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Modal Testing of Complex Hardened Structures

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ABSTRACT

A new testing method is being developed by the Air Force Research Lab to excite a desired multi-dimensional response in a structure using tuned resonances. The structure consists of a Aluminum plate and a perpendicular shelf. The test article is excited through the use of either an impact hammer or pyrotechnics (e.g., a pyrotechnic plunger) which in turn inputs a specific frequency profile. The dynamic response of the plate and shelf spans the entire spectrum from low (10 Hz) to high (10 kHz) frequency as well different peak amplitudes (i.e., accelerations). They are captured by a variety of instrumentation methods including modal accelerometers, laser vibrometers, and a digital image correlation system. The location of the shelf as well as its material and stiffness properties is modified to reproduce the design objective (frequency response functions with the desired amplitude and phase spectrum). These modifications are achieved through interpretation of modal data.

INTRODUCTION

The Air Force Research Lab (AFRL) conducts research in a wide variety of energy regimes. This research is designed to evaluate aspects of a test article over a variety of scales from components to systems and sub-scale to full-scale. One area that AFRL is specifically interested in is multi-axially exciting a system over the entire frequency spectrum from low (10 Hz) to high (10 kHz) as well as different amplitudes (i.e. – accelerations). The ranges desired will be demonstrated through the use of a Shock Response Spectrum (SRS). The desire is to develop a scientific, repeatable, field experiment that can reproduce the desired forces in order to determine the failure mechanisms in the systems under test. The test fixture, currently under design, consists of an aluminum plate with a shelf on the back where the item under test will be placed. The front of the plate will be excited through the use of pyrotechnics (e.g. a pyrotechnic plunger or detonation cord) which in turn will input a specific force and frequency profile. This paper will provide a brief overview of similar test fixtures used in industry, discuss the data from one pyrotechnic test, and compare that data with three LS-DYNA simulations. It will conclude with a discussion of how AFRL plans to develop this test apparatus.

BACKGROUND

In 2001 AFRL contracted with Wyle Laboratories to perform a pyroshock test on a system component. The results from that test were intriguing as they were able to impart low frequency energy over a significant duration on all three axes. This was the impetuous to develop our own unique test apparatus, where we would expect to impart the low energy into our test article, but also evaluate the ability to excite the high frequencies as well. In 2006 Ensign-Bickford Aerospace & Defense Company (EBA&D) presented a similar type of test article [1]. AFRL is currently trying to compare the data gathered from these tests using computer simulations in their effort to develop the Multi-Axial Pyrotechnic Plate (MAPP) test apparatus. The current design of the test fixture consists of an 8’ x 4’ aluminum plate approximately 1” thick and supported in 2 locations along the top edge of the plate; which simulates free-free end conditions. A support shelf, or “bookshelf” is located on the back of the plate and is where the item under test is located. It is assumed that the shelf and its supports are welded to the plate.

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APPROACH

Pyroshock is the desired method to excite the MAPP test apparatus because it differs from other types of mechanical shock. Compared to mechanical shock, there is very little rigid-body motion of a structure in response to pyroshock. The acceleration time-history of a pyroshock, measured on the structure, is oscillatory and approximates a combination of decayed sinusoidal accelerations with very short duration as shown in Figure 1 [2]. When a test article is very close or in contact with the explosive, it is considered near-field. In these cases the Pyroshock acceleration time-history consists of a high-frequency, high-amplitude shock that may have transients of microseconds or less. This near-field energy is distributed over a wide range of frequencies and is typically not dominated by a few selected frequencies. The energy deposition time for a pyrotechnic event is very small and does not strongly excite the rigid body modes of the structure. The resulting stress waves, from the explosives, propagate through the test article and high-frequency energy is gradually attenuated due to various material and structural damping mechanisms. That high-frequency energy is then transferred or coupled into the lower frequency modes of the structure. It is through these modes that AFRL hopes to tune the structure and the “bookshelf” to excite specific modes.

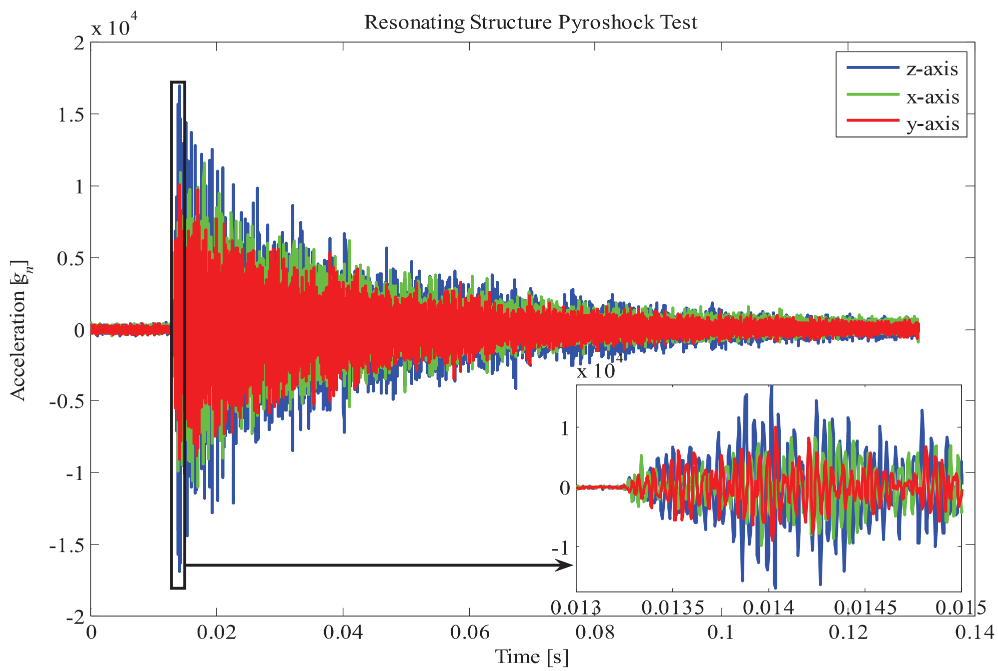
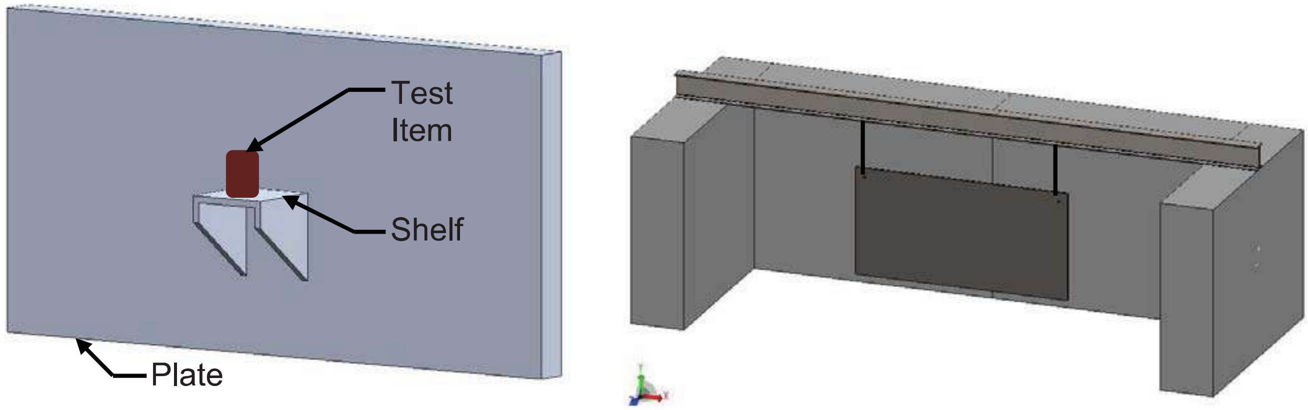


Figure 1 Pyroshock Time History

TEST SET-UP

AFRL is developing a test apparatus called the Multi-Axis Pyrotechnic Plate (MAPP) that consists of an aluminum plate with a “bookshelf” type support on the back. The current design utilizes a 8’ x 4’ x 1” plate that is supported at two locations along the top of the plate to simulate a free-free-free-free boundary condition. The bookshelf on the back is attached to the plate for 12” along one edge and protrudes out another 12”. The shelf itself is 1” thick and made out of aluminum. Stiffening supports are placed along both edges of the plate and are also constructed of 1” thick aluminum. The “bookshelf” will be welded to the Aluminum plate at the desired location, which is currently under investigation. The location, stiffness, and material properties of the shelf will determine what type of multi-axial accelerations the item under test will be exposed to. Schematic drawings of the MAPP set-up and the test bunker are shown in Figure 2 (a) and (b), respectively.

In order to determine the properties and location of the shelf on the MAPP system the desired forces and frequencies applied to the system under test needs to be determined. In the complex environment that AFRL is interested in there is a methodology of developing test requirements using a Shock Response Spectrum (SRS). The shock response spectrum, or SRS, has been proposed as a tool for evaluating the damage potential in a given acceleration time history. The SRS is defined using an array of 1-D spring-mass systems, each with a spring constant tuned to a different resonant frequency ($\omega = \sqrt{k/m}$). The maximum acceleration by an oscillator

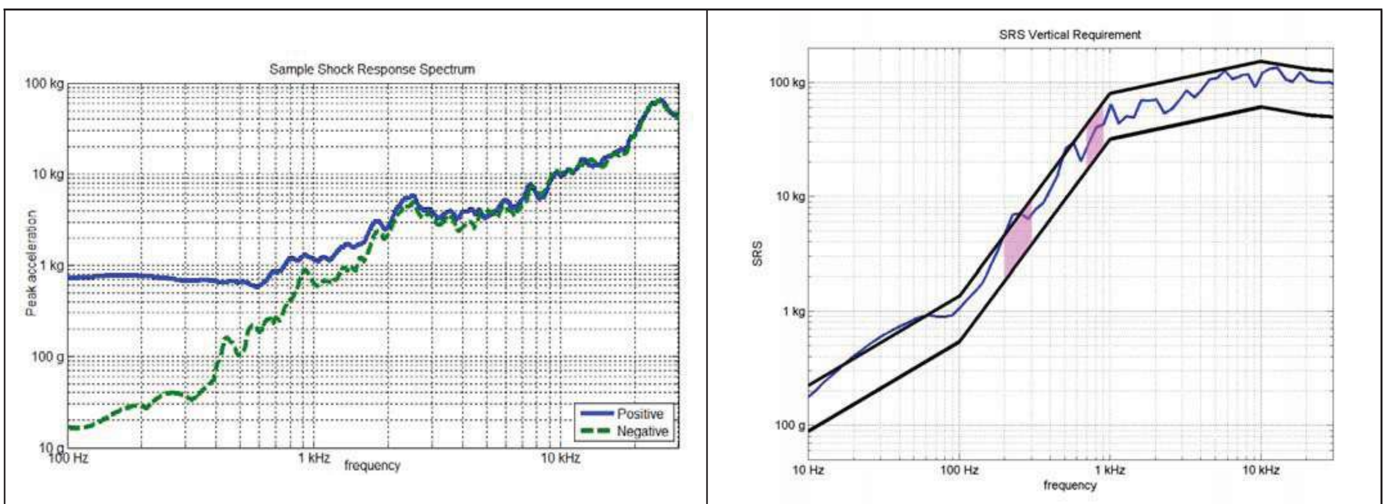


a) MAPP test apparatus

b) MAPP test bunker set-up

Figure 2: Schematic drawing of the MAPP test article and arena

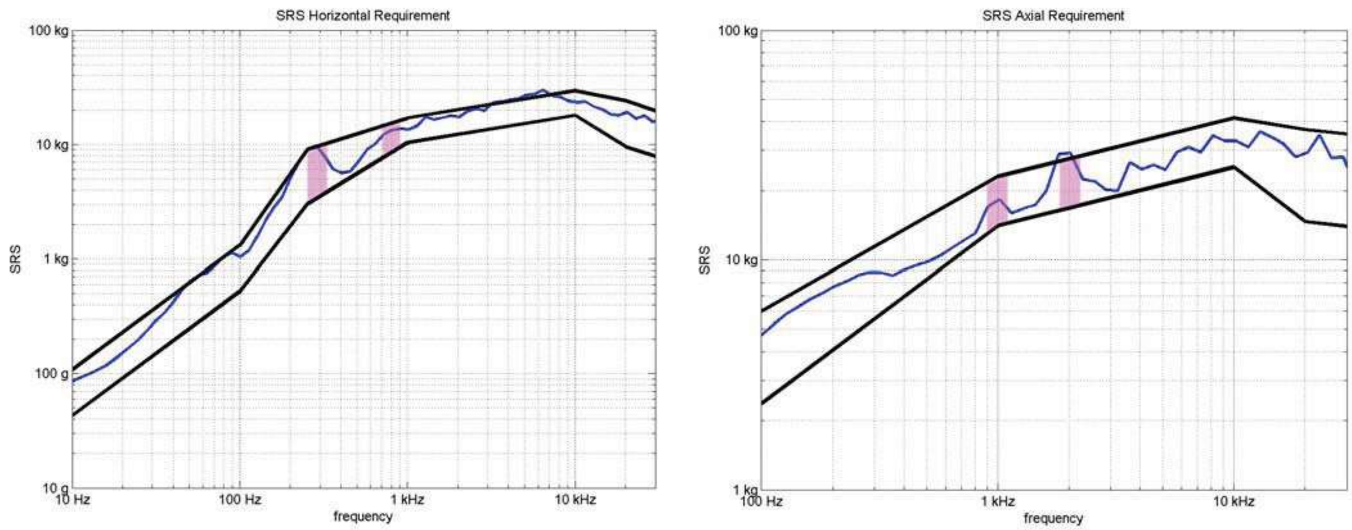
when coupled to a rigid base moving with the specified acceleration time history defines the “positive” or “negative” SRS depending on the direction of the shock. Further details on the SRS can be found in comprehensive reviews, e.g., Irvine [3]; other spectral analyses can be found in Scavuzzo and Pusey [4]. The SRS is calculated in this paper using the improved filter bank method developed by Smallwood [5, 6]. The positive and negative maximum SRS gives the maximum acceleration of the 1-D spring mass in the respective directions due to the acceleration time history. An example SRS of impact test data is shown below in Figure 3(a). The SRS provides a measure of the effect of the pyroshock on a simple mechanical model with a single degree of freedom. Generally, a measured acceleration time-history is applied to the model and the maximum acceleration response is calculated. An ensemble of maximum absolute-value accelerations responses is calculated for various natural frequencies of the model. Since near-field pyroshock usually has broad-band frequency content its SRS exhibits a more complex shape. [2] Figure 3 compares SRS’s determined from two different types of impacts. The one on the left [Figure 3(a)] is from a pyroshock event and [Figure 3(b)] is a combination of SRS’s from a variety of traditional impact tests. The differences in the shape of the SRS is apparent. In the pyroshock data the slope of the SRS increases, then plateaus, after which it continues to increase. The SRS of the impact data follows a more traditional shape and has an increasing slope until it levels off in the high frequency range.



a) Pyroshock SRS Example	b) Impact SRS Example

Figure 3: Shock Response Spectra

The desired testing requirements for the MAPP system were determined by evaluating the results from a variety of impact tests. The acceleration profiles of the different axes (vertical, horizontal and axial) were evaluated separately and SRS's were created. For the development of the testing requirements a desired envelope was established as shown by the black lines in Figure 3(b) and Figure 4. In order to further demarcate our testing goals energy requirements at specific frequencies were identified. They are shown highlighted in pink in the following figures. Figure 3(b) shows the vertical requirement, Figure 4(a) depicts the horizontal requirements, and Figure 4(b) shows the axial requirements. These will be used to evaluate the effectiveness of the MAPP system and fine tune the inputs. Specifically the input energy (pyroshock) and the location and stiffness of the shelf located on the back of the plate.

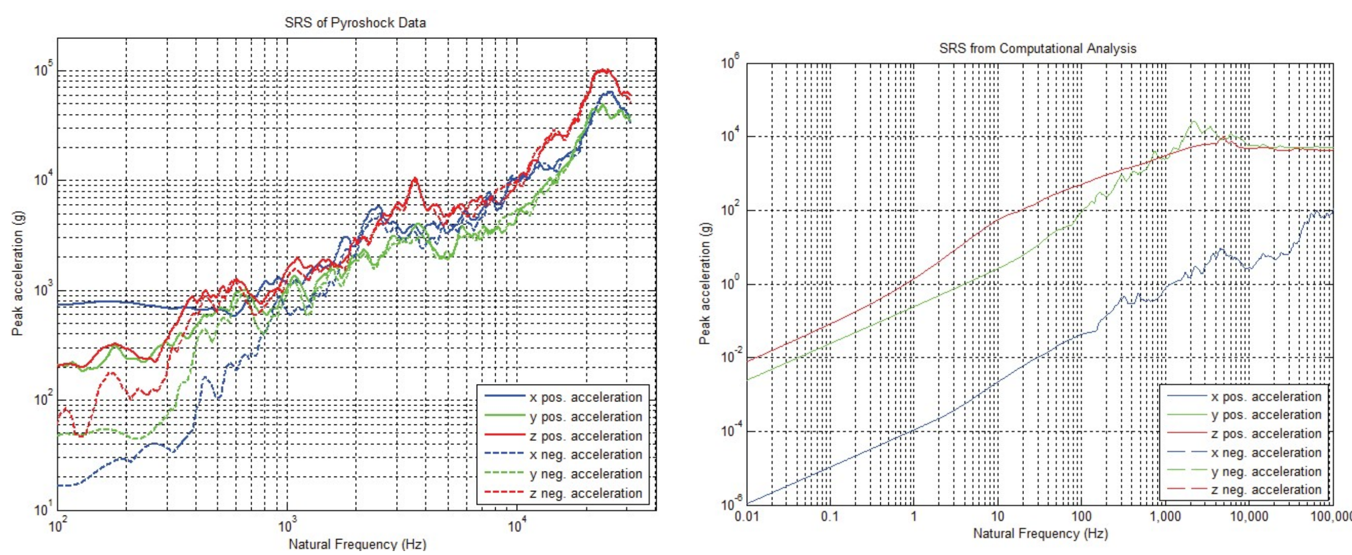


a) Horizontal Requirement b) Axial Requirement

Figure 4: Desired Shock Response Spectra

PYROSHOCK DATA

Data was gathered from one pyroshock event on a test set-up similar to the MAPP that is currently under design. A Shock Response Spectrum (SRS) of the data was created and shown in Figure 5(a). The SRS shows a typical pyroshock response as it is rising at approximately 10dB/decade. [2]. The plot depicts both the positive and negative values for the SRS. The autopower spectra of the data were calculated and one of the autopowerss will be shown, and described, below.

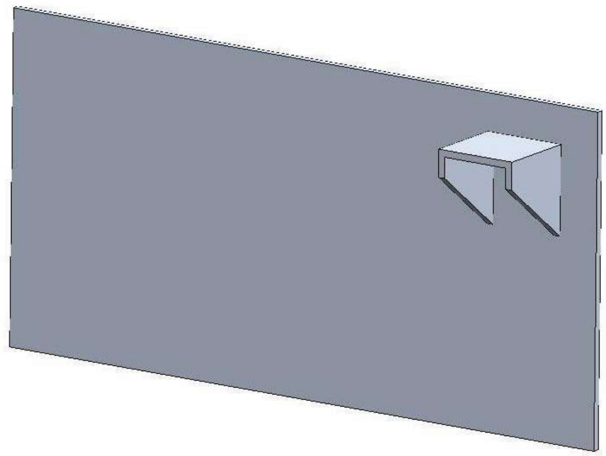


a) SRS from Pyroshock Data b) SRS from Computational Analysis

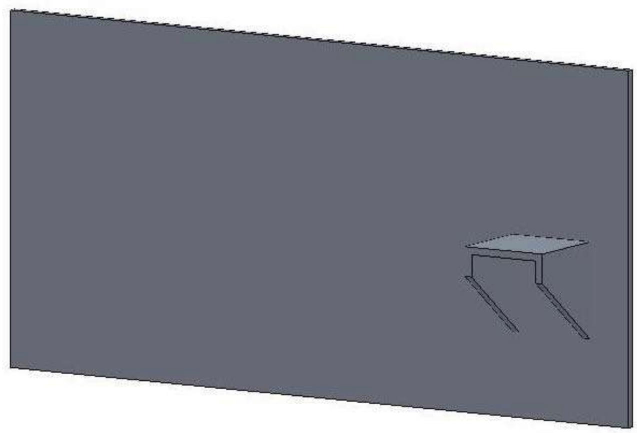
Figure 5: Shock Response Spectra

COMPUTATIONAL SIMULATIONS

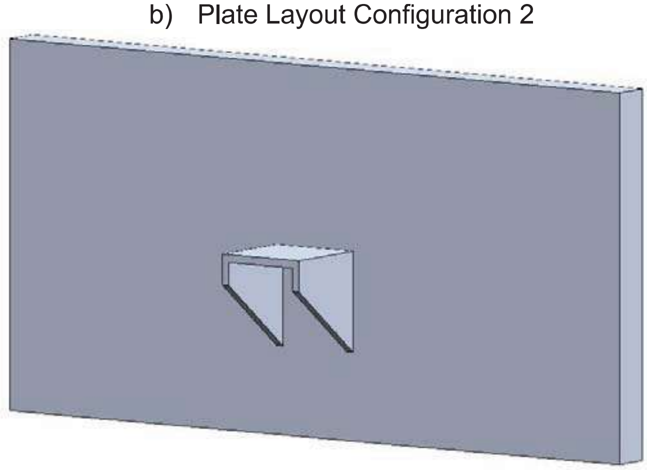
Computational analyses were performed on the Multi-Axis Pyrotechnic Plate (MAPP) test set-up. The purpose of these calculations is to evaluate the effect of the “bookshelf” location. Three locations were evaluated. The first configuration located the shelf in the upper right hand corner of the plate [Figure 6(a)]. The second configuration located the shelf in the middle of the plate on the right hand side [Figure 6(b)]. The final configuration placed the “bookshelf” in the center of the plate [Figure 6(c)]. These configurations were meshed in Truegrid [7] using solid brick elements. The analysis was performed in LS-DYNA [8] where the plate and shelf were modeled as a single body using a Plastic-Kinematic material model. An explicit calculation was performed on each of the configurations. A triaxial acceleration trace was recorded at the center node of the shelf for all analyses. A triangular impulse was applied to the face of the plate opposite of the shelf. A peak pressure of 1,000 psi was applied at 0.1 milliseconds; by 0.2 milliseconds; the pressure had returned to zero. The results from these analyses are discussed below.



a) Plate Layout Configuration 1



b) Plate Layout Configuration 2



c) Plate Layout Configuration 3

Figure 6: Plate Configurations for Computational Analysis

A modal analysis of the three configurations was performed using SolidWorks [9]. That analysis showed that the location of the “bookshelf” had a very small impact on the modal behavior of the plate. The mode frequencies were typically within 5% of each other. The first five mode range from 21.51 Hz to 94.917 Hz.

The SRS’s were calculated for each of the test cases. Figure 3(b) shows the SRS from Test 2. The other tests had very similar responses. The autopowers were also calculated for the data, some of which will be discussed below.

ANALYSIS AND DISCUSSION

An analysis of the accelerometer traces were performed for the three different configurations shown to the right (Figure 6). Linear spectra, autopower spectra, and SRS’s were calculated from these traces and compared to the experimental data. A comparison of the SRS’s of the experimental and computational data is shown in Figure 5(b). They both exhibit similar shapes; however, the SRS from the experimental data is slightly more complex. This is to be expected from near-field pyroshock events. While the computational SRS does not show that same complex shape it has similar overall characteristics which shows that the plate is seeing an impulsive load and that that computational method being employed is a good guide for fine-tuning the design of the “bookshelf” and plate.

Linear spectra were calculated and autopwer spectra were computed from the computational and analytical data as well. Acceleration traces were analytically determined in all three principal axis: the axial direction (up and down on the shelf), the out-of-plane forces (perpendicular to the plate), and the in-plane forces (parallel to the plate). For the computational data, the linear spectra and autopower spectra did not change much from one configuration to another for the axial and in-plane directions. The out-of plane forces of configuration 3 were dramatically different when compared to configurations 1 and 2 as shown in Figure 7. By placing the shelf in the center of the plate it removed the effects of the modal behavior of the bending of the plate, thereby limiting the power that the test article would be subjected to. By designing the MAPP system to have a “bookshelf” on the edges of the plate the out-of-plane forces applied to the test article are dramatically increased.

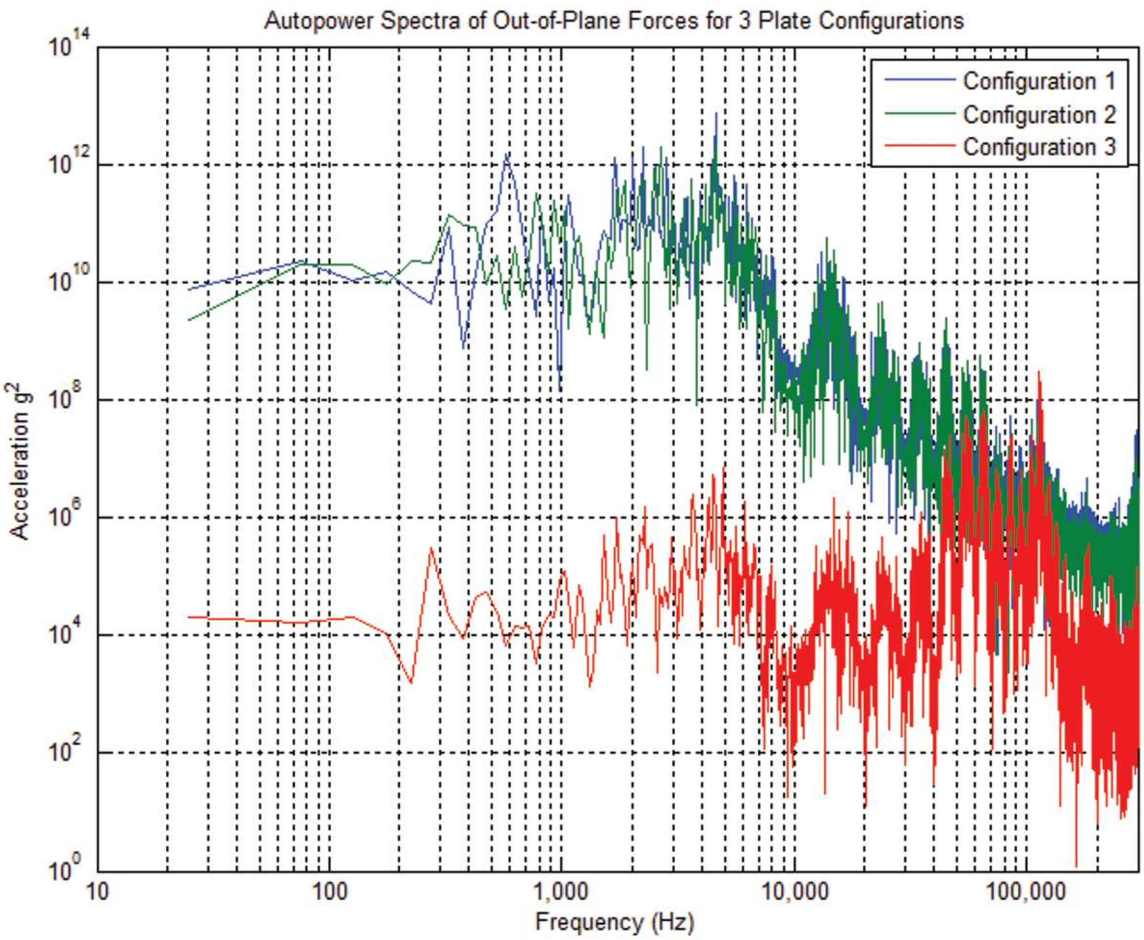


Figure 7: Computed Power Spectral Density of Out-of-Plane forces for 3 Plate Configurations

One of the desired outcomes of the computational analysis was to compare the effectiveness of the computer simulations to data gathered from a pyroshock experiment. This comparison was performed by evaluation the PSD’s of the three configurations and the experimental data in the axial direction. The computational analyses had similar PSD’s for all three configurations as depicted in Figure 8. The PSD of the experimental data in the axial direction is also shown on that plot. That figure shows that the computational analysis is over-predicting the acceleration induced by the experimental pyroshock event 20kHz. At that frequency the experimental data has a severe increase in acceleration while the analytical data continues to decrease. This jump in frequency could be attributed to weaknesses in the data acquisition system or in sensor resonance. Since we do not have any additional data on either of those aspects no definite conclusion can be made on the effectiveness of the calculation at those high frequencies. However, we have discovered that the computational capabilities are limited to less than 10kHz, after which the results become un-reliable [10]

FUTURE WORK

The design of the MAPP system will be modified on the initial computational analysis. Evaluations of the plate size, thickness, material, and shelf location will be determined though a sensitivity study of the system. Various inputs will be applied and the desired acceleration outputs will be determined. The actual test set-up will then be built and tested within the next year. The test set-up will be improved upon as additional testing requirements are determined.

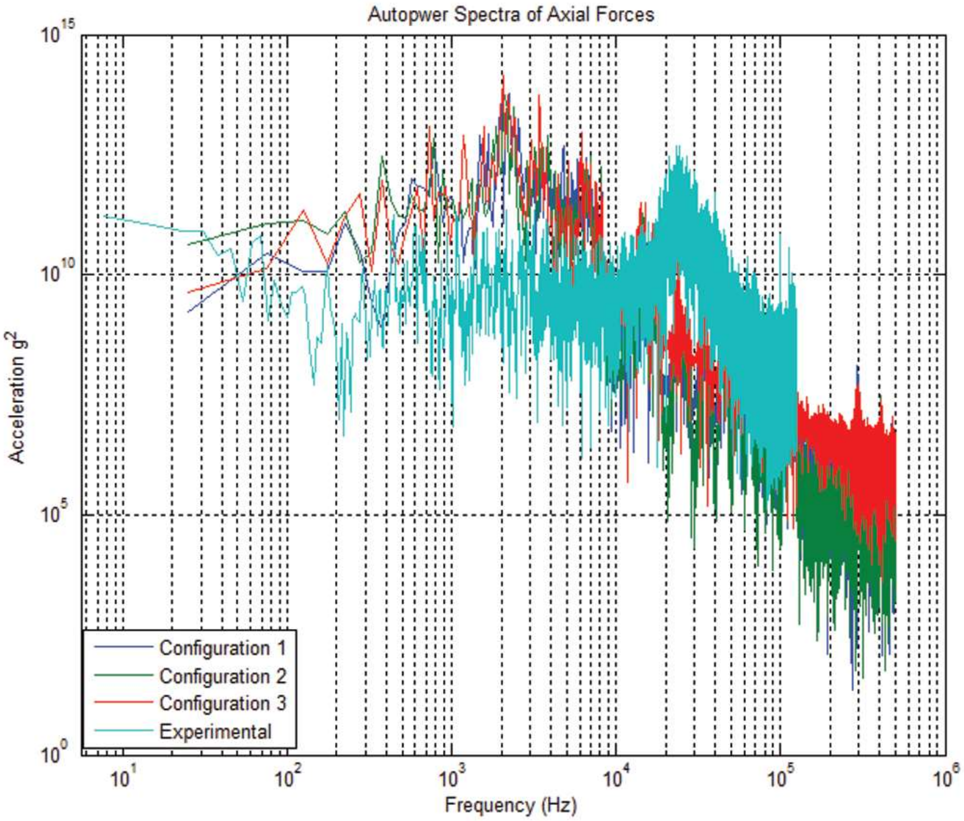


Figure 8: Power Spectral Density of Axial Forces for Computational Analysis and Experimental Results

SUMMARY

The Air Force Research Lab is currently designing a new test apparatus to impart a specific shock level (amplitude and frequency) that has been exhibited under impact tests. Computational analysis were performed to compare the results with a near-field pyroshock test. A possible system design was evaluated with three different configurations. The Power Spectral Density in the axial direction was shown to over-estimate the forces from the pyroshock event. Further analytical studies will be performed to reach desired levels specified through the use of a Shock Response Spectrum. The Multi-Axis Pyrotechnic Plate will be built in the near future and tests using live explosives will be performed.

ACKNOWLEDGEMENTS

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REFERENCES

1. Keon, S.P., *Pyrotechnic Shock Testing: Real Test Lab Experiences at EBA&D*. 2006: Spacecraft and Launch Vehicle Dynamic Environments Workshop.
2. Harris, C.M. and A.G. Piersol, eds. *Harris' Shock and Vibration Handbook*. Fifth ed. 2002, McGraw-Hill.
3. Irvine, T., *An Introduction to the Shock Response Spectrum*. 2002.
4. Scavuzzo, R.J. and H.C. Pusey, *Principles and Technizues of Shock Data Anlaysis*. 2nd Edition ed. 1995, Arlington, VA: SAVIAC.
5. Smallwood, D.O., *The Shock Spectrum at Low Frequencies.* Shock and Vibration Bulletin, 1986. **56**(No. 1, Appendix A): p. 9.
6. Smallwood, D.O. *Improved recursive formula for calculating shock response spectra*. in *Proceedings of 51st Symposium on Shock and Vibration*. 1981. San Diego, CA: SAVIAC.
7. *TrueGrid Users Manual*. 2009: XYZ Scientific Applications.
8. *LS-DYNA Users Manual*. 2009: LSTC.
9. *Solid Works User Manual*. 2009: Dassault Systems SolidWorks Corp.
10. Foley, J.R., et al. *Wideband Characterization of the Shock and Vibration Response of Impact-Loaded Structures*. in *SEM IMAC XXVII*. 2009. Orlando, FL: SEM.