# MINIATURIZED RESONANT PLATE TESTING WITH HIGH SHOCK LOADS

Carl Sisemore
ShockMec Engineering LLC
Cedar Crest, NM 87008

Elliott Pelfrey
Sandia National Laboratories[1]
Albuquerque, NM 87185

## ABSTRACT

Resonant plate shock testing is a common technique for simulating pyrotechnic shock events in the laboratory. The technique typically involves using a relatively long pneumatic gas gun to accelerate a heavy projectile into the back of a modest sized resonant plate. It is also a method that typically requires a significant amount of floor space in the laboratory. While this configuration is often quite reasonable, it is occasionally necessary to perform this type of testing in a highly confined environment. This may happen in a testing scenario where multiple environments are required to be tested simultaneously. In order to study this, a series of extremely short pneumatic gas gun barrels were fabricated and tested against a range of different resonant plates. As the gun barrel length becomes very short, the diameter must be increased in order to allow for sufficient projectile mass. This paper presents the results of multiple resonant plate shock test experiments using pneumatic gas guns as short as 5.2 inches and compares these results to similar testing using more traditional 36 inch long gun barrels. In addition to barrel length, a comparison is also made with projectile diameter. The results show that it is possible to obtain extremely high shock test levels from miniaturized pneumatic gas guns. Potentially opening the door to some highly specialized shock testing.

## INTRODUCTION

Resonant plate shock testing has been used for many years to simulate pyrotechnic shock events in the laboratory. Figure 1 shows a sketch showing a brief overview of resonant plate testing. A test article is attached to the front side of a tuned resonant plate with free-free boundary conditions while a gas gun projectile or hammer impacts the plate at the back center. The impact of the projectile against the plate causes the plate to resonate, exciting the test article. The size of the resonant plate is tuned so that the primary excited resonant frequency corresponds to the primary frequency in the shock test requirement. While Figure 1 shows a square resonant plate design, both round and square resonant plates have been used in practice.

The goal of this research was to examine the feasibility of miniaturizing the existing resonant plate shock test capability. This type of shock testing typically involves using a relatively long pneumatic gas gun to accelerate a heavy projectile into the back of a modest sized resonant plate. This typically requires a significant amount of floor space in the laboratory. While this configuration is often reasonable, it is occasionally desirable to perform this type of testing in a highly confined environment. This may happen in a testing scenario where multiple environments are required to be tested simultaneously.

The research approach used here was a combination of numerical analysis and testing. ShockMec Engineering LLC has developed a small, modular laboratory sized resonant plate shock test machine used for simulating pyrotechnic shock events in the laboratory. The modular shock machine can support interchangeable resonant plates as well as interchangeable pneumatic gas guns and compressed air reservoir tanks. Figure 2 shows a photograph of the shock machine. The machine uses an air gun to provide the shock excitation to the underside of a specifically sized resonant plate. The unit under test is attached to the top

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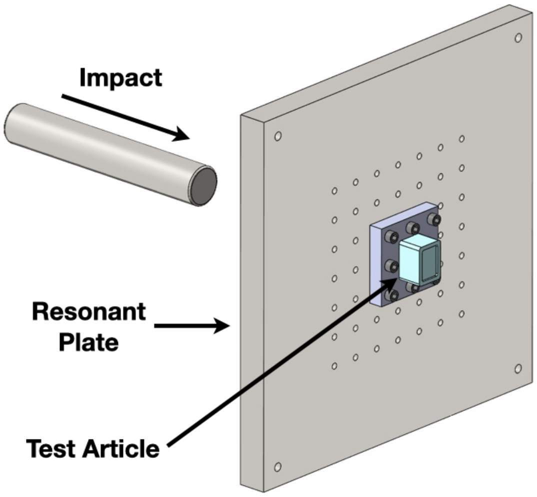

Figure 1: Resonant Plate Pyrotechnic Shock Testing Overview

Figure 2: ShockMec Engineering Resonant Plate Shock Test Machine

side of the resonant plate at the center. Figure 2 shows the shock machine with a high-frequency resonant plate mounted for testing.

This paper presents the results of multiple resonant plate shock test experiments using pneumatic gas guns as short as 5.2 inches and compares these results to similar testing using more traditional 36 inch long gun barrels. In addition to barrel length, a comparison is also made with projectile diameter. As the gun barrel length becomes very short, the diameter must be increased in order to allow for sufficient projectile mass. Projectiles with diameters of approximately 0.88 inches and 1.94 inches were tested to see if projectile frontal area affects resonant plate shock test results. The results show that it is possible to obtain extremely high shock test levels from miniaturized pneumatic gas guns.

## SHOCK TESTING SETUP

Shock testing was performed on the ShockMec Engineering High-G 1 resonant plate shock test machine. This machine is a modular design that allows for interchangeable gas guns as well as various resonant plate sizes and shapes. As part of this research, two simple short barrel gas guns were fabricated from 2 inch schedule 80 iron pipe. Figure 3 shows a photograph of the longer of the two simple pneumatic guns. Since the ShockMec resonant plate machine is designed to use a nominal 36 inch gas gun, this test gun used a 27 inch long piece of half-inch trade-size schedule 40 iron pipe was installed as a standoff between the short gun and the machine's breech support. The top portion of this half-inch pipe can be seen in Figure 3. While the use of iron pipe for research gun barrels may seem a little crude at first, schedule 80 seamless pipe is typically very straight, adequately stiff for the purpose, quite affordable, and easy to work with for early research and concept development.

An Endevco 7270A accelerometer was mounted to the gun barrel near the breech end as shown in Figure 3. This accelerometer was used to estimate the time of first motion for the projectile. This time, coupled with the timing of the shock on the resonant plate, measured with a second Endevco 7270A accelerometer, is used to estimate of the projectile's flight time. These measurements, along with similar measurements on the full length gas guns, were used to calibrate the numerical gas gun simulations performed as part of this research allowing for an estimate of the projectile impact velocity.

Three projectiles were machined for this test series. Figure 4 shows a photograph of the three projectiles. The two short projectiles are approximately 2.7 in and 2.8 in long and weighing 2.2 lbf and 2.3 lbf, respectively. The longer projectile is 5.94 inches long and weighs about 4.9 lbf. While recent research has shown that excessively large pneumatic hammer weights are unnecessary, some weight is needed, especially when driving the lower frequency resonant plates [1]. This is a significant change from the current resonant plate test philosophy at many laboratories. Table 1 shows the three barrel and projectile combinations used for this research. Gun configurations A and B used the same short barrel while gun configuration C used a second gun with a barrel approximately four inches shorter than the first short barrel gun. Slight variations in the pipe's inside diameter, necessitated the third projectile as shown in Table 1. For performance reasons, a relatively small gap between the projectile and the barrel is important for rapid projectile acceleration. All of the projectiles used here were turned on a lathe to a diameter approximately 0.010 inches less than the minimum barrel inner diameter. Table 1 lists the distance from the top of the projectile to the gun barrel's muzzle in each configuration. The actual travel distance is slightly larger in all cases since it is necessary to maintain a nominal gap between the barrel muzzle and the resonant plate anvil.

**Table 1: Short Barrel Gas Gun and Projectile Configurations**

| Gun Configuration | Barrel Length | Muzzle Distance | Projectile Travel Distance | Projectile Length | Projectile Weight |
|---|---|---|---|---|---|
| A | 9.1 in | 6.44 in | 6.60 in | 2.80 in | 2.3 lbf |
| B | 9.1 in | 3.25 in | 3.50 in | 5.94 in | 4.9 lbf |
| C | 5.2 in | 2.50 in | 2.75 in | 2.70 in | 2.2 lbf |

The goal of this testing was not to finalize the design, but rather to determine if sufficient shock levels could be reached with an extremely short gas gun barrel and limited run-up. In essence, can the projectile be adequately accelerated in the limited distance available. Sizes were selected based on readily available

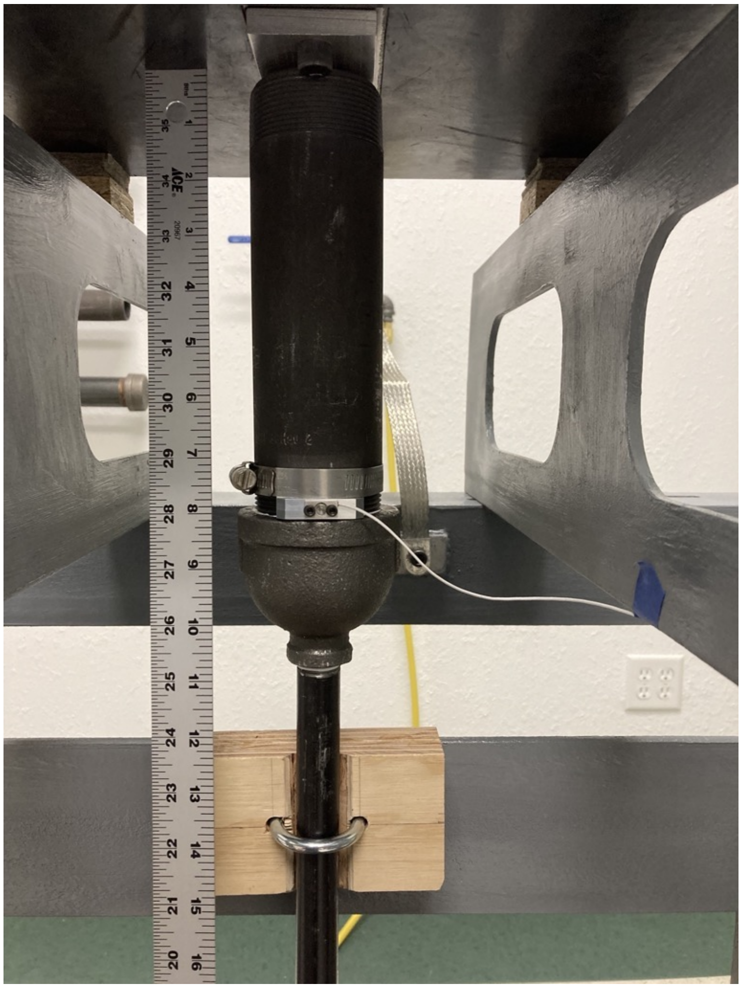

Figure 3: Configuration A/B Short Barrel Test Gun Mounted in the Resonant Plate Shock Test Machine

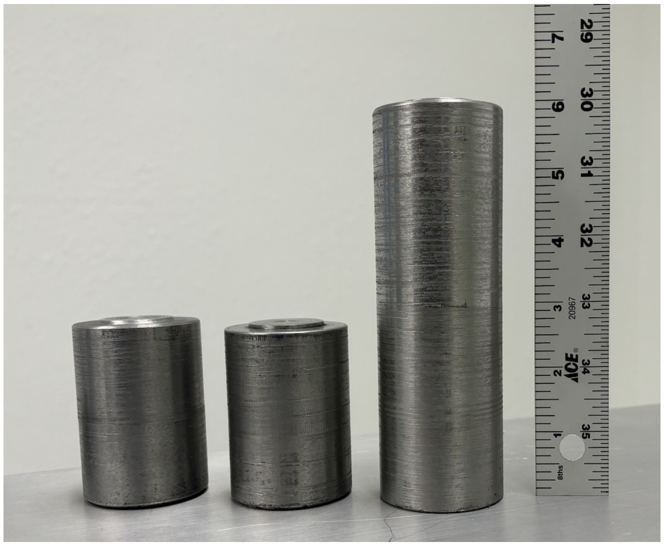

Figure 4: Short Projectiles for Concept Test Guns

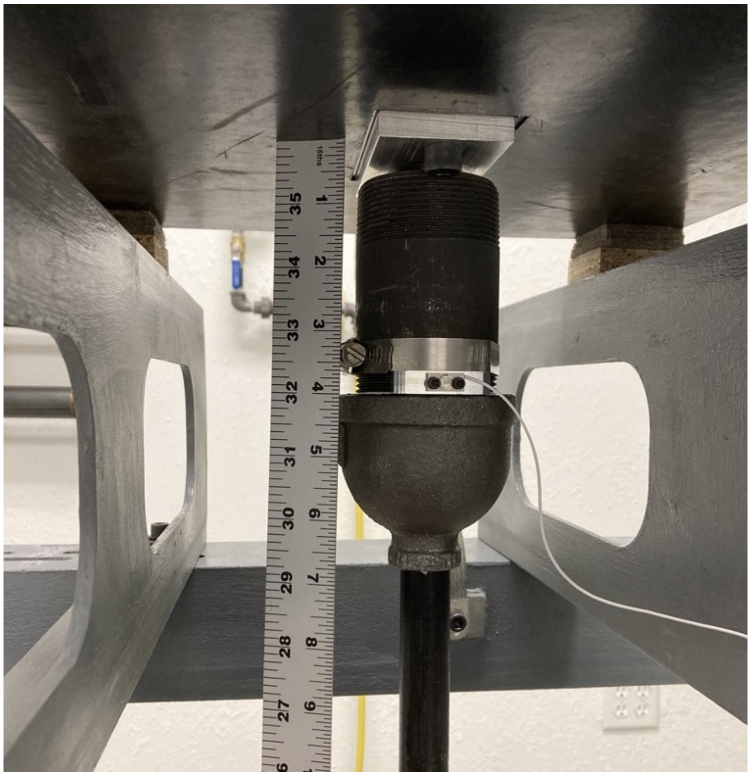

**Figure 5: Configuration C Mini-Gun Mounted in the Resonant Plate Shock Test Machine**

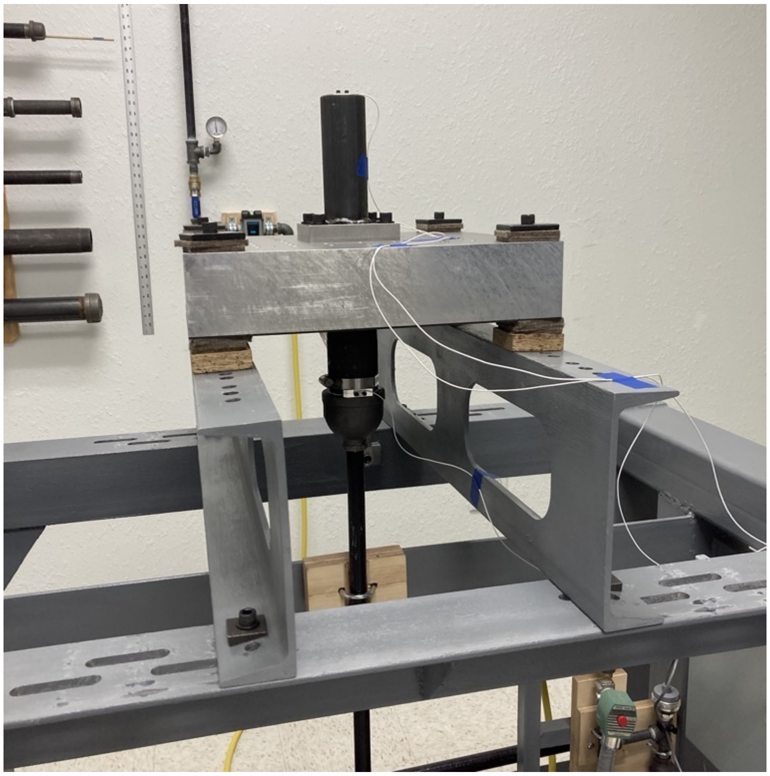

**Figure 6: Configuration C Mini-Gun and Mass Mock Configured for Shock Testing**

material. A larger diameter gas gun barrel would allow similar projectile weights with shorter lengths. It should be noted here that the configuration A, 2.8 inch projectile appeared to work very well for high-frequency plate testing; however, there is some understanding that short projectiles will need a certain length in order to travel smoothly down the barrel. It is unclear at this time what the minimum length to diameter ratio for the projectile should be, but it is assumed that a minimum length to diameter ratio does exist.

Configurations A and B from Table 1 were built and tested first. After the initial testing, the short configuration C gun was assembled from similar 2 inch schedule 80 iron pipe. This second mini-gun was approximately four inches shorter than the first short barrel gun. Figure 5 shows a photograph of this mini-gun. As stated previously, slight variations in the pipe's inside diameter necessitated a third projectile for use with this mini-gun. This projectile was 2.7 inches in length and weighs about 2.2 lbf. With this extra-short barrel configuration, the projectile sits only 2.5 inches below the gun's muzzle giving it 2.75 inches of travel distance before impacting the resonant plate anvil.

Figure 6 shows a photograph of the configuration C mini-gun test configuration with a 7.9 lbf steel mass mock test unit mounted to the 3 kHz resonant plate. Some additional testing was performed with both this 7.9 lbf mass mock as well as a taller 13.3 lbf mass mock. The mass mocks used here represent a very severe loading on the resonant plate system because they add substantial mass but very little additional stiffness to the resonant plate. This is a result of their tall, narrow design which concentrates their mass at the plate center. Most heavy test items will also have larger footprints on the resonant plate, stiffening the resonant plate slightly while simultaneously adding mass. Stiffening the resonant plate raises the plate's response frequency while additional mass will lower the response frequency. With small to medium sized components, the overall effect is usually minimal but with very heavy or stiff items, it can result in a measurable response frequency shift.

## REVIEW OF HIGH-FREQUENCY RESONANT PLATE TEST DATA

Figure 8 shows the measured acceleration data from a test shot using a 3 kHz aluminum resonant plate with the configuration A gun-projectile combination. Configuration A uses a 2.3 lbf projectile and 6.6 inches of projectile travel distance. The measured peak acceleration was 6,168 g from a modest 48.5 psi gun pressure. This was a bare plate test; however, the level was quite high, and would be indicative of a lightweight test article. Figure 8 shows the SRS from this test. The SRS peak at the 3 kHz knee frequency is 11,300 g SRS. Furthermore, Figure 8 still shows the expected SRS peaks at the first three double-symmetric plate modes [2]. Figure 9 shows the FFT magnitude plot from the test shot shown in Figure 7. Here again, the three resonant plate modes are clearly seen as expected. This data indicates that the resonant plate is being well rung, despite the relatively short projectile travel distance. Lightweight projectiles are very beneficial for testing at these frequencies so the projectile weight was not concerning for these high-frequency tests. Finally, Figure 10 shows the measured acceleration data from both the accelerometer on the resonant plate and the accelerometer at the base of the short barrel gas gun. While the levels at the base of the gun are low, they are distinctive enough to estimate the time of first motion, which is subsequently used to estimate projectile impact velocity. In this case, the estimated time of flight was 43.4 milliseconds to travel 6.6 inches. This results in an estimated impact velocity of about 24 ft/s. A relatively modest velocity for such a short distance and resulting peak acceleration.

Figure 11 shows a comparison of the SRS from five configuration A test shots using the 2.3 lbf projectile with 6.6 inches of travel distance against the 3 kHz resonant plate. These shots used the same short gun and projectile configuration with the only change being gun pressure. As the plot shows, the first shot was quite low, although still almost 1,000 g. The later shots, at higher pressures, showed a steady increase in the measured peak acceleration and the corresponding SRS. In all cases, the plate modes are still readily apparent in the SRS as expected.

Figure 12 shows sample measured acceleration time history data from the configuration C 2 inch diameter mini-gun shown in Figure 5. The data shown in Figure 12 was measured on the bare 3 kHz resonant plate. The data shows the measured peak accelerations were quite high given the extremely short projectile travel distance. One issue of concern is that the data shown here indicates two or three impacts per test shot. This is because of the inability to vent excess compressed air from the system fast enough after the initial impact. Vent holes in the short barrel may reduce or eliminate this issue, but were not tested here. Figure 13 shows the SRS from the four acceleration signals shown in Figure 12. The SRS data shows very high spectral

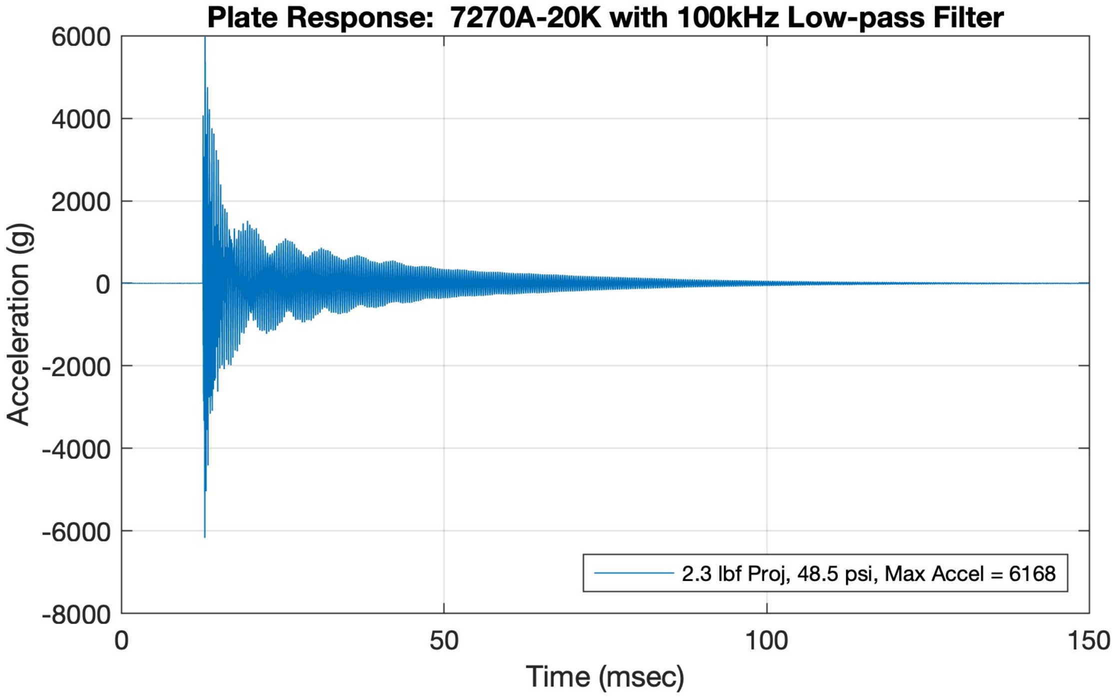

**Figure 7: Measured Acceleration Response from Small Projectile Impacting 3 kHz Plate**

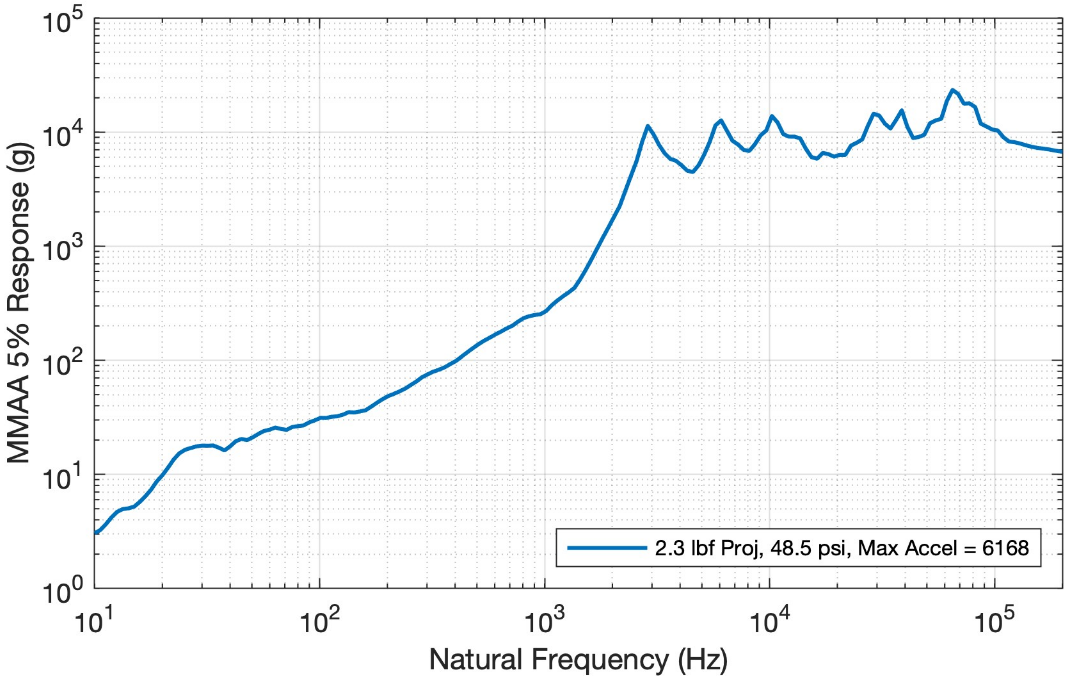

**Figure 8: SRS from Small Projectile Impacting 3 kHz Plate**

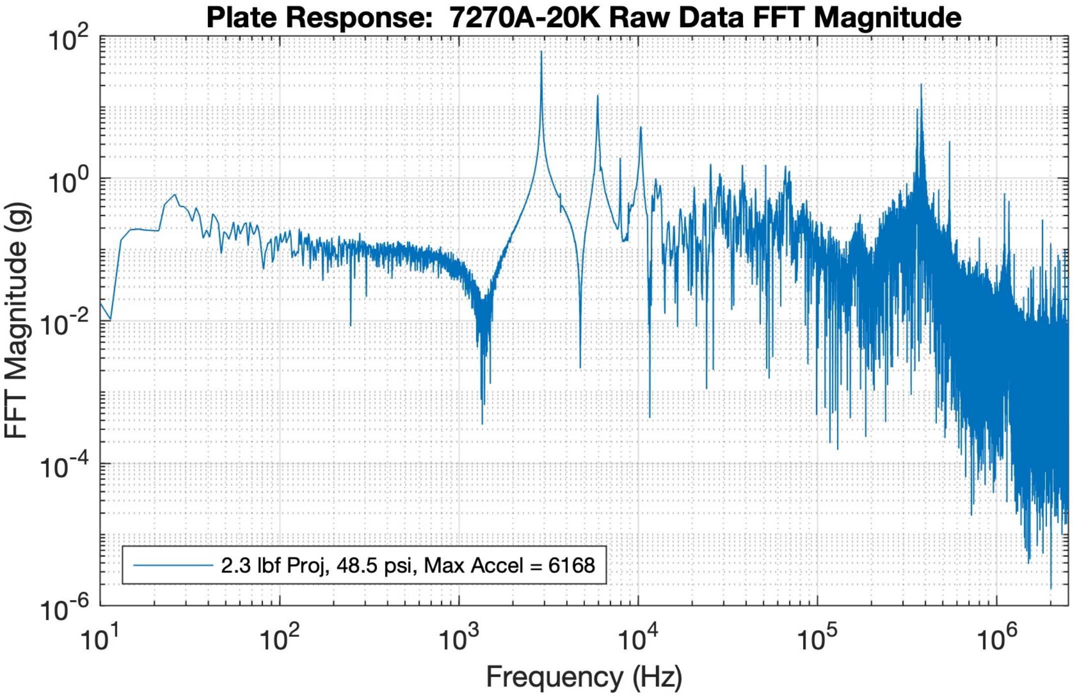

**Figure 9: FFT from Small Projectile Impacting 3 kHz Plate**

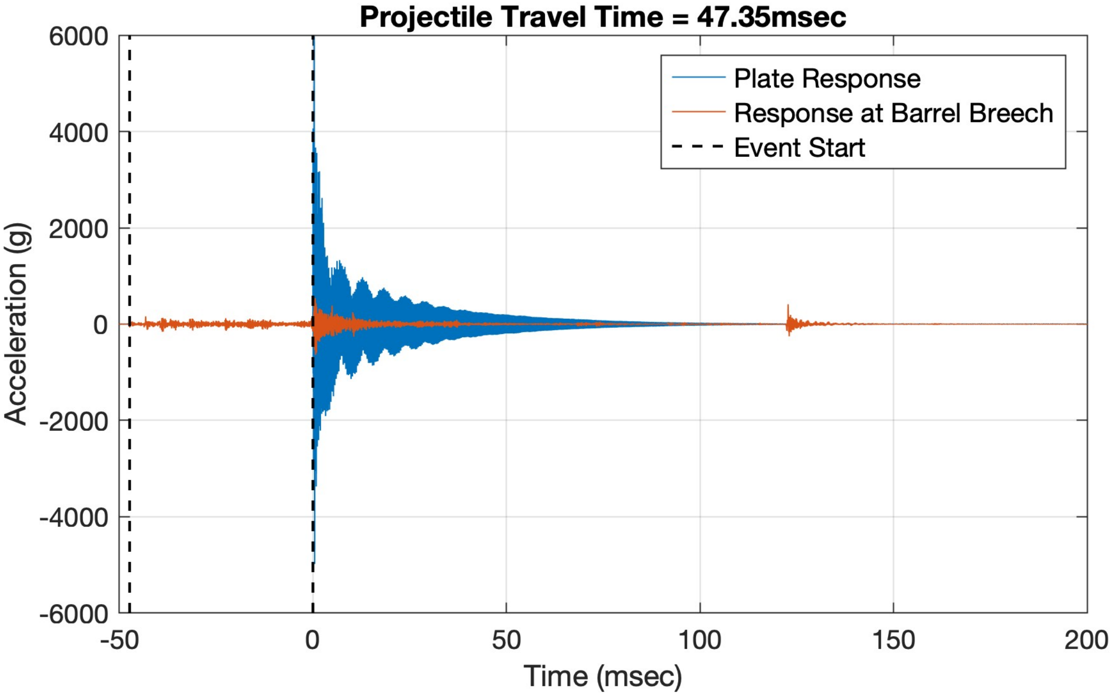

**Figure 10: Measured Acceleration Responses Showing Small Projectile Time of Flight**

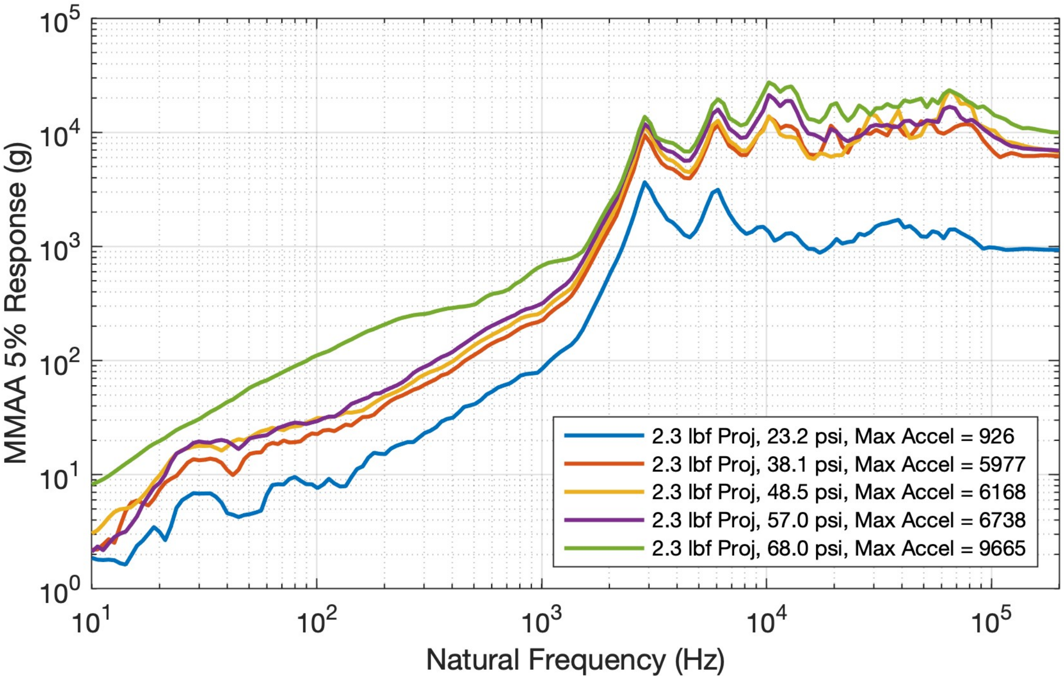

**Figure 11: Comparison of SRS from Small Projectile Impacting 3 kHz Plate at Different Gun Pressures**

responses from this very short gas gun. While there are certainly additional design details needed, this test demonstrates that a very high shock level is possible from a very short gas gun on a high-frequency resonant plate.

Figures 14 and 15 present a comparison of two shots using similar 2 lbf projectiles from the two short barrel gas guns. Both of these test shots were done on the 3 kHz resonant plate. Figure 14 shows the measured acceleration time history data from the two test shots. In these plots, the configuration C gas gun is clearly creating three hits per shot with the second and third hits having a substantially smaller amplitude than the first. This is caused by the inability to vent gas from the barrel and reservoir system fast enough. It is possible that this could be corrected with additional barrel venting, although the extremely short length of this configuration C gas gun barrel makes this a more challenging problem. The two SRS shown in Figure 15 indicate a high degree of similarity between the two short-barrel gas gun configurations despite differences in barrel length.

As a final point of comparison for the high-frequency resonant plate tests, the configuration C mini-gun was compared against a more traditional 3 ft long gas gun. For this test, a 7.9 lbf steel mass mock was mounted on the 3 kHz resonant plate to provide some realistic test article weight. The 3 ft long gas gun uses 1.5 lbf, 10 inch long projectile with approximately 27.5 inches of travel distance compared to the configuration C gas gun with a 2.2 lbf projectile and 2.75 inches of travel distance. Figure 16 shows the measured acceleration time history responses from four similar test shots. The top two plots in Figure 16 are from the mini-gun where the bottom two plots are from the traditional long-gun. The top two plots again highlight the multiple impact problem with very short barrel guns. In contrast, the longer barrel gun has more air volume and a few vent holes near the muzzle. Adding vent holes to the mini-gun will be beneficial but it is not known at this time if it will completely eliminate multiple impacts.

Finally, Figure 17 shows an overlay of the SRS data from the four shots shown in Figure 16. While there is some natural variation in the SRS due to differences in gun pressure and projectile weights, the overlay of the four plots is very good. This shows that the configuration C mini-gun and the more traditional long-gun are giving essentially the same responses. In other words, gun length does not appreciably affect the resonant plate's response so long as other compensating adjustments are made to the system.

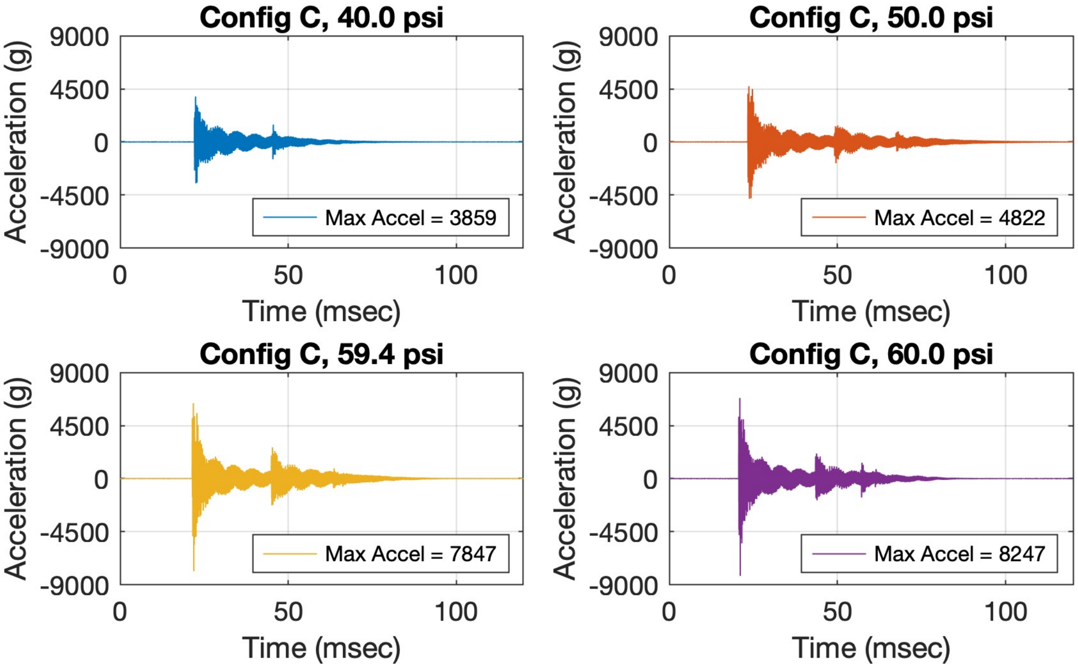

**Figure 12: Acceleration Time History Responses from the Configuration C Gas Gun with 2.75 inches of Projectile Travel**

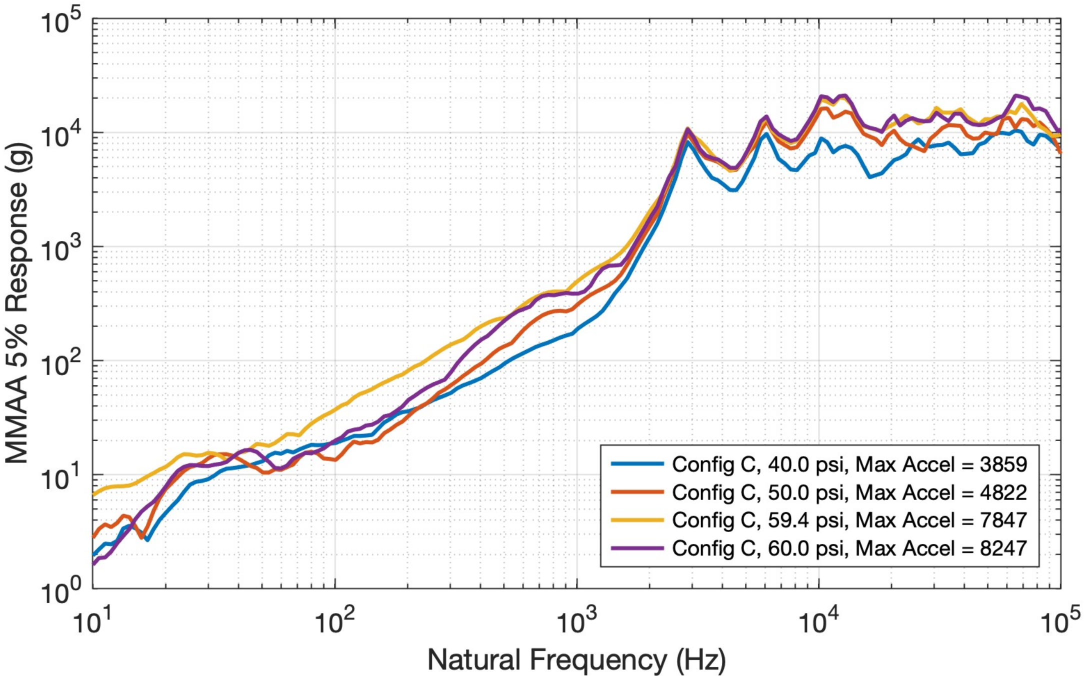

**Figure 13: SRS Comparisons from the Configuration C Gas Gun with 2.75 inches of Projectile Travel**

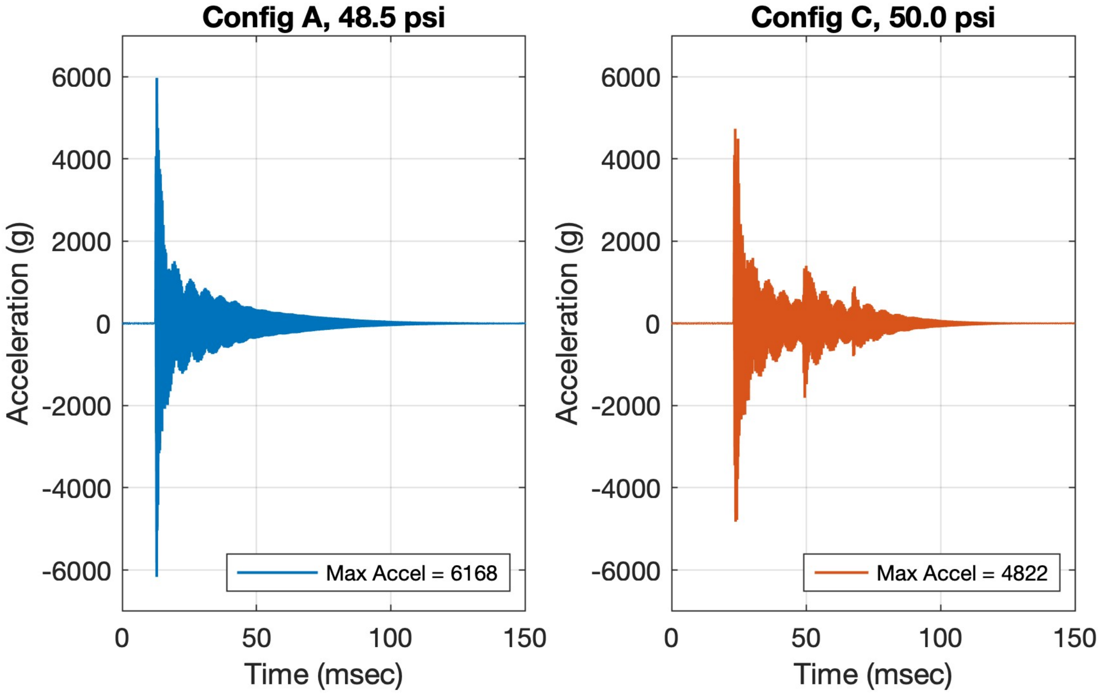

Figure 14: Acceleration Time History Responses from Configurations A and C Gas Guns

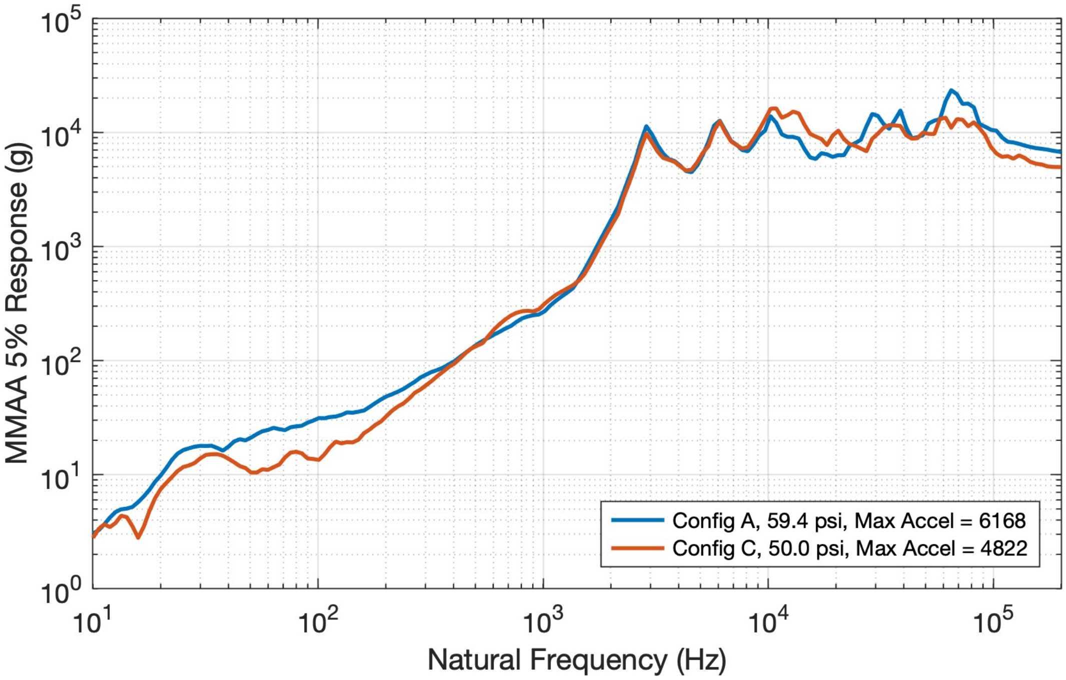

Figure 15: SRS Comparisons from Configurations A and C Gas Guns

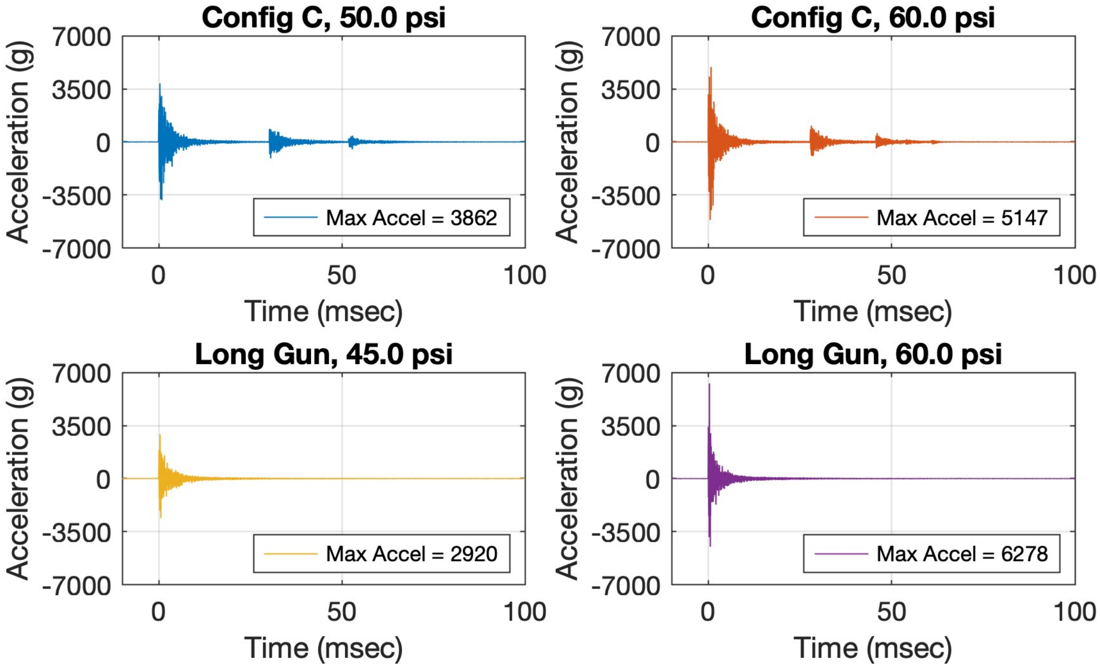

**Figure 16: Acceleration Time History Responses from Long and Short Barrel Gas Guns**

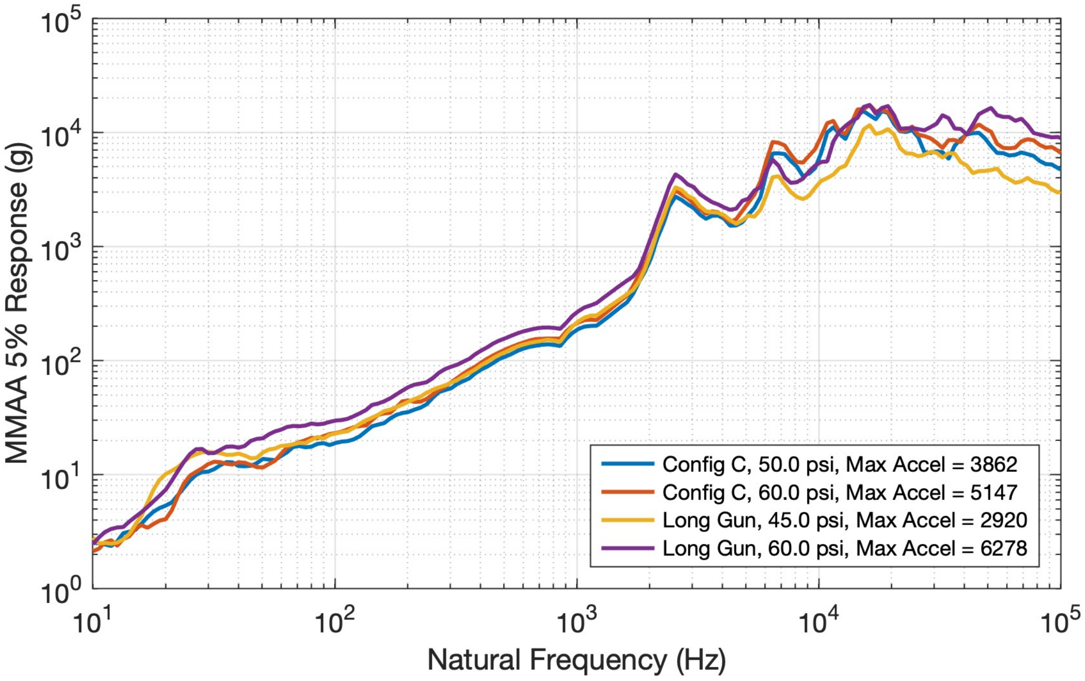

**Figure 17: SRS Comparisons from Long and Short Barrel Gas Guns**

## REVIEW OF LOW-FREQUENCY RESONANT PLATE TEST DATA

Figure 18 shows a similar SRS comparison from five test shots using the configuration B 4.9 lbf projectile on a low-frequency resonant plate. The longer 4.9 lbf projectile has approximately 3.5 inches of travel distance in the configuration B gas gun. For this testing, a 600 Hz round steel resonant plate was used. Round resonant plates have fewer excited modes compared to square resonant plates. As such, only two strong resonances are seen in the Figure 18 SRS data. It should also be noted that the peak accelerations are noticeably lower for the low-frequency plate. However, even here, the peak accelerations easily reached 1,000 - 2,000 g on a 76 lbf resonant plate. In addition, the SRS and peak acceleration trend in the data is good. The modal response of the plate remains the same and the peak acceleration increases with increasing gun pressure. This is a very desirable result, especially given the short travel distance of this gas gun configuration.

It is expected that the SRS data from Figure 18 could be reproduced with a slightly larger diameter gas gun. The 2 inch diameter gun used here was the limit for what was easily assembled and tested for this feasibility study. A larger, 3 inch diameter gas gun should allow for a nominal 5 lbf projectile to be manufactured at only 2.5 inches long, allowing for an overall shorter gas gun. In general, heavier projectiles are needed to excite lower frequency resonant plates.

To test a more extreme case, an 80.5 lbf mass mock was made from a 7 ft long piece of C8×11.5 channel section. This section was mounted to the 600 Hz round steel resonant plate using two one-inch thick aluminum standoffs and 3/8-16 screws. The 600 Hz round steel plate weighs approximately 76 lbf making the total driven weight approximately 156.5 lbf. Figure 19 shows a photograph of this C-channel mass mock configuration. For this test, the configuration B gun and 4.9 lbf projectile was used. Test shots were performed at 70, 85, and 100 psi. Figure 20 shows the measured acceleration time response during the three test shots. Peak measured accelerations were 1136 g, 1743 g, and 2194 g, respectively. Figure 21 shows the corresponding SRS plots from these three test shots. The first mode in the SRS was relatively unchanged in frequency from the bare plate response. The SRS data also shows that slightly more energy was driven into the resonant plate's second plate mode compared to the first. This could be changed with a slightly heavier projectile or a change in the anvil system. Regardless, these are very acceptable shock levels for an 80 lbf mass mock on a 76 lbf resonant plate with a lightweight projectile and a short gas gun.

One final test was conducted, adding a 13.3 lbf mass mock on top of the 80.5 lbf C-channel, creating a nominal 94 lbf mass mock, including the weight of the additional bolts. A maximum 100 psi test shot with the configuration B 4.9 lbf projectile generated a 1899 g peak acceleration on the resonant plate. A very respectable response considering the 94 lbf payload on top of the already heavy 76 lbf resonant plate.

## PROJECTILE VELOCITY ESTIMATES

Estimating the projectile impact velocity on a very short gas gun is challenging. The traditional method for measuring projectile velocity involves using two light gates a short distance apart near the gun's muzzle. However, for these experiments, two light gates a short distance apart will not properly estimate the velocity because the velocity is changing very rapidly over the short barrel distances used here. The approach used for this research was to measure the time of first motion and the impact time and then use a numerical simulation to estimate the projectile motion inside the gas gun barrel. First motion was measured with an accelerometer attached near the breach of the short gun barrel. This does not exactly measure the time of first motion per se, but the accelerometer does "hear" the compressed air coming into the breach area behind the projectile. These accelerometers were shown in Figures 3 and 5. This is approximately equal to the time of first motion and is used as such in this analysis.

The travel time calculation starts with an initial gas pressure in the gas gun reservoir tank. When the valve opens, the gas pressure is immediately reduced as the gas expands into the volume of plumbing between the valve and the projectile base. Then, as the projectile accelerates up the barrel, the pressure continues to decrease as the barrel volume behind the projectile increases. Once the integrated displacement from the numerical simulation reaches the projectile's available travel distance, it is assumed to have impacted the resonant plate.

Table 2 lists the integrated impact velocity estimates for the five configuration A high-frequency test shots shown in Figure 11. The SRS data indicates the first shot was quite low. The remaining shots produced reasonably high SRS levels near the 3 kHz knee frequency. Gun pressures used here are relatively modest

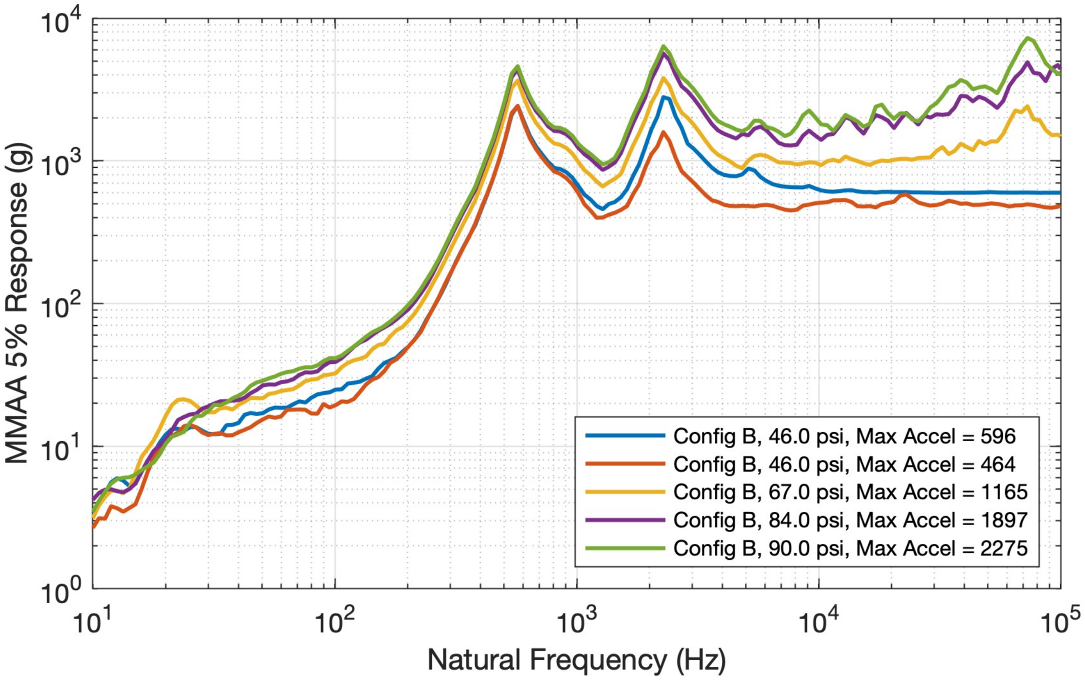

**Figure 18: Comparison of SRS from Configuration B Gas Gun and Projectile Impacting 600 Hz Plate at Different Gun Pressures**

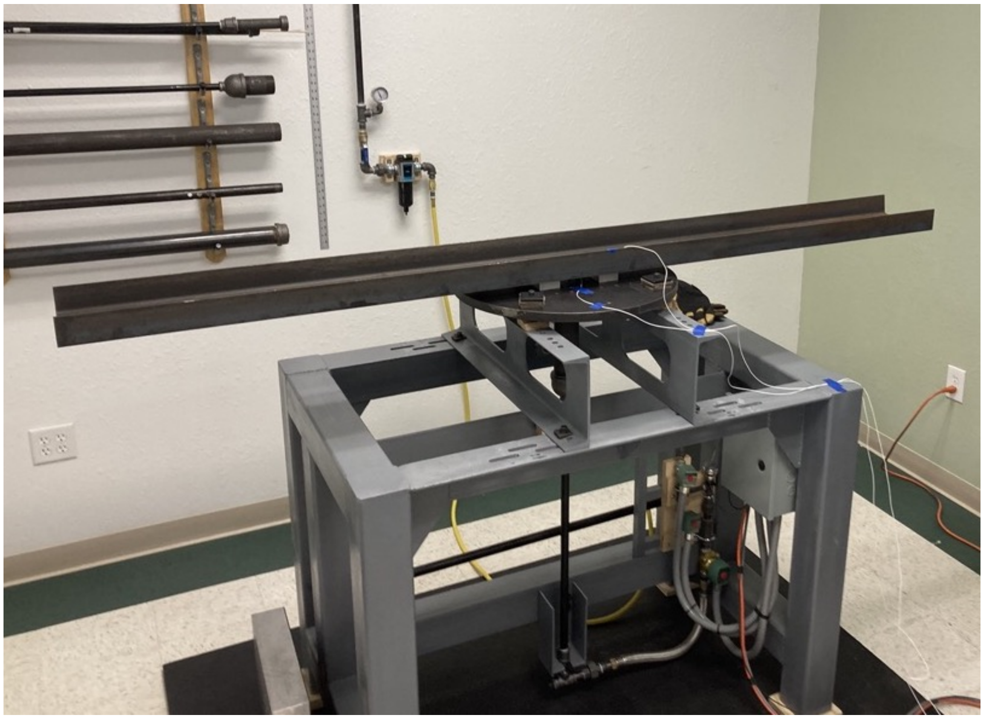

**Figure 19: 600 Hz Round Plate with 80 lbf C-Channel Mass Mock**

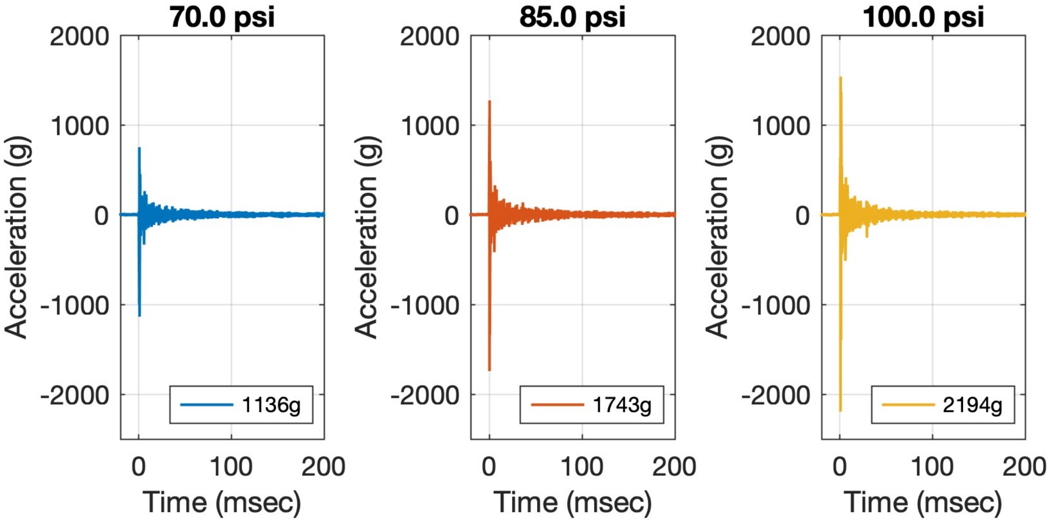

Figure 20: Measured Acceleration Response from Three Configuration B Test Shots on the 600 Hz Round Steel Plate with the 80 lbf C-Channel Mass Mock

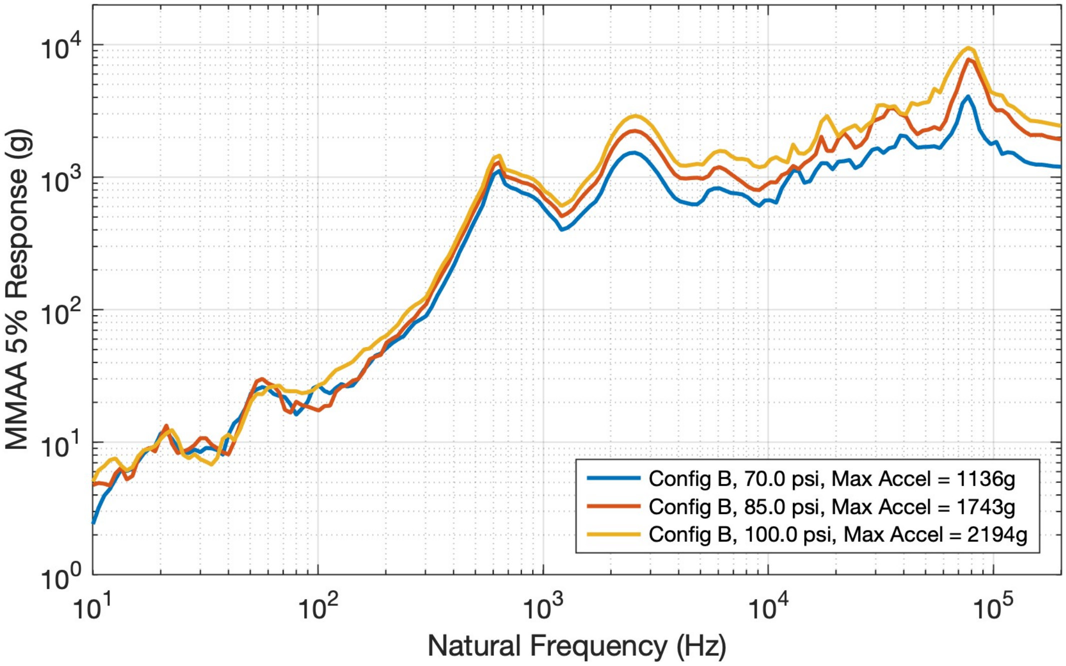

Figure 21: SRS Comparison of Three Configuration B Test Shots with the 80 lbf C-Channel Mass Mock on the 600 Hz Round Plate

and all test shots produced very reasonable impact velocities despite the very short projectile travel distance of only 6.6 inches.

**Table 2: Estimated Impact Velocity for Configuration A High-Frequency Tests**

| Gun Pressure | Travel Time | Impact Velocity |
|---|---|---|
| 23.2 psi | 81.7 msec | 12.7 ft/s |
| 38.1 psi | 38.1 msec | 22.0 ft/s |
| 48.5 psi | 48.5 msec | 24.2 ft/s |
| 57.0 psi | 57.2 msec | 28.9 ft/s |
| 68.0 psi | 31.8 msec | 32.9 ft/s |

The estimated projectile velocities from Table 2 are similar to velocities used with the traditional long gas gun and the 3 kHz resonant plate. Similar testing with the traditional long gun showed impact velocities of 30 - 35 ft/s with a one-inch bore gas gun using a 1.5 lbf projectile and similar pressures of 45 - 60 psi. While this may seem initially counterintuitive, the short gas gun used a nominal two-inch diameter projectile where the long gas gun used a nominal 0.92 inch diameter projectile. The force applied to the projectile's aft end is proportional to the area presented to the compressed air. In this case, the two-inch projectile presents over four times the area compared to the one-inch projectile. This area difference increases the applied force on the projectile and proportionately increases the projectile's acceleration.

Table 3 lists the integrated impact velocity estimates for the five configuration B low-frequency test shots with SRS shown in Figure 18. The data here was somewhat more difficult to interpret because the time of first motion was less obvious in the accelerometer data. As such, the estimates in Table 3 likely have a greater margin of error than the velocity estimates from the lighter weight projectile. Nevertheless, the heavier projectile coupled with the significantly shorter travel distance leads to significantly reduced impact velocities even with generally higher gas gun pressures. Since low-frequency resonant plates require heavier, slower moving projectiles to properly ring the lower frequency modes, the data obtained here is still quite promising. The data from Table 3 was obtained from the 600 Hz round steel plate and the plate response was tonally clear. This is readily apparent by the two clearly significant peaks in the SRS shown previously in Figure 18. Once again, all of the gun pressures used here were reasonable and all produced acceptable impact velocities despite the very short projectile acceleration distance of only 3.4 inches.

**Table 3: Estimated Impact Velocity for Configuration B Low-Frequency Tests**

| Gun Pressure | Time of Flight | Impact Velocity |
|---|---|---|
| 46.0 psi | 47 msec | 11.5 ft/s |
| 67.0 psi | 38 msec | 14.1 ft/s |
| 84.0 psi | 35 msec | 16.0 ft/s |
| 90.0 psi | 33 msec | 16.6 ft/s |

Configuration C high-frequency test shots had a proportionately lower impact velocity. The projectile weight and gun pressures were similar to the Configuration A tests but the shorter barrel length and shorter travel distance resulted in proportionately lower impact velocities. This is a potential concern since impact velocities more similar to the Configuration A velocities are desirable for high-frequency shock tests. This may be correctable with a slightly larger diameter gun and projectile. Larger diameter projectiles present more surface area to the compresses air entering the barrel. Higher applied forces result in a proportionately higher impact velocities.

## CONCLUSION

The experiments documented here utilized several tests with extremely short pneumatic gas gun concepts and standard sized resonant plates. All of the testing performed here indicate that the short barrel guns were capable of accelerating appropriate mass projectiles and ringing the resonant plates. While further optimization of the designs are warranted, the concept testing was considered successful. This work opens the door for the development of extremely small shock test machines for unique and highly space-constrained applications.

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