Informing the Simulation: Bridging the Gap Between Model and Reality in Extended Range Artillery

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ABSTRACT

For the first time ever the collection of base pressure data, on a projectile with a metal rotating band, has been achieved throughout the interior and intermediate ballistic cycles of a next-generation extended range howitzer. This novel approach utilizes a gyroscopically stabilized Instrumented Ballistic Test Projectile (IBTP) equipped with an On-Board Recorder (OBR). The results offer key insights into the base pressure to breech pressure ratio within next-gen systems. Real-world data is compared to Interior Ballistics of High Velocity Guns (IBHVG2) simulations to identify discrepancies used for improving model accuracy. The collected data, combined with propellant charge dynamics, allows for higher-fidelity structural analyses, conducted with Finite Element Analyses (FEA), and provides a deeper understanding of internal ballistics, paving the way for improved next-generation applications.

Keywords: Base Pressure, Interior Ballistics, Finite Element Analysis, IBHVG2, Howitzer

INTRODUCTION

Next-generation extended range howitzer systems represent a significant leap forward in battlefield capabilities. Their ability to deliver precision strikes at longer ranges translates to greater operational reach and tactical flexibility. These systems are an important part of the Army's Long-Range Precision Fires (LRPF) program that strives to provide capability for warfighters to penetrate an adversary's anti-access/area denial (A2AD) complex from a far distance [1]. Optimizing the performance of extended range artillery requires a deep understanding of the complex ballistics that govern projectile motion within the gun barrel. One critical aspect, base flow dynamics and the associated pressure exerted on the projectile base, has remained elusive due to the limitations of traditional measurement techniques.

Although certain forces have yet to be characterized in the field due to the precarious environment, Interior Ballistics of High Velocity Guns (IBHVG2) simulations have been instrumental in the development and advancement of modern munitions. IBHVG2 is used to predict the magnitude of many unknown forces for engineers and designers. While the progression of IBHVG2 represents a monumental achievement and allows engineers to design for ballistic environments, there are still areas where the simulation can be improved. As capabilities increase and the collection of real-world data becomes possible, it is important to gather data points to verify and improve the values computed by IBHVG2 simulations.

One elusive characteristic is base pressure of a round equipped with a metal rotating band. Base pressure is the force that builds up inside of the gun tube and pushes on the projectile base causing propulsion and spin of a munition. This paper presents a groundbreaking achievement: the first-ever successful acquisition of projectile base pressure data from a round equipped with a metal rotating band within a next-generation extended range howitzer system.

The nature of this test presented several unique challenges. For the design of this Instrumented Ballistic Test Projectile (IBTP) [2] there were many complex, integration, assembly, and survivability considerations that had to be taken into account. Some of those factors will be reviewed in this paper.

The data was successfully obtained using innovative techniques and sheds a new light on the base flow behavior within a next-gen extended range gun tube. The initial findings are compared with IBHVG2 predictions and discussed in furthering the accuracy of Internal Ballistic (IB) simulations. This comparison offers valuable insights for refining IBHVG2 models and enhancing their accuracy within long-range cannon artillery. This knowledge will pave the way for advancements in the next generation of design and performance optimization.

TEST REQUIREMENTS & OBJECTIVES

Collect base pressure of projectiles to confirm base to breech pressure ratio assumed for Internal Ballistics (IB) simulations and validate load cases used to design extended range artillery.

Collect triaxial accelerations to inform load cases for projectile components.

MECHANICAL DESIGN AND CONSIDERATIONS

The test system used in this experiment was an inert gyroscopic projectile fired in a next-generation extended range howitzer. The projectile base was modified to accommodate instrumentation including two (2) base pressure transducers and an on-board recorder (OBR) equipped with a Selectable Telemetry Enhanced Electronics (STEEL) system [3]. The internal OBR electronics package was constructed to house Printed Circuit Boards (PCBs), batteries and a high-g triaxial accelerometer. For some test iterations, an instrumented fuze was used. For other trials, a conventional inert fuze was used. The parametric model illustrating the projectile and OBR system is depicted below:

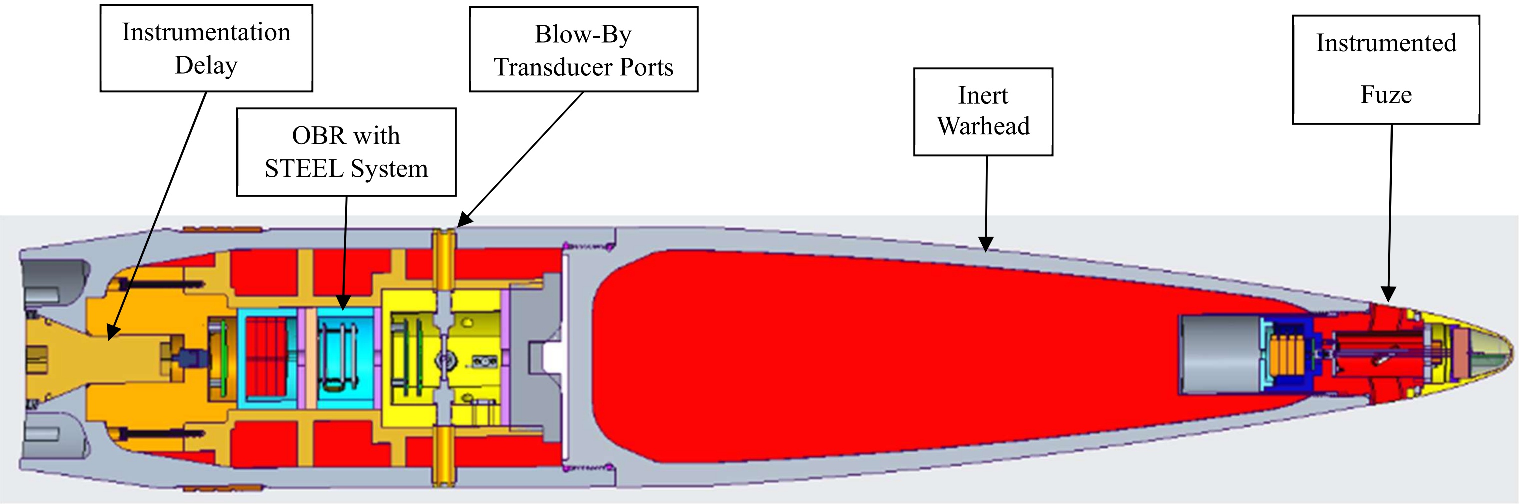

Figure 1: Gyroscopic IBTP with OBR Cutaway Perspective (with Labels)

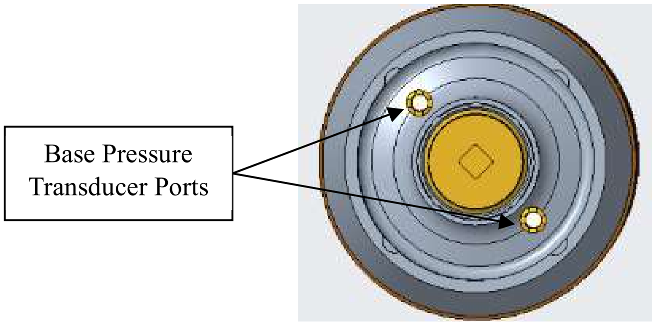

Figure 2: Base Pressure Transducer Illustration, Projectile Aft Perspective (with Label)

Testing within the confines of a gun tube presents a harsh environment for instrumentation. This is particularly true for OBR systems that capture and store data internally, unlike traditional telemetry systems which transmit live data, as they need to survive testing and then be recovered to collect data. To ensure this OBR's survivability, extensive Finite Element Analysis (FEA) was conducted during the design process. These analyses identified potential risks, allowing for the selection of high-strength components and design tweaks that ensured survivability.

The mechanical design features a modular cup-based approach, enhancing cross-compatibility with other systems and increasing reusability. It also reduces overall system risk as the modularity allows for individual cup replacement in cases of failure, eliminating the need to scrap the entire assembly. Additionally, cups can be assembled and shelved ahead of time, reducing lead times on project builds.

The unforgiving test atmosphere and the presence of internal instrumentation necessitated robust measures to prevent intrusive gun gasses from potentially obliterating the system in addition to surviving the actual test event. A significant challenge arose from the need to arm the OBR before deployment at the test site. This required an interface for the telemetry team to communicate with the OBR in the field. Traditional sealing methods, typically employed in controlled laboratory environments, were not feasible under field conditions. To overcome this, the standard delay mechanism, which involves getting pressed in with a sealing ring, was replaced with a more practical solution: a threaded delay. This innovative delay, easily removable in the field, provided capability to arm the system and could then be torqued in and sealed onsite, eliminating entry points for gun gasses. It is worth noting that throughout testing, although most of the projectiles were protected by the sealing measures that were implemented, leakage of gun gasses was observed in one (1) instance. The leakage inside the system resulted in the melting of electric components and no data could be recovered. While this failure was an anomaly, the sealing capability and methodology has room for improvements in future test runs. The damage caused by the leakage is shown below, alongside a successfully sealed projectile for comparison:

Figure 3: Side-by-Side Comparison of Recovered Projectiles with Gun Gas Leakage (L) and without Leakage (R)

Figure 4: Connector & Shorting Plug Melted by Gun Gasses

Aside from the selection of robust sensors, protective measures needed to be implemented to ensure the survivability of the on-board electronics. To safeguard electronics, in particular Printed Circuit Boards (PCBs), from the high-g forces experienced during the test event, encapsulation, underfill and load path management techniques were employed. In high-g environments, the primary cause of electronic failures is PCB flexure. Underfill is used on a component level and is a polymer that offers protection by fully covering the bottom of a component and reinforcing the fragile solder connections between the chip and the PCB. It also fills any unwanted gaps that traditional encapsulation materials may be too viscous to reach, enabling mechanical stresses to be dispersed uniformly, instead of in a concentrated manner that can result in an electrical failure. Encapsulation, used for full board level and above coverage, provides structural support to the components embedded within it. In addition, it acts as a damper to absorb and dissipate mechanical energy imparted to it. At a system level, mechanical design and material selection was executed considering the load paths delivered to the electronics package to help mitigate failures as well as protect the integrity of the data collected by minimizing shock and vibration [4].

SURVIVAL & REUSABILITY

The designed OBR (On-Board Recorder) system stands out for its reusability after testing, due to critical design features. The OBR's metalwork is manufactured from high-strength materials, chosen to withstand the punishing forces of launch and impact. This robust structure acts as a shield, protecting the sensitive electronics from the harsh environment. The OBR's unique cup-shaped design offers several benefits for reusability. This configuration controls the internal load path helping to direct and absorb mechanical shocks and impacts experienced during testing. The OBR's electronic components are designed and built to endure the high-g environment experienced. This process is detailed in the previous section.

The ability to reuse OBRs after testing offers significant advantages for programs as reusability translates to substantial cost savings. By eliminating the need to build entirely new systems for each test, the program saves significantly on material and labor costs. The reusability factor also eliminates the downtime required to rebuild OBRs between tests. Once functionality is verified after recovery, they can be readily prepared for the next test cycle, significantly accelerating the overall testing schedule, allowing for a more efficient testing process. OBRs can be quickly deployed for subsequent tests, minimizing downtime, and maximizing the number of tests conducted within a given timeframe. In addition, recycling OBRs translates to less waste generation and a smaller environmental footprint for the program.

Following recovery, the OBR undergoes a rigorous inspection process. The rocket motor bodies (RMBs) are stripped, and the internal OBR is examined for any signs of damage. A series of electrical verification tests confirm full functionality of all OBR functions. Once deemed operational, the OBR is placed in a controlled storage environment to minimize any potential degradation of components over time. This ensures the OBR remains ready for its next mission.

DATA ANALYSIS & FINDINGS

The IBHVG2 model uses the Baer Frankel model [5, 6] to simulate the pressure that builds in the gun tube. The simulation first calculates the gas temperature, T, by using Resal's equation, Eqn. (1), where N is the number of propellants plus the igniter and $i \in \{1 \,..\, N\}$. The terms m_i, F_i, T_{F_i}, and γ_i are the mass of gas, adiabatic flame temperature, impetus, and frozen ratio of specific heats (C_p/C_v), respectively, of the i^{th} propellant. L is the sum of energy lost during the interior ballistic cycle including the energy imparted to the projectile and the energy required to move the gas-solid propellant mixture, rotate the projectile, engrave, and resist projectile motion, recoil the barrel, displace the air in front of the projectile, and heat the exposed chamber and tube wall [6].

$$T = \frac{\sum_{i=1}^{N} \frac{m_{gi} F_i}{(\gamma_i - 1)} - L}{\sum_{i=1}^{N} \frac{m_{gi} F_i}{T_{F_i}(\gamma_i - 1)}} \qquad (1)$$

To calculate the mean pressure, the volume available for the expansion of gaseous constituents, V_c, needs to be determined. Eqn. (2) modifies the initial chamber volume, V_0, by accounting for the volume occupied by unburnt propellant, the covolumes of gas members, b_i, and the volume created by the projectile's movement towards the muzzle. The variables c_i, m_{gi}, and ρ_i, represent the charge weight, mass of gas, and solid propellant density of the ith propellant, respectively. A is the base surface area of the projectile, and s is the projectile's travel distance.

$$V_c = V_o - \sum_{i=1}^{N} \left[\frac{C_i}{\rho_i} - \frac{m_{gi}}{\rho_i}\right] - \sum_{i=1}^{N} m_{gi} \cdot b_i + A \cdot s \tag{2}$$

The mean pressure, P, is then calculated by applying Dalton's Law of Partial Pressure, Eqn. (3).

$$P = \sum_{i=1}^{N} P_i = \sum_{i=1}^{N} \frac{F_i \cdot m_{gi} \cdot T}{V_c \cdot T_{Fi}} \tag{3}$$

The mean pressure from Eqn. (3) can be used to find the pressure at the base of the projectile by applying either the Lagrange [8] or Chambrage [9] derived pressure gradients [5].

For this test, specific areas examined include:

Ramp-Up (Set Forward) – The phase during which the pressure inside the gun barrel increases as the propellant burns and the projectile begins to overcome static friction and start moving.

Peak – The highest pressure the munition undergoes inside the gun tube.

Muzzle Exit (Set Back) – The rapid drop in pressure felt as the projectile exits the gun barrel.

These areas of interest are encircled on the following graph, which represents the two full data sets, real-world vs IBHVG2, graphed against each other. Each individual range is then enlarged in smaller subsequent figures to provide a better illustration of observed discrepancies.

For this paper, two samples of real-world data are examined. One will illustrate a data set where the IBHVG2 showed a high level of accuracy. The other data sample will show areas for improvement where discrepancies observed in the IBHVG2 model and the real-world data.

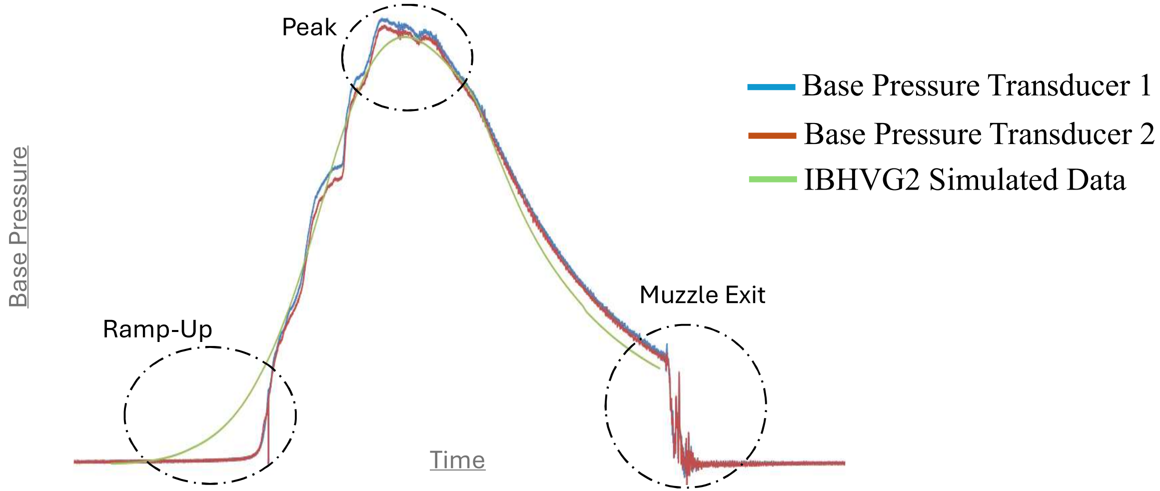

Figure 5: Graphical Comparison & Overlay of Simulated vs Actual Data (Sample 1)

The overall pressure curve produced by the IBHVG2 well represents the field-collected data.

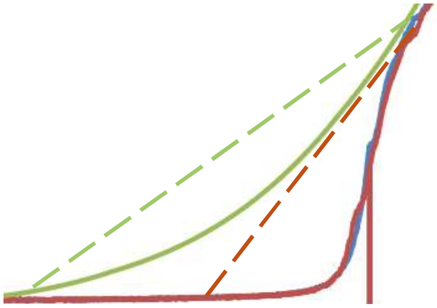

Figure 6: Graphical Comparison & Overlay of Ramp-Up Period – Simulated vs Actual Data (Sample 1)

The slope of the ramp-up periods of the real-world data and IBHVG2 values has been drawn onto the graph for better visualization. The actual ramp-up pressure occurs faster than what is simulated by IBHVG2 slope, resulting in a steeper ramp-up slope than what is predicted.

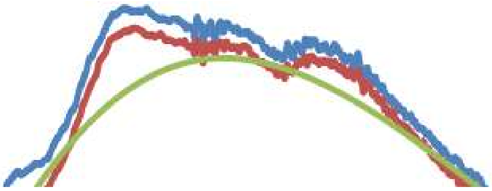

Figure 7: Graphical Comparison & Overlay of Pressure Peaks – Simulated vs Actual Data (Sample 1)

The observed peak pressures of the collected data are marginally greater than the maximum that was computed by the IBHVG2.

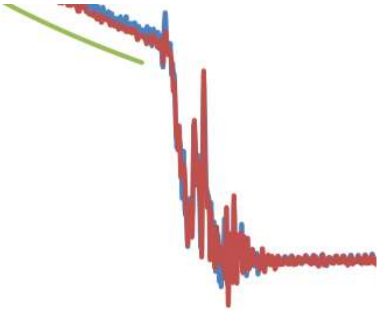

Figure 8: Graphical Comparison of Muzzle Exit Data – Simulated vs Actual Data (Sample 1)

The pressures felt at the muzzle exit are slightly higher than the IBHVG2 calculates them to be. The following graphs show the data overlaid in the second sample set:

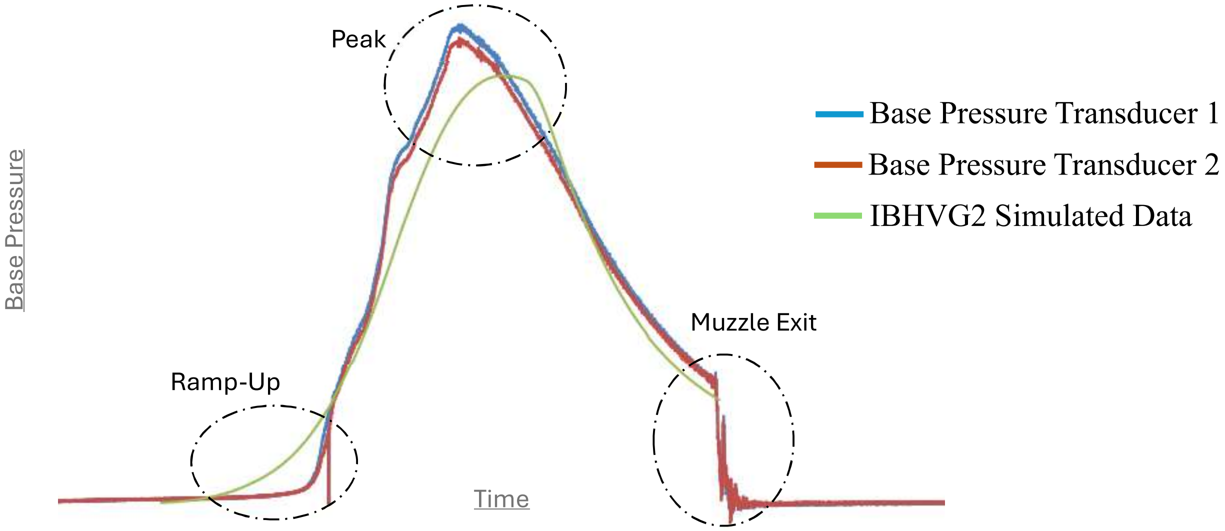

Figure 9: Graphical Comparison & Overlay of Simulated vs Actual Data (Sample 2)

This second sample set of collected data shows a greater degree of discrepancy when compared to the IBHVG2 than the first set.

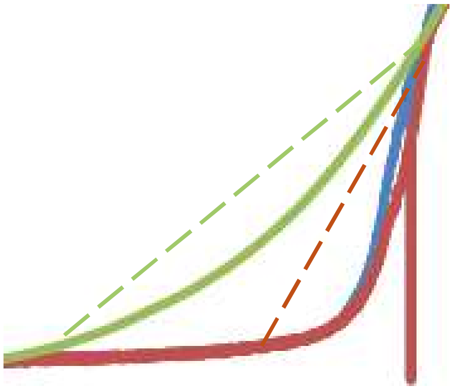

Figure 10: Graphical Comparison & Overlay of Ramp-Up Period – Simulated vs Actual Data (Sample 2)

The actual ramp-up pressure is considerably quicker than when compared with the simulated IBHVG2 slope, resulting in a considerably steeper ramp-up slope.

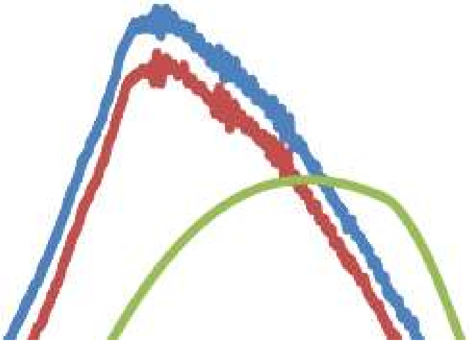

Figure 11: Graphical Comparison & Overlay of Pressure Peaks – Simulated vs Actual Data (Sample 2)

The observed peak pressures of the collected data are markedly higher than the maximum pressure that was computed by the IBHVG2.

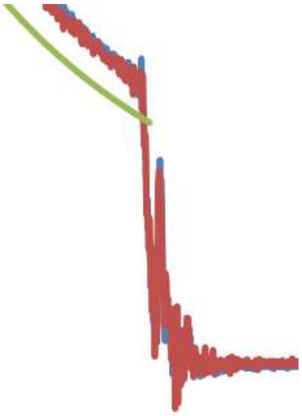

Figure 12: Graphical Comparison of Muzzle Exit Data – Simulated vs Actual Data (Sample 2)

The pressures shown at the muzzle exit that were collected by the OBR are considerably higher than the IBHVG2 calculates them to be.

CONCLUSION

The development of modern munitions is undergoing a revolution with the emergence of Interior Ballistics of High Velocity Guns (IBHVG2) simulations. IBHVG2 offers a powerful alternative to traditional in-field testing, enabling ballisticians to explore design concepts with unparalleled efficiency and safety.

IBHVG2 simulations are a cost-effective solution, requiring minimal resources compared to in-field testing. A single engineer can initiate an IBHVG2 simulation with ease, eliminating the need for elaborate setups and manpower. Moreover, simulations are conducted entirely within a computer environment, completely independent of external factors like weather.

However, while IBHVG2 represents a significant leap forward, it is important to perform real-world validation. Key areas such as ramp-up (set forward), muzzle exit (set back), and peak pressures have a significant impact on the mechanical design and survivability of the weapon system. By comparing simulation results with data from real-world tests, engineers can confirm the accuracy of IBHVG2 and identify areas of refinement. This verification process strengthens confidence in the model's future use and ensures its continued advancement in reliability.

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