## DATA COLLECTION & MODEL OUTPUT

Acceleration data from testing was captured using the Genesis High Speed data acquisition system from HBM, Inc. and three orthogonally mounted model 350C02 accelerometers from PCB Piezotronics, Inc. (Figure 6 left). The 350C02 accelerometers have an internal electrical low pass filter with a cutoff frequency of 13 kHz as well as an internal mechanical filter with a resonant frequency of 23 kHz. As previously mentioned, the analog signal was filtered using an AAA filter (Performance Filters, Inc.) with a cutoff frequency of 20 kHz and the data was then sampled at a rate of 1 MHz.

Comparable data is extracted from the simulation by tracking the acceleration-time history of a single node on the shelf at the location where the accelerometers are mounted during the test as shown in Figure 6 (right). The coordinate system shown in Figure 6 (left) is also utilized in the model, and the X, Y, and Z accelerations of the node are written to a file every 1 microsecond, replicating the 1 MHz sampling rate. The acceleration output from the model is then filtered with a digital low pass Butterworth filter at 13 kHz to reflect the internal filtering of the PCB 350C02 accelerometers. Since the time step in the simulation is much lower than 1 microsecond, saving results every 1 microsecond is equivalent to downsampling, and therefore the model results can potentially be corrupted by aliasing. To verify aliasing did not occur in the model results, the acceleration output was integrated to calculate nodal velocity and then compared with the actual nodal velocity output directly from the model.
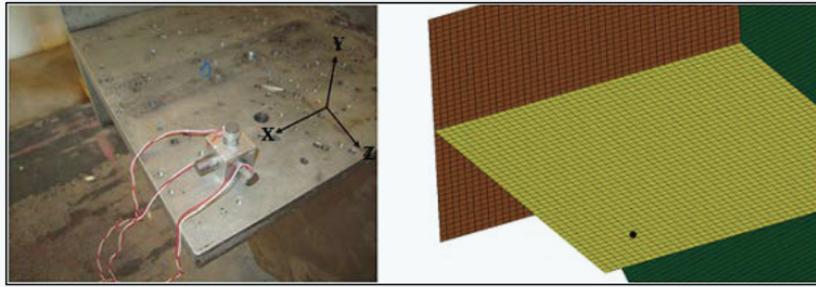
Figure 6. Triaxial accelerometer block location during testing (left) and the finite element node chosen to output comparable results from the model (right)

## MODELING RESULTS

A parametric study involving two detonation locations and three detonating cord lengths was utilized to validate the modeling approach. Results are presented in this section for only one configuration, 2 ft of detonating cord at location 1(see Figure 4 and Figure 5); the comparison between the model and the test results was comparable for all configurations investigated.

Figure 7 shows simulation results with contours of von Mises stress at 200 and 400 microseconds. Transverse stress waves can clearly be seen emanating from the detonation location, propagating through the test fixture, and reflecting from the plate boundaries. The entire simulation is allowed to proceed to 20 milliseconds after the initial detonation to provide two full oscillation periods at a frequency of 100 Hz. In order to ensure that this cutoff time did not have a significant impact on the calculated SRS, the SRS was calculated on the full test data sets (roughly 1 second duration) as well as the test data after truncating to 20 milliseconds; no appreciable deference was observed. The wall clock time for each simulation was roughly 40 minutes on a workstation with an Intel Core i7 CPU and 4 core license of LS-DYNA.
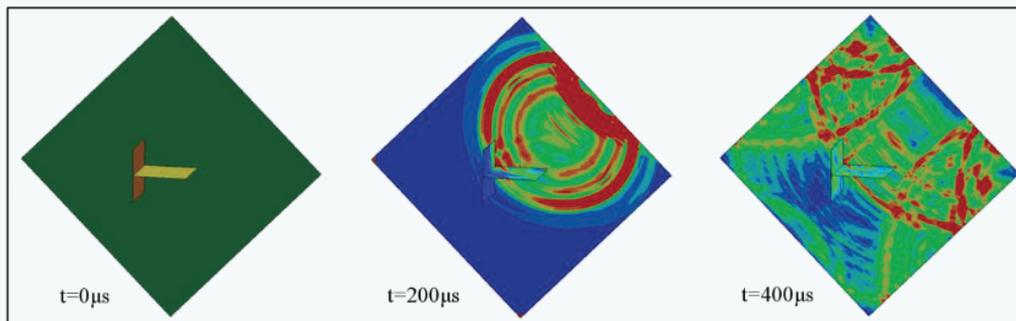


Figure 7. Simulation results showing stress waves emanating from the detonation location and propagating through the test fixture

Figure 8 through Figure 10 show the X, Y, and Z acceleration-time history comparison between the test data, the unfiltered model data, and the model data after low pass filtering at 13 kHz. There is significant frequency content above 13 kHz with very high acceleration levels (>15,000 g) in the model prediction before filtering. After filtering, the model predictions are more consistent with the measured results, especially in the second half of the simulation. During a test program the test data is evaluated based on the SRS and therefore accurate prediction of the SRS is the most appropriate metric by which to judge the model. The SRS calculated from the model is plotted alongside the SRS calculated from test results in Figure 11. The test was repeated four times in order to establish the repeatability of the test data; results from all four tests are provided. The model agreement with the test data in the X and Z axes is excellent.

The agreement in the Y-axis is not as good, although is still likely acceptable from a test design perspective. The disagreement in the Y-axis is most likely a result of the simplification implemented in the model whereby the bolted connections between the aluminum plates are approximated by merging the nodes along the plate boundaries. The Y-direction is the vertical excitation caused by bending of the mounting shelf and therefore responds to torque and shear applied along the mounting plate edges. The other two directions are driven by normal forces along the plate edges and are therefore less sensitive to the modeling simplification.

Overall, the SRS results are in good agreement with the test data and provide confidence that this modeling approach can be utilized as a predictive tool to design ordnance-induced pyrotechnic shock tests.
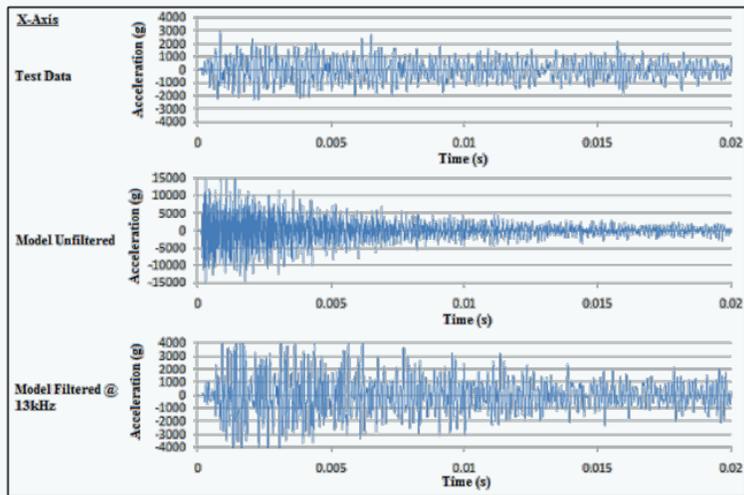
*Figure 8. Comparison of measured data with filtered and unfiltered simulation results, acceleration-time history, X – axis*
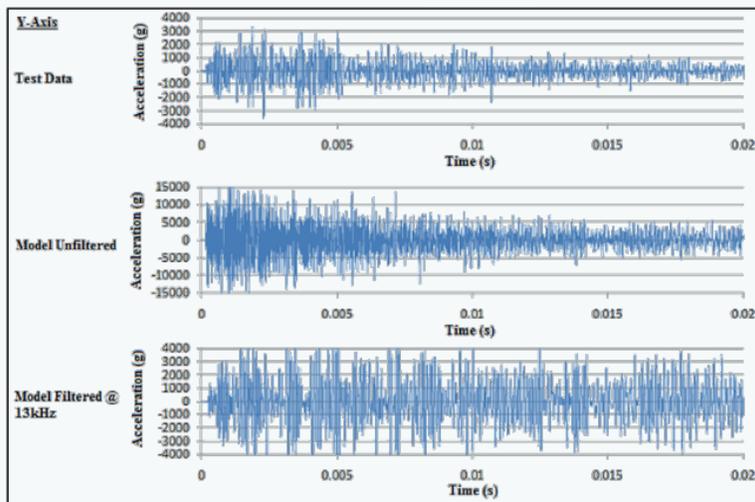


*Figure 9. Comparison of measured data with filtered and unfiltered simulation results, acceleration-time history, Y – axis*
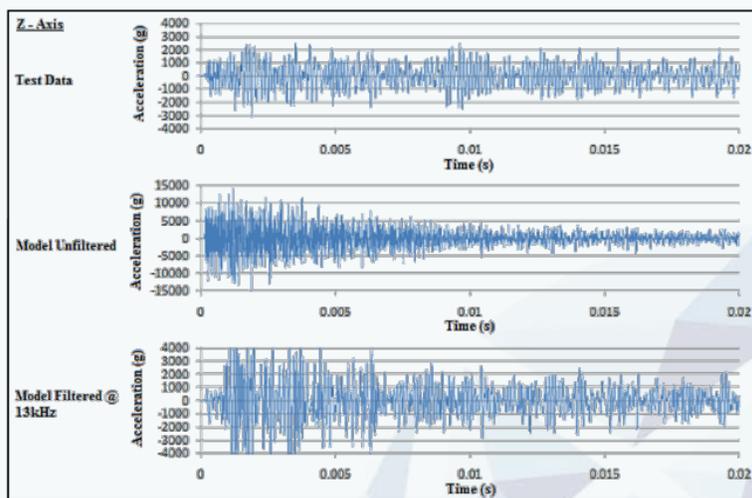


*Figure 10. Comparison of measured data with filtered and unfiltered simulation results, acceleration-time history, Z – axis*
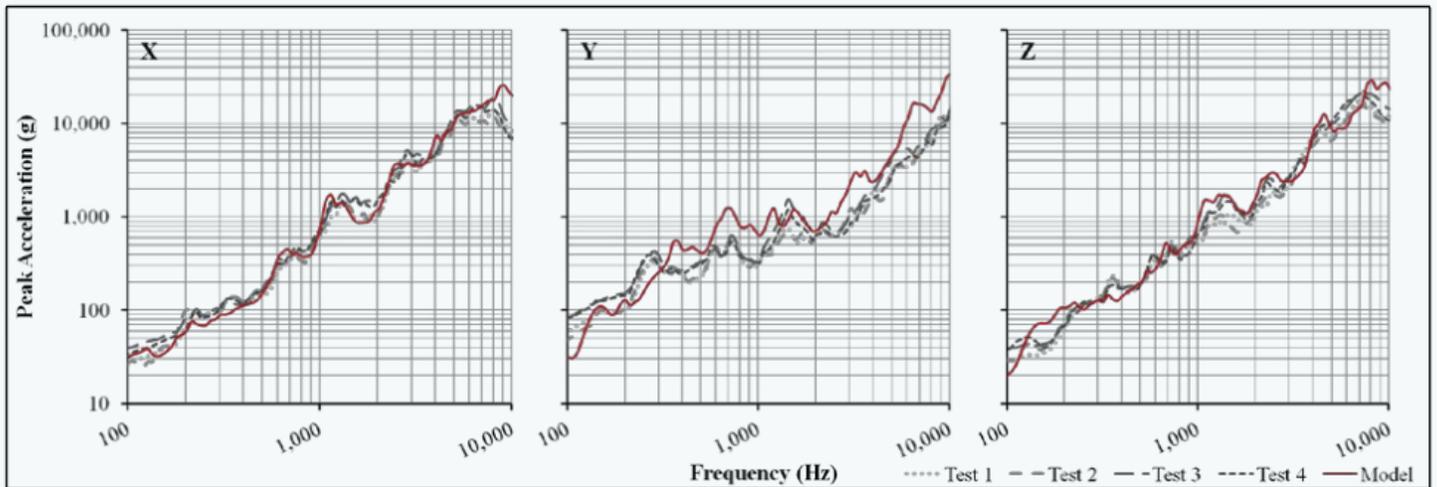
*Figure 11. Comparison of model and experimental SRS levels*

## TEST FIXTURE DESIGN

The previous discussion has demonstrated that, given a specific test configuration, this modeling approach can predict the SRS which will result from testing. The true value of the model can only be realized if the inverse problem can be solved. Specifically, given a test requirement in the form of an SRS, what test configuration should be utilized to create the desired environment? Certainly the same trial-and-error process which has traditionally been used in pyrotechnic shock testing can also be exercised with the model, however, this section explores additional insight into test fixture dynamic response which can be extracted from a model and used to assist with test fixture design.

After the detonation energy is deposited into the resonating plate, the transient response is dictated by the combination of all of the excited free vibration modes of the structure. It is reasonable to expect that free vibration modes which involve out of plane motion of the resonant plate in the vicinity of the explosive impact will be preferentially excited by the detonation event and will likely dominate the structural response. Based on this expected behavior, specific SRS levels could potentially be achieved by designing a structure with the right combination of natural frequency and mode shape and then preferentially exciting this mode by locating the explosive material at an anti-node of this mode.

In order to investigate whether or not this approach would prove to be effective, a modal analysis of a pyrotechnic shock test fixture was performed and three separate modes which all resulted in a lateral +/-Z swinging motion of the mounting shelf were identified. Figure 12 shows these three modes at 194 Hz, 334 Hz, and 568 Hz, all colored based on relative displacement where blue is zero displacement and green-yellow-red are areas with increasing displacement.

Areas with little displacement can be considered the nodes of the mode and areas with significant displacement can be considered the anti-nodes. Within these three modes, two locations have been identified which should preferentially excite one mode over another and therefore produce an increase in the SRS level at the frequency of the excited mode.

These locations are shown on each mode in Figure 12, labeled as Location 1 and Location 2. Location 1 is near an

anti-node of the 194Hz mode and the 334Hz mode, but is on a node of the 568Hz mode. Location 2 is on an anti-node of the 568Hz mode but is located on a node of the 194Hz mode and the 334Hz mode. Therefore it is expected that placing the explosive charge at Location 1 should produce and SRS with elevated levels at 194Hz and 334Hz and that placing the explosive charge at Location 2 should produce an SRS with elevated levels at 568Hz.
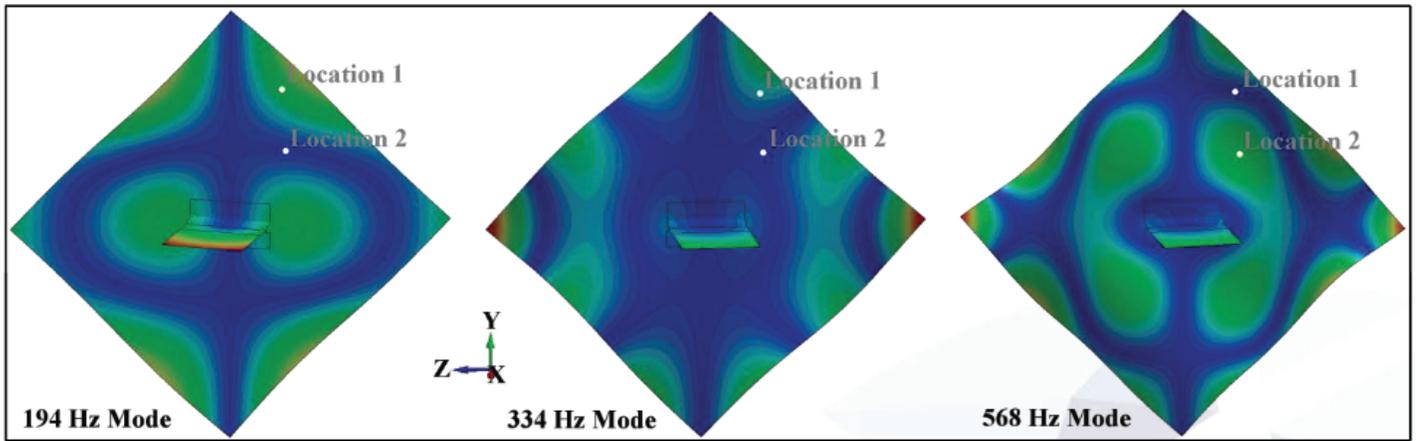
*Figure 12. Three free vibration modes of the pyrotechnic shock test fixture which produce +/-Z axis excitation on the mounting shelf*

Figure 13 shows the Z-axis SRS after running a simulation using the explicit finite element model and varying only the explosive location between Location 1 and Location 2. Below 1 kHz the differences in the SRS levels predicted by the model are dramatic. At 194 Hz there is a factor of four increase in the SRS level from the Location 1 simulation over the Location 2 simulation and there is nearly a factor of three increase at 334 Hz. Conversely, the Location 2 simulation predicts SRS levels twice as high at 568 Hz as compared to Location 1. It is clear that the desired effect has been achieved and therefore test fixture design coupled with modal analysis to determine charge location can be utilized to tailor the SRS response achieved during test. It is worth noting that this approach does have limitations, especially when attempting to tailor the SRS in multiple directions simultaneously or at higher frequencies. In both situations it becomes difcult to isolate modes in which the nodes and anti-nodes do not overlap, either in their influence on the direction of excitation at the mounting plate or based on frequency as wavelength decreases.
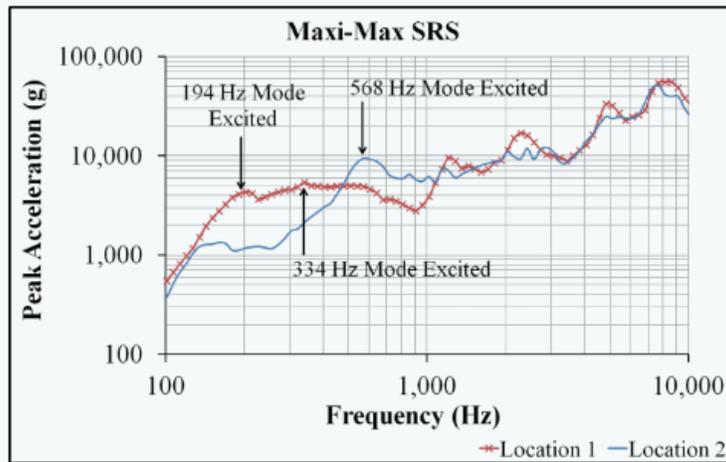


*Figure 13. Comparison of the Z-axis SRS results calculated from simulation results with the explosive at Location 1 and Location 2*

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## SUMMARY AND CONCLUSIONS

An explicit finite element model of ordnance-induced pyrotechnic shock has been developed. The approach directly models the high explosive material and the detonation process, thereby avoiding any ad hoc tuning approach to determine the shape, amplitude, or influence region of the explosive-metal interaction. In addition, the model allows for non-linear response, specifically material behavior in the form of local plastic deformation in the region of the explosive detonation. Through comparison with test results, it has been demonstrated that the model can accurately predict the SRS resulting from a variety of test configurations. The ability to accurately predict SRS levels, coupled with a simulation run time of less than an hour, should allow this modeling tool to be useful to the pyrotechnic shock test community as an alternate approach to test fixture design.

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