STATISTICAL COMPARISON BETWEEN COMPONENT LEVEL AND SYSTEM LEVEL TESTING FOR THE EXCALIBUR PROJECTILE

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A Ballistic Rail Gun is used as a time and cost efficient approach to perform testing on electrical and mechanical components and subsystems at the development and qualification levels, for the Army's new 155-mm precision guided projectile, Excalibur. Being able to test gun launch survivability at a component level, and the ability to recover and analyze the hardware afterwards, provides a significant benefit to the Army. Critical failures in the components can more easily be identified and corrected before being incorporated into the entire system. The Ballistic Rail Gun has also been used because it is cheaper and quicker than Live-Fire Gun Launch testing at Yuma Proving Grounds.

The environments experienced in the Ballistic Rail Gun, however, do not directly correlate to those experienced from testing in the field. The process used by the Ballistic Rail Gun to softly recover the hardware after exiting the barrel subjects the items being tested to environments which are different than those in a conventional gun launch. Firing data recovered from Excalibur Soft-Recovery Vehicle tests conducted at Yuma Proving Grounds supports these findings.

This paper discusses comparisons between the gun launch environments of the Ballistic Rail Gun and conventional firing platforms using data collected by On-Board Recorders from both systems. This paper examines the differences in the setback, balloting, and set-forward accelerations and considers both the advantages and disadvantages of using the Ballistic Rail Gun as a development and qualification testing tool for components being used in today's increasing development of precision guided munitions.

INTRODUCTION

The Army uses a Ballistic Rail Gun in order to test gun launch survivability of electrical components on the new 155-mm guided projectile, Excalibur. The Ballistic Rail Gun fires a modified M483 projectile with a scoop mounted in place of the ogive into a trough of water to safely recover the hardware and determine its condition. [1] The utilization of the Ballistic Rail Gun system for testing on the component level has provided advantages to the Army throughout the development and qualification of the Excalibur projectile. It presents a cost-effective alternative to Live-Fire Gun Launch by providing the capability to test gun launch survivability at a component level, and the ability to recover and analyze the hardware afterwards. Critical failures in the components can be identified and corrected before being incorporated into the entire system. It also helped in fuze qualification testing in support of the Excalibur Early Fielding because a larger quantity can be fired in the same time frame at a fraction of the cost. A Live-Fire Gun Launch test costs approximately 10 times as much as a Ballistic Rail Gun test.

Although the Ballistic Rail Gun exposes the hardware to a ballistic gun launch much like that experienced during Live-Fire Gun Launch testing on conventional gun platforms, there are differences in the two environments that need to be investigated. This will be accomplished by analyzing the differences in the three basic sections of a ballistic cycle known as setback, balloting, and set-forward. Setback is the large initial axial acceleration. This pulse is usually of 8-10 milliseconds in duration depending on weapon, projectile and charge design. Balloting is the side to side random impacts of the projectile with the tube walls and can reach levels of up to 5,000 g’s. The final phenomenon to be introduced is the muzzle exit transient known as set-forward. This is caused by the rapid drop in projectile base pressure as the gun gases vent when the projectile “uncorks” from the muzzle of the weapon. The resulting dynamic response of the projectile can be very dramatic. [2]

In this paper, Excalibur test environments at the component and system level are represented by the Ballistic Rail Gun and Live-Fire Gun Launch respectively. Differences in the two environments will be considered along with other factors to evaluate the true value and functionality of the Ballistic Rail Gun for component level testing.

LIVE-FIRE GUN LAUNCH TESTING

The Live-Fire Gun Launch data analyzed was from firings that used a M232 MACS 5 propelling charge conditioned to 70°F. The data collected was from shots with pressure and accelerations that were approximately the same. All Live-Fire Gun Launches were conducted at Yuma Proving Grounds.

Accelerations during a Live-Fire Gun Launch test are recorded using either an On-Board Recorder (OBR) mounted inside of a Soft Recovery Vehicle (SRV), which contains accelerometers in both the axial and transverse orientations or by using an encrypted telemetry system. This telemetry unit is housed inside a test projectile and sends acceleration data through a signal which is monitored at a remote station. Typical accelerations seen during tests can be seen in Figure 1.

The setback region of the data shows a large rise in acceleration to a maximum at around 0.008 seconds (8 milliseconds). Setback continues until about 16 milliseconds where the projectile exits the gun and enters the set-forward region.

Setforward in a normal gun launch results from when the base pressure causes a compression in the projectile. At muzzle exit, this base pressure decompresses within a very short time (~.1 to .5 ms). The dynamic decompression allows the projectile to spring back, thus creating a set-forward acceleration. [3] The accelerations resulting from the set-forward event is only a few milliseconds in duration.

Balloting occurs both while the projectile is in the gun barrel and immediately after muzzle exit. The balloting accelerations after muzzle exit are generally larger in amplitude than those experienced within the barrel.

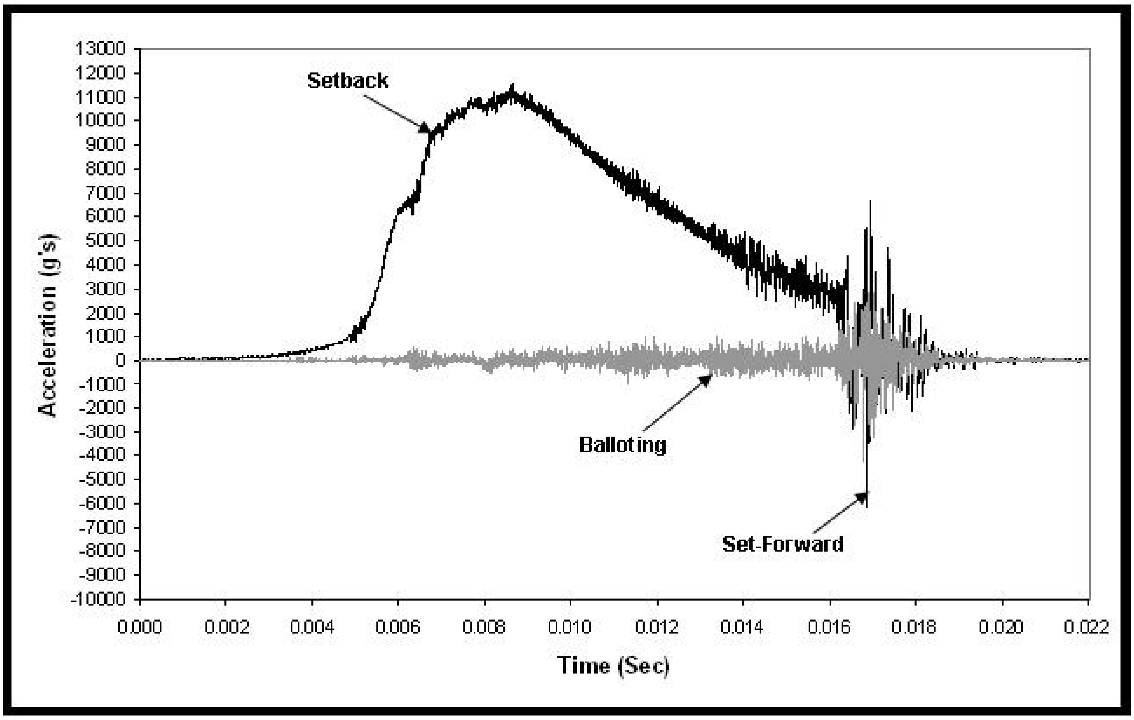

Figure 1. Typical Live-Fire Gun Launch Environment

BALLISTIC RAIL GUN TESTING

The Ballistic Rail Gun was fired using a Zone 7 M4A1 propellant. For the data that was analyzed additional M203A1 stick propellant was added to the chamber in order to increase the pressure. All propelling charges were at the ambient temperature. The data collected was from shots with roughly the same pressures and accelerations.

The accelerations experienced during a Ballistic Rail Gun test are captured by an OBR similar to those used in Live-Fire Gun Launch. Typical accelerations seen during testing can be seen in Figure 2.

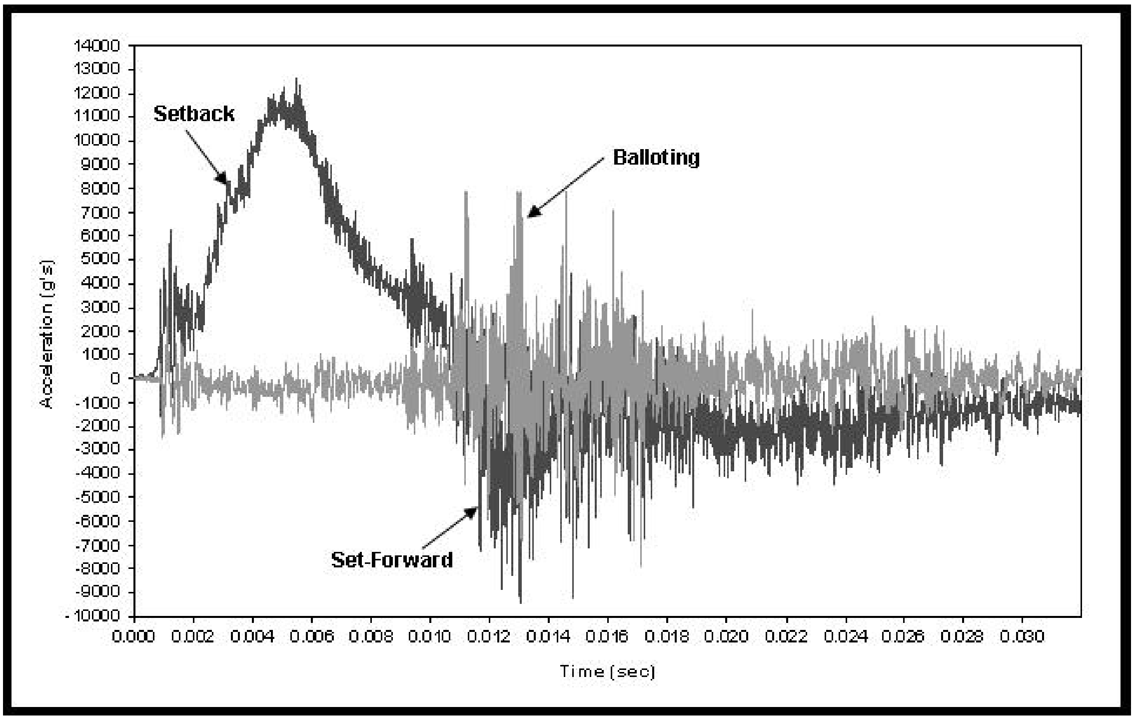

Figure 2. Typical Ballistic Rail Gun Launch Environment

The setback region of the data shows setback rising to a maximum at around 0.005 seconds. Setback continues until about 11 milliseconds where the projectile exits the gun and enters the set-forward region. The barrel used on the Ballistic Rail Gun system is significantly shorter than those normally used during Live-Fire Gun Launch which will aid in creating a smaller setback duration.

In the Ballistic Rail Gun set-forward occurs as the projectile exits the gun tube as described above, however, this event takes place at relatively the same time that the scoop on the front of the projectile contacts the water, creating acceleration in the set-forward direction as well. These set-forward accelerations continue as the projectile slows to a stop.

Balloting data is obtained throughout the gun launch and the recovery in the rails. The accelerations tend to be the highest at the muzzle exit to rail transition section and continue through the entire recovery.

COMPARISON OF DATA

Five Live-Fire Gun Launch tests were compared to five Ballistic Rail Gun tests using standard statistical methods. Differences in the projectile, gun barrel, and charges have been described above. The following four accelerations were compared:

1. Maximum Axial Acceleration, occurring in the gun tube, referred to as 'Setback'
2. Transverse Acceleration, occurring in the gun tube at the same time as the Setback acceleration was recorded, referred to as 'Balloting'
3. Minimum Axial Acceleration, occurring shortly after muzzle exit, referred to as 'Set-forward'
4. Maximum transverse acceleration, occurring shortly after muzzle exit but not necessarily when the Set-forward acceleration occurs, referred to as 'Balloting'

For design, accelerations 1 and 2 are generally combined with blow-by for the Setback load case. Accelerations 3 and 4 are combined and viewed as the Muzzle Exit load case. Gun structures are routinely designed to survive Setback and Muzzle Exit. Tables 1 and 2 summarize the recorded accelerations used for comparison.

Table 1. Live-Fire Gun Launch Accelerations, 5 Tests

	Shot Name	***Max. Axial Acc. Gs***	***Transverse @ Setback Gs***	***Min. Axial Acc. Gs***	***Maximum Transverse Acceleration, Gs***
Live-Fire	TM-22A	12327	91	-4287	2779
Live-Fire	TM-21A	12544	31	-2282	894
Live-Fire	TM-20A	11935	24	-6164	3245
Live-Fire	TM-19A	12374	50	-2618	1863
Live-Fire	Truck-5B	11550	212	-6126	4389
Average		12146.	81.6	-4295.	2634.
Standard Deviation		400.9	77.4	1851.4	1332.0

Table 2. Ballistic Rail Gun Accelerations, 5 Tests

	Shot	Max. Axial	Transverse	Min. Axial	Maximum Transverse
	Name	Acc.	@ Setback	Acc.	Acceleration,
		Gs	Gs	Gs	Gs
Rail Gun	FSA8_Hot	12558	236	-9488	11077
Rail Gun	FSA12_Hot	12283	542	.-11623.	10705
Rail Gun	FSA11_Cold	13493	79	-14838	13939
Rail Gun	FSA10_Cold	12470	325	-7706	7719
Rail Gun	FSA9_Hot	14516	4252	-21894	11673
Average		13064	1086.8	-13481.5	11022.6
Standard Deviation		936.9	1777.3	6374.8	2233.0

The statistical '*t*' test was used to determine if the average accelerations in the Ballistic Rail Gun tests and Live-Fire Gun Launch tests were significantly different. The *t* test is a standard text book method for comparing average values of sample populations. [4] The *t* assumes equal variances between the two test populations. For the comparison between the Live-Fire Gun Launch and Ballistic Rail Gun tests, the *t* value for the acceptance range was based on 10 samples, 8 degrees of freedom, 5 percent level of significance, and a two-sided critical region. The Ballistic Rail Gun accelerations are considered in the same test population as the Live-Fire Gun Launch tests if the calculated *t* was within the following limits:

$$-2.31 < t < 2.31 \quad (1)$$

The *t* was calculated from the averages and variations of the accelerations shown in Tables 1 and 2. Statistical results are shown in Table 3. The calculated *t* values are shown in the 4th column. The two setback accelerations have *t* values consistent with the acceptance region in equation (1). The two muzzle exit accelerations have *t* values exceeding the acceptance range. The statistics indicate that the two average setback

Table 3. Results: T-Test Comparisons

Acceleration	Gun Launch	Rail Gun	Calculated	Comment
	Average	Average	t value	
Maximum Axial Acceleration, Setback	12146	13064	0.71	Fits Criteria
Transverse Acceleration at Setback	81.6	1086.8	1.26	Fits Criteria
Minimum Axial Acceleration, Muzzle Exit	-4295	-13109	3.35	Doesn't Fit
Maximum Transverse Acceleration, Muzzle Exit	2634	11022.	7.21	Doesn't Fit

accelerations have similar average values for the Ballistic Rail Gun and Live-Fire Gun Launch tests. In contrast, the two muzzle exit accelerations do not have the same statistical averages. From Table 3, the Muzzle Exit accelerations are significantly higher for the Ballistic Rail Gun tests than for Live-Fire Gun Launch tests.

The '*F*' test [4] was used to compare the variances for the Live-Fire Gun Launch and Ballistic Rail Gun tests. The *F* test roughly compares the squares of the standard deviations. Calculations assumed 4 degrees of freedom for each of the two samples, a two sided critical region, and a significance level of 0.1. The axial setback acceleration and the maximum transverse acceleration had statistical variations that fit the *F* test (similar variations in the test samples for these two accelerations). The transverse acceleration during Set Back and the set-forward acceleration had significantly more variation in the Ballistic Rail Gun tests.

In conclusion, based on the 10 samples studied, only the axial setback acceleration is statistically consistent for both the Ballistic Rail Gun and Live-Fire Gun Launch. Average Ballistic Rail Gun accelerations exceed Live-Fire Gun Launch accelerations at muzzle exit. If a larger sample size is available, the statistical test should be repeated.

DISCUSSION

Though the Ballistic Rail Gun provides a cost-effective method to test components, it exhibits differences to a Live-Fire Gun Launch that must be considered to determine its value. The axial setback environment is statistically similar between the two environments, but the Ballistic Rail Gun is limited to about 12,000 g's in setback due to the pressure and weight constraints in the system. Although this tends to sufficiently match accelerations observed at MACS 5, it does not allow the Ballistic Rail Gun to be used as a margin test at the component level for setback evaluation. This issue may be resolved once testing is completed on a new test projectile, the Ballistic Rail Gun Test Projectile (RGTP). Data collected indicated that the RGTP was able to achieve higher G levels than the old projectile at the same pressures. [1]

The set-forward environment and the balloting environment during both setback and after muzzle exit of the Ballistic Rail Gun have accelerations that are statistically higher than those in a Live-Fire-Gun Launch. The largest accelerations in both cases occur right after muzzle exit, much like in a Live-Fire Gun Launch, but the nature of the recovery of the round in the rails results in a longer duration of the accelerations, and may possibly be the source of much of the higher accelerations.

The Ballistic Rail Gun typically provides set-forward and balloting accelerations with higher amplitude and duration than those experienced during Live-Fire Gun Launch. This allows the opportunity to evaluate hardware at a margin greater than those experienced at the system level during a Live-Fire Gun Launch. Testing at a margin allows components to be evaluated at a level higher than they should ever be exposed to during normal use. This helps to provide a degree of assurance in a design and to expose possible design weaknesses. On the other hand, testing at too large of a margin can pose problems and eliminate the usefulness of the component level tests.

CONCLUSION

The Ballistic Rail Gun has provided the Excalibur program with the capability to easily and cost-effectively test and evaluate components during the development phases to eliminate design flaws before being incorporated into the entire system. It has also been used to qualify components that required a large number of shots. The Ballistic Rail Gun proved to be a beneficial test asset for Excalibur by supporting a component level testing requirement. The advantages provided by the Ballistic Rail Gun are described below:

- Cost: Roughly 10 percent of a Live-Fire Gun Launch
- Schedule: Ability to fire larger quantities of hardware in the same timeframe and eliminates much hardware production
- Margin Level Testing: Set-forward and balloting accelerations are higher than in Live-Fire Gun Launch. Exposes weaknesses due to elevated test levels, higher cycles, and longer durations

As discussed, the Ballistic Rail Gun does not ideally replicate the environment experienced during a Live-Fire Gun Launch, but it can still be a very useful test tool as long as it is understood that it is a margin test for balloting and set-forward accelerations.

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