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Evaluation of a Multiaxis Shock Fixture Concept

David E. Soine
Sandia National Laboratories[1]
P.O. Box 5800 – MS0557
Albuquerque, NM 87185

Tyler F. Schoenherr
Sandia National Laboratories[1]
P.O. Box 5800 – MS0346
Albuquerque, NM 87185

Jack D. Heister
Sandia National Laboratories[1]
P.O. Box 5800 – MS0557
Albuquerque, NM 87185

ABSTRACT
Mechanical shock testing utilizing different types of resonating fixtures is an aerospace environmental testing practice useful in simulating mid-field pyroshock. Qualification tests using these methods may be specified in single or multiple test axes, with each axis performed individually or sometimes all at once. Simple structures such as bars, beams, and plates have been used to repeatably perform single axis resonant shock tests, while plates of varying sizes along with a 90 degree bracket have been used to perform tests that meet all axes requirements in a single shock test event.

This work will evaluate a different fixture concept, used in conjunction with a resonant plate. The fixture is designed to create a controlled resonant response in two axes, which when combined with the plate motion in the third axis can achieve a repeatable resonant shock response in all axes at once, with minimal setup time or operator trial-and-error. Modal properties of a combined fixture and plate assembly are used as performance objectives for the fixture design. Finite element modeling is used to evaluate and modify the fixture design. A fixture is then fabricated and tested in several configurations to evaluate modal response characteristics, shock response performance, and the performance of the model when predicting those quantities of interest.

Keywords: Mechanical Shock, Pyroshock, Modal Analysis, Resonant Fixture, Plate

INTRODUCTION
Pyroshock is the high-acceleration transient transmitted to a structure due to the use of an explosive bolt, joint or other device containing energetics. These devices have been used to perform critical structure separation activities, such as stage separation in spacecraft. In the 1960s and early 1970s, the identification of pyroshock as a significant cause of electronics failure on spacecraft and other aerospace vehicles led to the development of pyroshock simulation techniques, and those test techniques began to be used to demonstrate that aerospace components can withstand these types of events. Resonant fixture

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shock testing was adopted as a technique for pyroshock simulation, and methods were developed utilizing simple plates, bars, or beams to provide a resonating platform for test article attachment. The test is performed by striking the resonant fixture assembly with a projectile or hammer in an appropriate direction, resulting in a rapid onset acceleration followed by a decaying sinusoidal acceleration corresponding to the excited resonant frequencies of the assembly. When a test is carefully designed and performed, the acceleration measured near the test article has a shock response spectrum similar to that of actual pyroshock events measured during vehicle field tests.

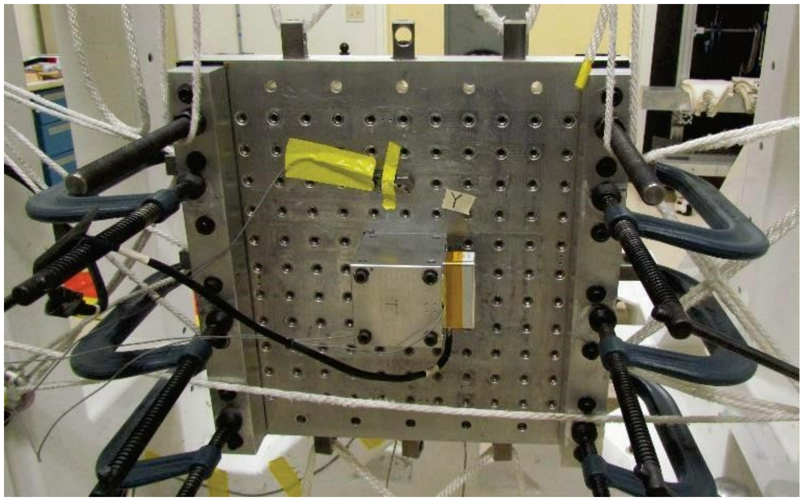

Fig. 1 A rope suspended resonant plate with isolated damping bars and clamps added to achieve the desired shock response spectrum. A test fixture with a test unit is attached to the center of the plate. The projectile impact occurs on the opposite side of the plate.

RESONANT FIXTURE FUNDAMENTALS & EXTENSION TO MULTI-AXIS RESPONSE

The fundamentals of resonant fixture design for uniaxial shock response, as developed at Sandia National Laboratories, were documented by Neil Davie and Vesta Bateman [1,2]. Three techniques were developed, exploiting the fundamental modes of vibration of simple structures. Handbook formulas were used as the primary design tool. The resonant bar technique exploits the extensional natural frequency and mode shape of a bar (free-free boundary conditions), with the resonant frequencies estimated by Equation 1. Dimensions of the resonant bar are selected such that the natural frequency of the extensional mode aligned with the desired peak in the shock response spectrum.

$$f_n = \frac{nc}{2L} \tag{1}$$

$$n = 1, 2, 3 \ldots$$

$$c = wave\ speed\ in\ the\ bar\ (\sim 199{,}000\ \text{in/sec for Aluminum})$$

$$L = bar\ length$$

When the end of the resonant bar is struck with a projectile, the resulting wave travels the length of the bar and reflections within the bar result in excitation of the extensional modes. The test unit is mounted to the end of the bar opposite the impacted end, and the bar end motion provides the shock simulation to the unit. The resonant beam and resonant plate techniques were developed in a similar fashion to resonant bar, except they exploit the first bending mode of the beam or plate. Design dimensions of the plate and beam are similarly estimated from handbook equations. The design approach for resonant beam can be found in the references [2] and are not discussed here. Regarding resonant plate, the method has been implemented primarily on square plates suspended to simulate free boundary conditions. The first three flexural modes of a square plate are the twist (torsion) mode, the saddle mode, and the breathing (plate bending) mode, respectively. The plate is struck with the projectile in the center, perpendicular to the plane of the plate. This location takes advantage of the fact that the twist and saddle modes both have node lines through the center point of the plate, whereas the center of the plate is a point of maximum motion of the breathing mode; therefore, response of the twist and saddle modes are minimized while the breathing mode is strongly excited. The test unit is mounted to the center of the plate opposite the projectile impact point.

The fundamental lessons from successful uniaxial designs for resonant shock test structures are 1.) utilize the lowest flexural modes possible when designing to the intended peak frequency, and 2.) exploit the mode shape (node lines, etc.) to suppress or enhance the modal response as needed. The approach taken in this work will attempt to extend these principles by combining simple structures into an assembly that responds strongly in three axes to a single projectile impact.

CYLINDRICAL CONCEPT FIXTURE DESIGN

A cylindrical adapter fixture to be attached between the resonant plate and the test article was designed and fabricated. With the cylinder attached perpendicular to the plate surface, the fundamental design concept was for the plate bending motion to provide one axis of shock response perpendicular to the plate, while the cantilevered cylinder bending response would dominate the motion parallel to the plane of the plate. The test article is mounted to the end of the cantilevered cylinder. For this work, “impact direction” or “Z-axis” motion will refer to motion perpendicular to the plate, while “transverse” or “X- and Y- axis” refers to motion parallel to the plane of the plate.

The design goal of the cantilevered cylinder was for a first bending frequency between 500 and 600 Hz. The fixture design was modeled in CAD, with a simulated test unit consisting of a seven inch square plate. Initial dynamic modeling and tailoring of the cylinder dimensions resulted in an estimated frequency of 593 Hz for cylinder bending of a combined plate, cylindrical fixture, and simulated test unit, which was deemed adequate to proceed with fabrication and testing. Flanges and bolted interfaces at each end of the cylinder were designed to match the standard bolt pattern (1.5 inch) common to the resonant plates in the test laboratory.

Fig. 2 Cylindrical concept fixture with a 7 x 1.25 inch square plate to simulate loading with a small test article.

Resonant plate testing was developed to perform single-axis shock tests, with a high response in the test direction, and very low transverse response. One concern for the cylindrical concept fixture was how to excite the bending modes that would hopefully dominate the transverse acceleration response of the test article. Methods considered to enhance the transverse response included changing the projectile impact location, impact direction, and changing the location of the fixture on the plate. It is known that for the bending mode, the surface of the plate exhibits rotation at locations away from the plate center [3], and the team investigated the phenomenon to achieve excitation of the fixture in the transverse direction. Only results obtained by changing the location of the cylindrical fixture on the plate are reported here.

MODELING AND AS-BUILT RESPONSE

To enhance model-driven test design in the mechanical shock laboratory, a substantial finite element modeling (FEM) effort was undertaken prior to and in conjunction with the testing. Several challenges to accurate modeling were observed - one significant observation was the contribution of bolted interfaces to the measured shock acceleration and shock response. To mitigate these effects, precision steel spacers were added to cylindrical fixture interface. This interface modification was found to improve agreement between the shock response of the test and FEM. [4,5]

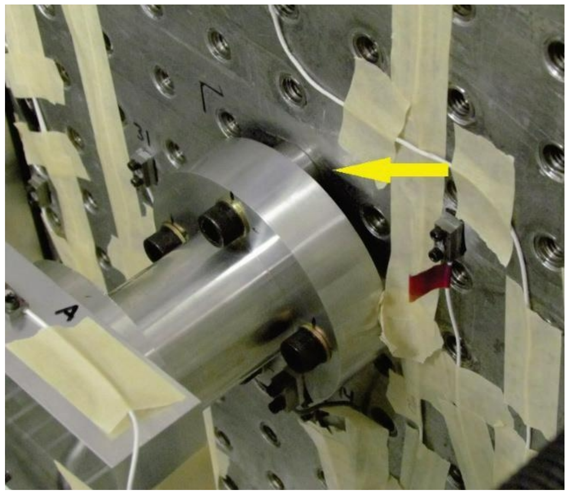

Fig. 3 A precision steel spacer (yellow arrow) installed between the cylindrical fixture and the resonant plate. In the future, this linearization of the physical system could be integrated into the machined surface of the fixture via a boss.

One goal of model-driven test design is to accurately estimate the natural frequencies of the resonant fixture assembly, since the actual natural frequencies delivered by the shock test need to be within approximately 10-20% of the design target to be successful. Table 1 contains some of the resonant frequencies of interest, derived from both finite element modeling and testing. The frequencies from testing are the peak frequencies of the FFT of the shock acceleration response.

Table 1 Natural frequency estimates from finite element modeling (FEM) and shock testing.

	Initial FEM	Hi Fidelity FEM	Hi Fidelity FEM	Shock Test	Shock Test
Plate Configuration	20.1x2.5" plate	20x2" plate assy.	20x2" plate assy.	20x2" plate assy.	20x2" plate assy.
Fixture Location	Center	Center	Offset 4.5,4.5"	Center	Offset 4.5,4.5"
Fixture Interface	Full Surface	Linearized	Linearized	Linearized	Linearized
Cylinder transverse "X" (Hz)	593	495	487	462	510
Cylinder transverse "Y" (Hz)	593	503	502	500	462
Plate saddle/bending (Hz)	-	710	769	677	724
Plate bending (Hz)	-	927	995	887	968

TEST RESULTS

Shock testing was conducted on a 20 x 20 x 2 inch resonant plate assembly. For these results the plate was struck in the center by a 24 pound projectile at a velocity of approximately 34 feet per second, with one half inch of felt placed between the plate and projectile to lengthen the input pulse rise time. Two locations for the cylindrical fixture are reported here: in center of the plate, and offset 4.5 inches in both the X and Y dimensions, see Figure 4. Shock acceleration measurements were made on the simulated test article.

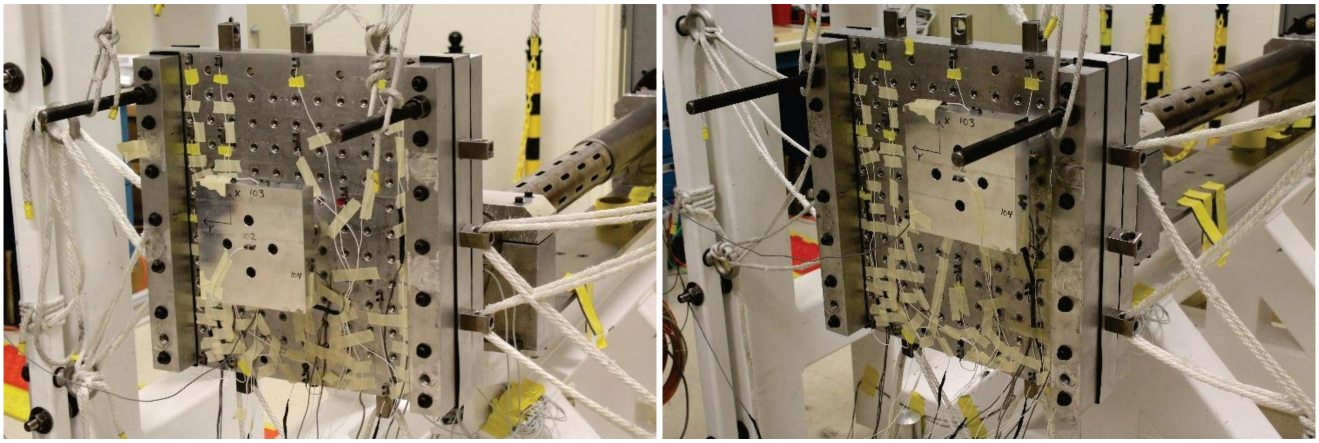

Fig. 4 Fixture Centered (left) and Offset 4.5 inches in the X- and Y- directions (right).

Resonant plate shock testing is usually specified using the shock response spectrum (SRS), with typical specifications having an initial slope of approximately 12 dB/octave, with the specification rising to the target natural frequency for the test. Above the target natural frequency the specification has zero slope. Typical test tolerances are ±6 dB from the reference. A reference shock response spectrum is used in this document for visual comparison to the measured shock response, see Table 2. Note that the initial slope of the reference spectrum in Table 2 is 9 dB/octave. In these results, the same reference spectrum is used for both the impact direction and transverse directions, but a better reference spectrum might have a target frequency of 550 Hz for the transverse axes, since that assumption was made (target natural frequency 500-600 Hz) during the design phase of the cylindrical fixture.

Table 2 Reference shock response spectrum used for visual comparison of results. The target natural frequency, sometimes called the "knee frequency," is 1000 Hz in this example,.

f_n (Hz)	MMAA SRS (g)
250	500
1000	4000
10000	4000

Figure 5 contains plots of the shock response spectra achieved with the test article in the center location on the plate (represented by Run 62, in red), and with the test article offset (Run 46, in blue). When the fixture is located at the plate center, a low transverse response is expected at the test article. This proved to be the case and the transverse shock response spectra were generally more than 18 dB below the response in the impact direction. The exception is at approximately 450 Hz in the X direction, where the transverse response slightly exceeded that of the impact direction. It appears that the cylinder bending response is excited by some aspect of the full test assembly motion. The plate assembly bending frequency has a peak at 887 Hz. Figure 6 shows the FFT of the acceleration response for both test cases.

With the fixture located in an offset location, 4.5 inches from the center in both the X- and Y- axes, the response in the impact direction (Z-axis) is 2 to 6 dB less than response when on-center, with a higher bending mode frequency of 968 Hz. Transverse response appears less than 12dB below response in the impact direction and reflects the transverse cylinder bending frequencies at 462 and 510 Hz.

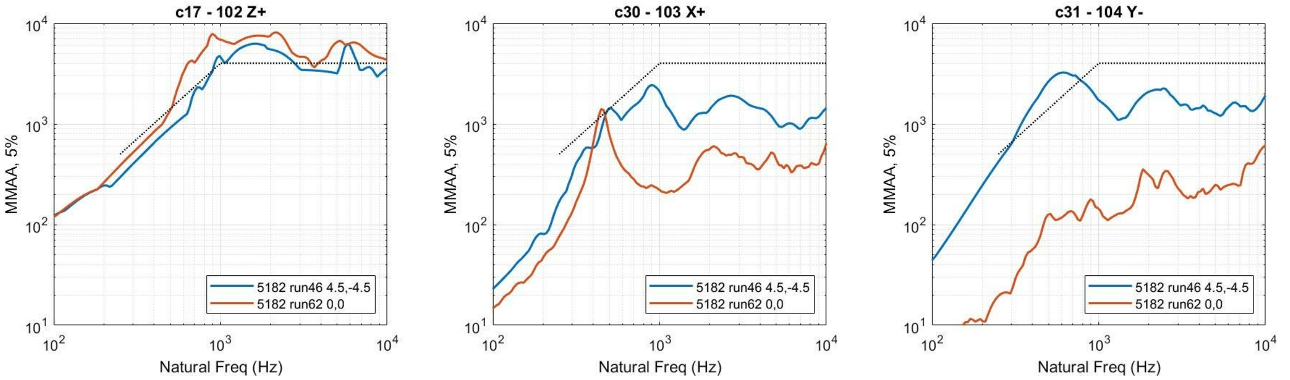

Fig. 5 SRS response at the simulated test article, with the fixture in the center of the plate (run62) in red, and the fixture offset 4.5 inches in X- and Y- axes (transverse axes) in blue.

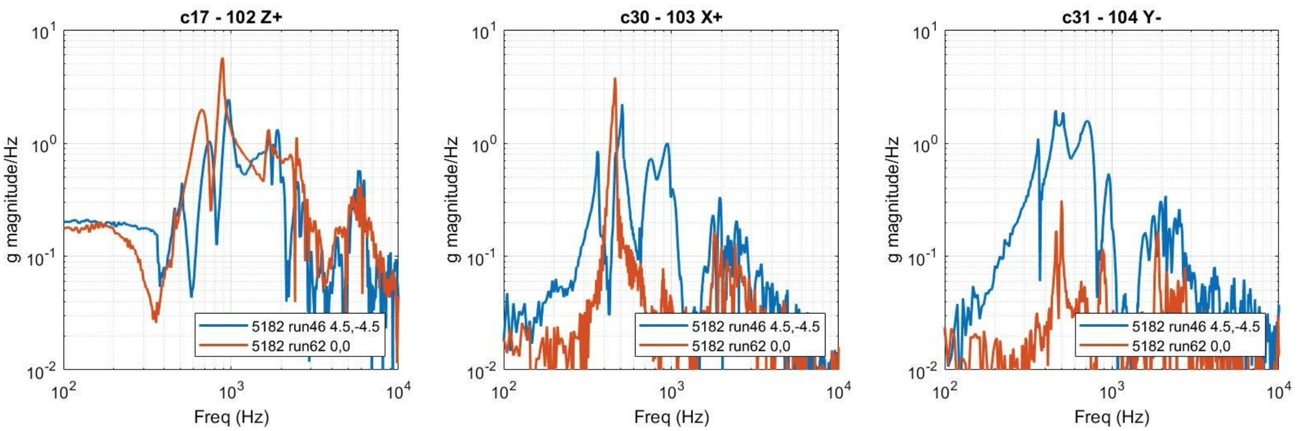

Fig. 6 FFT magnitude of Run 62 and Run 46.

SPECIFICATION GUIDANCE AND TEST EQUIPMENT DEVELOPMENT

This work demonstrates that the design approach used to develop the cylindrical fixture is viable to meet potential three-axis test specifications, with limitations. The specified SRS level of the transverse axes must be about 6-12 dB lower than the impact direction specification, and the frequency target for the transverse direction should be lower than the plate bending resonant frequency. Increasing the slope of the initial SRS profile in the transverse axes to 15-18 dB/octave would make the specification more producible, since the smaller expected velocity change in the transverse axes should drive a steeper slope in the SRS. Using this current work as an example, for the offset fixture location, the impact direction response would meet a specification like the reference SRS profile in Table 2. An example of a reference specification adjusted according to these guidelines is given in Table 3 below, and the data is plotted with the alternative reference specification in Figure 7.

Table 3 Example of a plausible SRS profile that the test assembly in this work would come close to meeting with a single impact. Note in the impact direction, the initial slope is 12dB/octave; in the transverse, initial slope is 15 dB/octave. The flat portion of the transverse SRS level is 9 dB below that of the impact direction.

f_n (Hz)	MMAA SRS (g) Impact Direction	f_n (Hz)	MMAA SRS (g) Transverse
250	250	125	44
1000	4000	500	1400
10000	4000	10000	1400

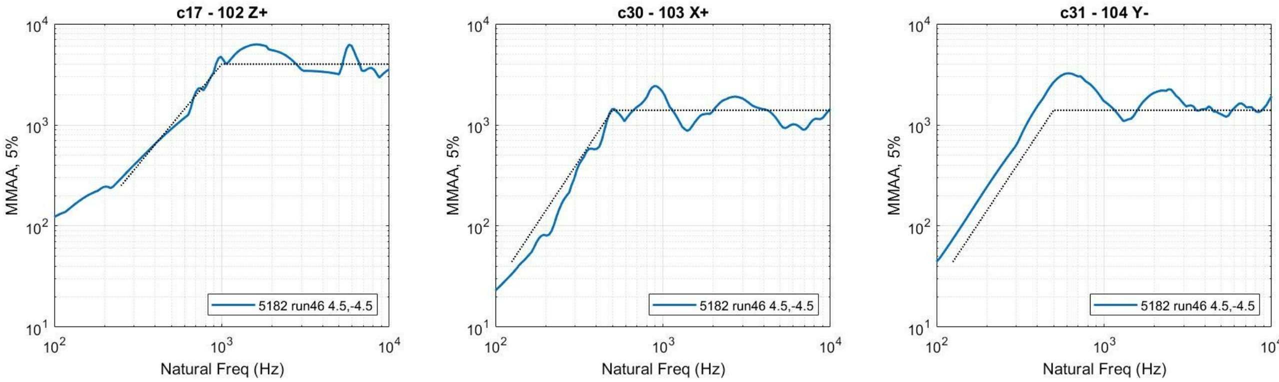

Fig. 7 Run 46 data, plotted with the reference SRS from Table 3.

In practice, an appropriate test specification could be developed according to these guidelines if the flight test or ground test data supported it. The test article fixture, cylindrical fixture, and resonant plate would subsequently be developed with CAD and FEM according to the design guidance given above.

CONCLUSION

Resonant plate shock testing has been a versatile and productive test method for simulation of mid-field pyroshock. Addition of the cylindrical test fixture concept to resonant plate techniques can expand the method to repeatably perform shock tests that provide a controlled response in three axes to a single projectile impact, by design, with minimal intervention from the shock testing practitioner.

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