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CHARACTERIZATION OF THE PARAMETERS THAT AFFECT
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CHARACTERIZATION OF THE PARAMETERS THAT AFFECT PROJECTILE BALLOTING USING FINITE ELEMENT ANALYSIS

A DISSERTATION APPROVED FOR THE SCHOOL OF AEROSPACE AND MECHANICAL ENGINEERING

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ABSTRACT

With the introduction and proliferation of technology in weapon systems, the United States Army has become concerned with the reliability of smart munitions. These munitions contain electronic components that sporadically fail in response to high accelerations. In gun-launched projectiles, a phenomenon known as balloting is responsible for generating large accelerations. Balloting is the transverse motion of a projectile inside a gun tube during launch, and until recently, balloting had generally been ignored. Balloting in the older projectiles generally did not cause projectiles to fail because these projectiles contained only high explosives and supplemental charges. Due, in part, to the use of electronic components in smart projectiles, balloting has become an issue that warrants investigation. This balloting causes structural ringing in a projectile, which propagates to the internal components. The electronic components in the projectile can fail when the vibration induced by balloting occur at frequencies close to their natural frequencies.

A 3D Finite Element Model was developed to simulate the behavior of a gun-launched projectile. The model simulates the actual characteristics of a projectile while it is in the bore of the gun tube. This model was developed using the general-purpose finite element package ABAQUS and is a general model that can be adapted to any gun/projectile system. This research will focus on the causes of balloting. If these parameters can be identified, engineers can apply these results in designing future projectiles and upgrading older ones to help decrease balloting.
and increase the survivability of smart munitions. The model developed herein is a unique and important tool that can be used to analyze balloting in any system, and represents an important achievement in the field of ballistics analysis.
CHAPTER 1: INTRODUCTION

This research created a 3D Finite Element Model (FEM) that had never before been created. The model can be used as a tool to analyze combinations of projectiles, cannons, and propellants to determine how each projectile parameter affects balloting. Prior to this research, models consisted of projectiles that used dynamic responses as inputs to analyze projectile response. This model provides the ability to computationally predict gun-launched projectile dynamic responses including the projectile to gun interactions, which can be used to optimize projectile design to minimize balloting.

1.1 BALLOTING

Balloting is the yawing or wobbling (transverse) motion of a projectile as it travels down a gun tube. This motion is believed to be a function of a number of small, difficult to measure parameters. These parameters include: manufacturing tolerances, lack of concentricity of the engraving of the rotating band, lack of concentricity of the projectile and tube deformation, asymmetric obturation of the propellant gases, rotating band wear, location of the center of gravity of the projectile both radially and axially, axial location of the rotating band, and length of
the wheel base (distance between bourrelets) of the projectile. Projectile balloting occurs because of the necessity to have clearances required between the bourrelets and the gun bore. In the past, balloting was only known to have caused excessive tube wear and inaccuracies of the projectile (Ansari and Baugh, 1988). This was due to the simple design of the projectile. Early projectiles were simply a banded shell, which contained high explosive materiel inside that was detonated by a supplementary charge when the fuze was activated. A simple HE projectile is shown in Figure 1 ("155MM Artillery Weapon Systems Reference Data Book", 1990).

![Figure 1 Example of a Basic Projectile](image)

1.2 PROJECTILE FAILURE

With the introduction of electronic components inside the projectile, balloting has also been shown to damage critical electronic components (Cordes,
Vega, and Carlucci, 2005). Smart munitions have a large number of internal electronic components inside as illustrated in Figure 2, which make them more susceptible to failure (Cole, 2006). Recently it has been noted that a large number of the failures of these smart munitions have been attributed to balloting (Cordes, Morris, Gast, and Carlucci, 2006).

![Figure 2 Example of a Smart Projectile with Electronic Components](Image)

The U. S. Army has become concerned with balloting in these rather expensive projectiles since balloting has been linked to their high failure rates. In order to improve the reliability of the projectiles, the dynamics of balloting needs to be better understood (Cordes, Morris, Gast, and Carlucci, 2006).
1.3 INTERIOR BALLISTICS

Gun-fired projectiles are subjected to relatively high dynamic forces. For example, a 155 mm projectile with a 47 kg (103.5 lbs) mass can reach a maximum dynamic acceleration early in the launch cycle of 15,000 Gs. At muzzle exit, the axial accelerations are around +6,000 Gs. The radial accelerations recorded at muzzle exit average between +2,000 Gs and +6,000 Gs (Cordes, Morris, Gast, and Carlucci, 2006). The projectile is subjected to many different dynamic events as it travels through the gun tube.

The first dynamic event a projectile experiences is actually prior to firing. The ramming of the projectile from the gun breech into the bore which seats the rotating band about one-eighth of an inch into the lands and grooves of the gun tube as shown in Figure 3 is a fairly violent event (Vega, 2004). The next event the projectile is subjected to is the inertial response due to the burning and expanding propellant gases. This event is known as set back. The acceleration forward causes the forward end of the projectile to compress rearward. This phenomenon is similar to an amusement park ride where the ride experiences a relatively large forward acceleration that forces the rider back into his seat.
There are two instances in the gun tube where the components inside the projectile are forced forward relative to the base. First, when the projectile is rammed and seated in the rifling of the gun tube as stated earlier. The second forward loading is more significant and occurs when the base of the projectile clears the muzzle and the propellant gases suddenly disperse. The projectile is no longer compressed as much by its own inertia and attempts to spring back to its original shape (Cordes, Morris, Gast, and Carlucci, 2006).

One can visualize the effect of the axial acceleration on the projectile by considering a projectile to be a large, axially deformable spring. The spring-like projectile compresses under its own inertia as it accelerates. If the compressive
loading is suddenly removed, the spring decompresses and oscillates. This event can be characterized by the effective spring constant of the system. The resulting vibration after the removal of the load would be a free vibration if it were not for material damping, Coulomb damping (friction) at all of the interfaces and joints, aerodynamic drag, and any other damping caused by the cargo or warhead material. In Figure 4, it is shown that, during the set back event, all of the material, and therefore the center of gravity (C.G.), move rearward relative to the base when a force is applied to the base. Upon release of this load, the ends of the projectile oscillate about the C.G. with respect to the C.G. (Cordes, Morris, Gast, and Carlucci, 2006).

Figure 4  Illustration of a Set Forward Event
During the launch event, not only is the round compressed in the axial direction, but it also swells in the radial direction. When the projectile is initially subjected to the axial force, it causes the projectile to expand radially at set back. During the set forward event, when the axial force is removed, the projectile oscillates radially around the centerline of the projectile. This event also creates transverse accelerations of the projectile that couple not only with the axial vibration but with the balloting that had been occurring as the projectile traveled down the gun tube (Cordes, Morris, Gast, and Carlucci, 2006). This section described the dynamic events that a projectile undergoes immediately prior to and just after muzzle exit. This research will only focus on the events that occur after the ramming of the projectile and up to muzzle exit.

1.4 RESEARCH OBJECTIVES

This research will identify some of the factors that affect balloting in order to minimize balloting and reduce the number of failures in smart munitions. The result will be an analytical means to determine the significance of selected parameters. Based on the literary research, the proposed parameters that could affect balloting and will be analyzed are:

- CG position (both radially and axially)
- Band location
- Projectile length
- Wheel Base length (Distance between forward and rear bourrelets)
- Tube Bending (Deformation due to gravity)
The expected outcome of the research is to identify projectile parameters that can be modified to reduce the effects of balloting, and therefore optimize the survivability of smart munitions. This would prioritize which parameters have a more significant effect on balloting. Although new projectiles, which incorporate features to mitigate balloting, would be optimal, the Army needs to apply these modifications to existing rounds where possible, or at least incorporate the changes in future modifications. For this reason, it is important to understand the effects of each of the parameters and how each can be applied to existing projectiles and future designs.
CHAPTER 2: LITERATURE SEARCH

The objective of this section is to present a synopsis of the open literature that describes interior ballistics of guns and balloting dynamics. In order to investigate these issues, an understanding of internal ballistics is necessary. The ultimate objective is to apply this research to the examination of the causes of balloting and how those effects can be minimized.

The initial literary search on balloting produced a small set of literature that was mainly based on deriving the governing equations to represent balloting. The search was then expanded to interior gun tube ballistics, which produced a wide variety of literature. Some of this literature, published within recent years, even described balloting since the term balloting has only been recently adapted.

One of the earliest and only pieces of literature found that dealt with reducing balloting and its effects was the 1884 paper by Breeger. This paper examined the optimum axial position to place the rotating band on a projectile to increase its accuracy and range. This position was located between the base and the center of gravity of the projectile (Breeger, 1884). Although Breeger's objective was not to decrease balloting, he did so implicitly as a side effect of increasing the accuracy of the projectile.

Several authors investigated modeling gun dynamics and balloting. In order to predict the first maximum yaw after shot exit, Reno carried out a rigorous Lagrangian treatment of the angular motion of the projectile in the bore. He assumed that the plane of yaw rotates with the shell, but friction between the
projectile and the bore was ignored. The projectile was approximated by a single
degree of freedom pendulum system, and a closed-form solution was obtained
(Breeger, 1884; Reno, 1943). However, the initial yaw observed during
development of a 36-inch mortar in 1944 was greater than that predicted by Reno's
theory. In an attempt to find an explanation, Thomas generalized Reno's approach
by removing the constraint on the orientation of yaw and deduced the motion of the
plane of yaw (Thomas, 1945). His results showed little difference in the calculated
yaw.

Gay showed that the theories of Reno and Thomas do not predict that large
balloting energies may develop. Gay found that the yawing motion of the shell will
bring the shell bourrelet into contact with the lands early in the motion of the shell
and that yawing motion will be rapidly damped (Gay, 1973). Following Gay,
Walker developed a theory that predicted a growth in balloting energy might occur
(Walker, 1974). His theory extended Thomas' theory by further assuming friction
between the bore and rotating band. According to Walker, the impact impulse
generated by the bourrelet hitting a land is followed by a reaction force impulse that
occurs on the opposite side of the shell at the rotating band. This causes an added
frictional force on the rotating band and results in an added torque impulse that
could possibly increase the total transverse angular momentum possessed by the
shell.

Perdreauville presented an analysis of the projectile balloting problem using
Lagrange's equations and Euler angles (Perdreauville, 1971). The projectile was
assumed to have no center of mass offset and to be in dynamic balance about the principal geometric axes. The equations were written to represent complete lateral dynamic freedom of the projectile bourrelet within the bore. Impact was included, and the equations were set up so that the motion of the gun tube could also be introduced.

Chu and Soechting presented the same theory as Perdreauville although they resorted to Euler's dynamical equations (Chu, 1973). Perdreauville extended the analysis of his earlier work to include the effects due to an unbalanced projectile in a rigid gun tube. In a subsequent document, Perdreauville developed equations of motion describing the lateral motion of an artillery projectile as it moves down an elastic gun tube that vibrates laterally (Perdreauville, 1974). However, he did not generate any numerical results in either of these reports.

Langhaar and Boresi (1983) analyzed the problem of dynamics of a projectile in a concentric flexible moving tube. The motion of the tube was accounted for by using the Kirchoff-Clebsch theory of deformed rods. However, the effect of projectile balloting was ignored and no numerical results were shown.

Ansari and Baugh conducted further a study on the energy growth of balloting (Ansari and Baugh, 1988). This model was aimed at developing a simplified tube/projectile interface that represented the interface and is easily implemented. This work was essentially a nonlinear dynamic analysis of a balloting projectile. The mathematical model used was a six-degree of freedom-coupled model of the projectile and gun tube system. The effects of obturator
flexibility and projectile impact with the gun bore at the bourrelet were included in the analysis, and the nonlinear differential equations of motion of the system were derived using a Lagrangian formulation. Gaussian elimination and Newmark's constant average acceleration method were employed to obtain a solution. The methods discovered that a more rigorous multi-degree of freedom system analysis would be necessary.

Many authors have attempted to model balloting to obtain information of gun tube loading and accuracy. However, none of these authors have been entirely successful. In fact, most of the authors stated in their recommendations, a more rigorous analysis needs to be conducted.

With the exception of Breeger, little has been done to attempt to reduce the effects of balloting. Today, with the use of improved technology, researchers are able to use instrumentation to further investigate balloting. This instrumentation allows researchers to record data onboard the projectile as it is being fired. This allows researchers the ability to analyze the data to not only determine the dynamics of balloting, but also possibly identify the causes of balloting. Once the causes are determined, steps can be taken to reduce balloting and, therefore, increase the reliability of today's smart munitions.
CHAPTER 3: EXPERIMENTAL FACILITIES AND TOOLS

Currently, there are a limited number of methods available to fire a gun and recover an intact projectile. The Ballistic Rail Gun (BRG), Parachute Soft Recovery Vehicle (SRV), and firing into hay bales are a few examples. None of these methods provide the ability to completely simulate actual tactical projectile dynamics. These methods generally impose high loads during recovery not encountered during normal gunfire and thus are not completely representative. Currently, the only available method to test the high G survivability of tactically configured, gun-launched projectiles is through expensive and time-consuming open range testing with the subsequent destruction of the projectile upon impact.

3.1 ARDEC BALLISTIC RAILGUN

The BRG was established in 1970, and uses a 1945 vintage, M114, 155 mm, 21 Caliber Howitzer (Figure 5). A projectile in its full-up (tactical) configuration, i.e., fuze, payload, and projectile cannot be fired. Only a 155 mm M483A1 projectile or a special test projectile can be fired in this system, with a scoop in place of the fuze as shown in Figure 6, to decelerate the round. Payloads can be inserted in the projectile body for testing. Payloads consist of actual components as well as On Board Recorders which can be used to record axial and radial accelerations (Gray, 2005b).
3.2 PARACHUTE RECOVERY PROJECTILE TESTS

The parachute recovery projectile test is a projectile that is shot from a gun tube that deploys a parachute to slow its ascension and descent. As with the
ARDEC Rail Gun, a full-up tactical configuration cannot be fired. The ogive or payload is usually replaced with the parachute, the object being tested and a telemetry unit. These projectiles currently have a variety of base and nose deployed parachute designs in both spinning and non-spinning configurations. Each new system normally requires a new test unit design to meet the system requirements (Figure 7). The projectiles are designed to deploy the parachute and land softly without additional damage to sensitive electronic components. Following the landing, the projectile is taken apart, and the structural integrity of the parts is evaluated. If failures have occurred, the telemetry recorded pressures and accelerations are compared to other data sets as part of the root cause investigation for design improvement (Gray, 2005b).

Figure 7  Parachute Recovery Projectile Tests
3.3 SOFT CATCH GUN FACILITY

The Soft Catch Gun Facility provides design engineers a unique capability to non-destructively, soft catch experimental and developmental gun fired conventional, smart, and precision guided munitions, sensors, guidance devices, and fuzes. The projectile is fired from a conventional weapon then enters a slotted tube where propellant gases can vent. After passing through the slotted tube, the projectile then enters a solid tube at atmospheric pressure. Ahead of the projectile, air is compressed until a shock wave propagates to burst a diaphragm retaining a pressurized column of air. At the other end of the air column is a piston followed by a long, shallow trough of water. The compressed air in front of the projectile is used for transferring momentum to the piston and water, which decelerates the projectile. Finally, the projectile comes to rest at the recovery section (Figure 8). At the time of this writing, the construction on this facility is complete, but shakedown is still on going (Gray, 2005b).
Originally established in 1942, Yuma Proving Grounds (YPG) is responsible for managing testing at three locations: Yuma Test Center at YPG, Arizona, the Cold Regions Test Center, Alaska, and the Tropic Regions Test Center, which is headquartered at YPG and operates in Hawaii and other tropic areas. The Yuma Test Center is a multi-purpose test facility able to test nearly every weapon system in the ground combat arsenal. More than 1,300 square miles in size, the test center is one of the few places where military munitions and hardware can be tested in an area almost completely removed from urban
encroachment and noise concerns. Its sunny climate, terrain and excellent range facilities result in almost perfect free flight testing and training conditions.

3.5 INSTRUMENTED BALLISTIC TEST PROJECTILE (IBTP)

The IBTP is usually fitted with five pressure sensors as shown in Figure 9 to measure base pressure and blow-by pressure (Vega, 2006). The blow-by pressure is caused by propellant gasses escaping past the projectile’s obturator. Blow-by is a suspected contributor to balloting but is not treated in this research. Gage 1 is located in the base to measure base pressure. Gages 2-5 are located 90 degrees apart around the same circumference to measure blow-by pressure. This projectile is used in a real gun tube that is often fitted with pressure sensors as illustrated in Figure 10 ("Instrumented Ballistic Test Projectile Data Results and Analysis", 2004). The pressure sensor locations in the gun tube are shown as P1 through P7. Sensor P1 measures the breech pressure. Sensor P2 is close to the base at shot start and provides a reasonable estimate of base pressure, particular for the first few centimeters of motion. A triaxial cluster of accelerometers is located in the projectile in the On Board Recorder.
3.6 ON BOARD RECORDER (OBR)

The OBR is used to measure accelerations and is usually placed inside the test projectiles as part of the payload. An OBR can be placed in the M483A1 projectile and fired from the Ballistic Rail Gun or it is placed in an IBTP. Accelerations are measured throughout the in-bore gun firing and muzzle exit events. The requirements of the OBR specify at least three channels that measure accelerations, one channel in the axial and two channels in the transverse
(balloting) directions. The more common configuration of the OBR is shown in Figure 11, which consists of five accelerometers, two measuring the axial accelerations and four measuring the transverse accelerations. This configuration gives redundancy in both the axial and radial directions and can provide reliable data if one of the accelerometers fails (Vega, 2004). It also enhances the ability to separate spin from balloting by differentiating co-linear radial accelerometers.

![Figure 11 On Board Recorder (OBR) with Accelerometer Locations](image)

3.7 DFUZE

Similar to the OBR described in the previous section, the Army Research Laboratory (ARL) Diagnostic Fuze (DFuze) is the size of a standard fuze and is
designed to fit on any existing projectile (Figures 12 and 13). This capability allows the Army to gather data from projectiles without needing to modify the cargo regions. The DFuze can be fired from any platform. Accelerations are measured through the in-bore gun firing and muzzle exit events. The DFuze records data in a minimum of three channels that measure accelerations in the axial and two transverse (balloting) directions. The DFuze represents a high-g projectile-borne measurement system for obtaining in-bore and in-flight ballistic data that significantly contribute toward the design, development, failure diagnostics, and aerodynamics determination of artillery or other projectiles. The DFuze uses several commercial off-the-shelf micro-electro-mechanical systems accelerometers, magnetometers, and optical sensors for determining estimates of the projectile's body orientation, axial acceleration, radial acceleration, and roll rate (Davis, Hamilton, Hepner, 2002).
3.8 ABAQUS

ABAQUS software is a suite of interoperable applications for finite element analysis. ABAQUS offers a complete solution for simple to complex linear and nonlinear engineering problems, using the finite element method. The newest multiphysics capability in ABAQUS is a Coupled Eulerian-Lagrangian (CEL) approach, which provides engineers and scientists with the ability to simulate a class of problems where the interaction between structures and fluids is important. This capability does not rely on the coupling of multiple software products, but instead solves the fluid-structure interaction simultaneously within ABAQUS ("ABAQUS Superior Finite Element Analysis Solutions").
3.9 PRODAS

PRODAS is a lumped-parameter, interior ballistic computer code. The code, developed by Arrow Tech, uses an updated version of the classic Baer Frankle interior ballistic code. PRODAS is used for the calculation of interior ballistic trajectories, including gas pressure, projectile displacement and projectile velocity as a function of time. The code treats both regular and deterred propellants. It contains powerful variational and searching capabilities, so that it can, for example, search and find the best propellant dimensions, given the maximum allowable gas pressure. This code allows the user to create a projectile model, calculate mass properties, estimate aerodynamics and stability, and simulate a test firing. It is commonly used to gather information on the pressure-time curves of a given propellant, projectile and gun tube (PRODAS).
CHAPTER 4: EXPERIMENTAL DATA

This research is designed to examine the parameters that affect balloting. In Chapter 1, some concepts of interior ballistics were reviewed. In order to examine the parameters of balloting, boundary conditions and a baseline had to be chosen. For this research, the baseline needed to include a propellant, projectile and gun tube. The projectile and gun tube associated with this research are the M795 High Explosive (HE) projectile and the M284 gun tube. These were mainly chosen because currently the M284 is the most common gun tube in the U. S. inventory and there were already experimental data available for both the projectile and the gun tube.

The experimental data used in this research was based on a M795 projectile, which was fired from a M284 cannon at PIMP +5% (permissible individual maximum pressure +5%). The firings took place at the Yuma Proving Grounds in July 2006. The pressure and accelerations from the PIMP +5% propellant are about 5% more than the projectile and cannon would normally experience during firing in the field. In the PIMP +5% case, the peak pressure is around 60,000 PSI, resulting in an acceleration of 15,000 Gs on the projectile. In general, the larger the propelling charge, the higher the g-force is on the projectile. The available experimental data consisted of pressure, acceleration in both axial and radial directions, rotational velocity, and muzzle velocity. The muzzle velocity of the projectile analyzed in this research was 830 m/s spinning at 267 Hz.
4.1 M795 (HE) PROJECTILE

The M795 is a 155 mm high explosive (HE) projectile, approximately 31 inches in length ("155MM Artillery Weapon Systems Reference Data Book", 1990). It is filled with 23.8 pounds of TNT and weighs approximately 103.5 pounds (Figure 14). It is used for conventional fire support for harassment and interdiction fires, fragmentation, mining, and blast effects. The M795 is made of high fragmentation (HF1) steel and uses a welded rather than a swaged copper rotating band that encircles the body close to the base. For storage and transport, an energy absorbing lift plug is threaded into the nose cavity. This nose plug is removed prior to firing and replaced with a fuze.
The M109A6 Paladin howitzer is the latest product improvement to the original M109 155 mm self-propelled (SP) howitzer. The Paladin features improvements in the areas of survivability, reliability, availability, maintainability, responsiveness; and terminal effects (Figure 15).
The M284 cannon is the main armament for the M109A6 Paladin. The M284 is a 39 caliber 155 mm cannon with a range of up to 30 km ("155MM Artillery Weapon Systems Reference Data Book", 1990). Caliber is the Army’s unit of measure for tube length where one caliber is equal is equal to the diameter of the gun tube. The M284 tube has a rifled twist of 1 in 20. This means that during axial travel down the gun tube, ridges cut into the rotating band on the projectile and impart a spin. A 155 mm 39 caliber gun tube is 39 x 155 mm or 6045 mm (238 in) in length from the breech face to the muzzle (Carlucci and Jacobson, 2008). All 155 mm cannon are classified as rifled. A twist of 1 in 20
means the projectile makes one revolution in 20 calibers of travel. In this case, caliber is defined as the diameter of the gun tube. Multiplying 20 by the diameter of the tube (155 mm = 6.1 in) will result in the units of travel length per revolution. For a 155 mm cannon, a twist of 1 in 20 results in 122 inches of travel per revolution. As stated earlier, the entire length of the gun tube is 238 inches, however the rifled travel distance in the M284 cannon is only 199.5 inches. Thus, a projectile traveling in a M284 gun tube will rotate 1.62 revolutions before it exits the tube.

**4.3 EXPERIMENTAL DATA SUMMARY**

These experimental data will serve as a baseline for model verification as well as the inputs for loading the projectile. The data being used which was collected from Yuma Proving Grounds in July 2006 was from the M795 projectile fired from a M284 cannon at an angle (Quadrant Elevation or QE) of 70 degrees using a PIMP+5% charge (PXR6297A1). This projectile was fitted with a DFuze that collected acceleration data from the nose of the projectile. The recorded data showed the 103.5 lb M795 projectile rotated 1.62 revolutions achieving a spin rate of 267 Hz at muzzle exit. The projectile was traveling at a muzzle velocity of 830 m/s when it exited the cannon. The travel distance of the projectile within the gun tube was 199.5 inches in 12.05 msec. These data along with the pressure and acceleration data will be the basis of comparison and inputs for the model created
for this research. The following graphs are the unfiltered data of the pressure (Figure 16) and accelerations (Figure 17) from the July 2006 test.

Figure 16  Experimental Pressure vs Time Curve

Figure 17  Experimental Acceleration vs Time Curve
CHAPTER 5: ABAQUS MODEL

A 3D Finite Element Model (FEM) was developed to create a simulation of a real gun field-test firing of projectiles. The model was created to simulate the actual firing and the reactions of a projectile as it travels down the cannon. It was developed using the general-purpose finite element package ABAQUS. The original geometry was generated in Pro Engineer and imported to ABAQUS in *.stp file format. Once the parts were in ABAQUS, any modifications needed to each part were done in the Graphical User Interface (GUI) of ABAQUS. Most parts were modeled using 8-node brick elements with reduced integration and hourglass control. The final model was set up to run in two separate steps, using both a standard and explicit analysis (Figure 18), for static and dynamic analyses, respectively.

Figure 18 Complete Model of the M284 Cannon

5.1 Model Evolution:

Several projectile models have been created to analyze the effect of gun launch. These analyses did not include the gun tube in their model. Furthermore, these analyses used the dynamic responses (accelerations) as inputs to the model to
determine the effects on the projectile. Never before had an analysis been performed that created a model as a tool to determine the dynamic responses. The model can be used to determine and predict how different projectile parameters and variations thereof affect balloting.

Many different models were created and tested in this research before the model reached its final configuration. Initially, the model was created as one explicit analysis that included the gun tube settling due to gravity (tube droop), applied pressure, and spinning of the projectile. After several test runs, it was apparent that a different method was needed to simulate the tube droop of the gun tube. The displacements achieved during this explicit analysis would change as the run time was changed for each test. After many attempts at trying to bring the gun tube to equilibrium, an alternate solution was pursued. This method, described below, actually reduced the run time of the model by 8 hours when running on 32 processors.

The first step was a static analysis that uses gravity to force the model to equilibrium, this replicated a phenomena known as tube droop. Depending on the elevation of the gun tube, the deflection due to tube droop will differ. Knowing that the tube droop could affect balloting, the model was run at 0 and 70 degrees of quadrant elevation (QE). The second step (explicit) took the results from the first step and used them as input into an explicit analysis. To accomplish this, the deformed gun tube was exported from the static analysis and imported into the explicit analysis file.
5.2 PARTS

The static analysis model consisted of two main assemblies each with three subcomponents. The two main assemblies of the model were the M284 cannon and the M795 projectile. The gun tube consisted of a breech, bore evacuator, and muzzle brake (Figure 19). These components were only used in the static analysis to ensure the gun tube was subjected to the proper weight to obtain the correct tube droop. Of these components, the breech and muzzle brake were replicated as correct mass and center of gravity (CG) simulators. This was done to reduce the total number of elements, which in turn reduced the run time of the model. These parts were complex and the actual shapes of the parts were not as relevant to the analysis as the mass and CG of the parts. The model used several constraints to tie the components together. The constraints essentially couple overlapping nodes from two independent parts. Each tie constraint has a master and slave associated with it. In a tie constraint, the overlapping nodes are joined together and master nodes can penetrate a slave surface. For this reason slave meshes are usually finer than the master mesh. The breech, bore evacuator, and muzzle brake were fixed to the gun tube at the appropriate positions. The gun tube was given material properties of steel.
The second part, the projectile assembly, consists of the body, fuze, and rotating band (Figures 19 and 20). Tie constraints, as in the gun tube assembly, were used to connect the parts for the projectile assembly. The body was the master surface. The rotating band and fuze were tied to the body at their correct locations. The TNT was not created as a separate part but was rather partitioned as part of the body and assigned a different material property. The material properties used in this analysis are included in Table 1. In addition, Appendix A contains figures of each one of the parts. Table 2 lists part and model characteristics used in the models.
Table 1  M284 Gun Tube and M795 Projectile Materials

<table>
<thead>
<tr>
<th>Part</th>
<th>M284 Gun Tube</th>
<th>Fuze</th>
<th>Projectile Body</th>
<th>Rotating Band</th>
<th>TNT</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulus</td>
<td>2.90E+07</td>
<td>1.01E+07</td>
<td>3.00E+07</td>
<td>1.81E+07</td>
<td>6.00E+05</td>
<td>PSI</td>
</tr>
<tr>
<td>Poisson’s Ratio</td>
<td>0.320</td>
<td>0.350</td>
<td>0.290</td>
<td>0.307</td>
<td>0.400</td>
<td>None</td>
</tr>
<tr>
<td>Density</td>
<td>0.0007320</td>
<td>0.0003750</td>
<td>0.0007340</td>
<td>0.0008347</td>
<td>0.0001507</td>
<td>lbf s²/in⁴</td>
</tr>
</tbody>
</table>

Table 2  Part and Model Characteristics

<table>
<thead>
<tr>
<th>Part</th>
<th>Elements</th>
<th>Nodes</th>
<th>Model Weight (lbs)</th>
<th>Part Weight (lbs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gun Tube</td>
<td>60420</td>
<td>75420</td>
<td>3240.5</td>
<td>3241.0</td>
</tr>
<tr>
<td>Bore Evacuator</td>
<td>4760</td>
<td>7509</td>
<td>223.6</td>
<td>224.0</td>
</tr>
<tr>
<td>Muzzle Brake</td>
<td>5376</td>
<td>7616</td>
<td>374.2</td>
<td>374.0</td>
</tr>
<tr>
<td>Breech</td>
<td>4512</td>
<td>6251</td>
<td>760.4</td>
<td>761.0</td>
</tr>
<tr>
<td>Projectile Body</td>
<td>35281</td>
<td>39390</td>
<td>101.5</td>
<td>102.1</td>
</tr>
<tr>
<td>Fuze/Dfuze</td>
<td>1844</td>
<td>2547</td>
<td>1.4</td>
<td>1.4</td>
</tr>
<tr>
<td>Shaved Band</td>
<td>1370</td>
<td>2160</td>
<td>0.6</td>
<td>part of projo</td>
</tr>
<tr>
<td>Shell</td>
<td>90</td>
<td>105</td>
<td>Total Degrees of Freedom</td>
<td></td>
</tr>
<tr>
<td>Overall Standard</td>
<td>117680</td>
<td>140788</td>
<td>434124</td>
<td></td>
</tr>
<tr>
<td>Overall Explicit</td>
<td>106490</td>
<td>126077</td>
<td>378573</td>
<td></td>
</tr>
</tbody>
</table>

5.3 STATIC ANALYSIS

As stated previously, the static analysis was the first analysis performed on the model to apply the effects of gravity to the gun tube to obtain the proper tube droop. This analysis included all parts of the gun tube and projectile assemblies. The projectile assembly was placed inside the gun tube so that the leading edge of the rotating band was one eight of an inch forward of the forcing cone, simulating proper projectile seating. The forcing cone is the region where the diameter of the breech transitions to the smaller diameter of the gun bore. The contact in the static analysis was defined between the interior surface of the gun tube and the outer surfaces of the rotating band and the projectile body. The only load applied to the
static model was a gravity vector that was applied to each part depending on the
elevation of the gun tube (0 and 70 degrees). The coordinate system was defined
with the “1” direction running parallel to the gun tube, the “2” direction
perpendicular to “1” going into the page, and the “3” direction perpendicular to “1”
and up (Figure 21). For the 0 degree QE gun tube, gravity (-386.2 in/s²) was
applied only in the “3” direction. The 70 degree elevation gun tube case needed
gravity to be broken down into its “1” and “3” components or (-362.909 in/s²) and
(-132.088 in/s²) respectively.

Two boundary conditions were applied to the static analysis to replicate the
experimental setup. The first was an encastre applied to the breech end of the gun
tube to prevent it from translating or rotating in any direction. This boundary
condition represents the position in which the gun tube would be held in the cradle
and the trunnions. Since this analysis is only looking at the acceleration while the
projectile is in the gun tube, the gun tube can be held in the “1” direction,
neglecting effects of recoil on the gun tube. 98% of the recoil occurs after the
projectile exits the gun tube according to a study done by ARDEC at the Yuma
Proving Grounds in 2005. The second boundary condition was needed to keep the projectile from moving in the “1” or “2” directions, but to leave it free to displace in the “3” direction due to gravity.

These analyses were run with a the default standard time period of one with the expected results. The muzzle of the gun tube at 0 degrees QE deflected more (0.1 in) than the muzzle of the gun tube at 70 degrees QE shown in Figures 22 and 23. These deformed gun tubes with gravity already applied were then imported into the explicit analysis.

![Figure 22](image1)
Figure 22  Deformed Gun Tube Due to Gravity at 0 Degrees Quadrant Elevation (Magnified x 100)

![Figure 23](image2)
Figure 23  Deformed Gun Tube Due to Gravity at 70 Degrees Quadrant Elevation (Magnified x 100)

5.4 EXPLICIT ANALYSIS

The second step in the modeling was the explicit analysis. This step simulated the projectile being fired. In this analysis, the deformed gun tube from
the static analysis was used. This analysis uses several tie constraints, boundary conditions, and loads. Similar to the static analysis, the rotating band and fuze are tied to the body of the projectile. The boundary conditions differ in this analysis because the projectile needs to be able to move in all directions, so only the gun tube is held encastre. Again, the projectile was placed in the tube 1/8” into the forcing cone as seen in Figure 24. General contact was used to define the contact surfaces in this model. General contact is a module in ABAQUS Explicit that automatically solves which parts are contacting each other. This saves on the time because each contacting surface does not have to be defined by the user.

![Figure 24 M795 Projectile in Gun Tube](image)

### 5.5 LOADS APPLIED

Three loads were applied to the explicit model: gravity, pressure to the base of the projectile (Figure 25) simulating the pressure from the propellant gases, and
a torque to the rotating band. Even though the gun tube is already deformed due to gravity, the gravity load must still be applied to the projectile. The applied pressure was taken from the experimental data and is shown in Figure 16. Since the rifling was not modeled, an outside force must be used to drive the rotation of the projectile assembly. The torque vs time curve used in this analysis was derived from the base pressure (Figure 16) and the resistive pressures. Later in the chapter, the implications of rifling vs smooth bore modeling will be discussed.

Several methods are available to impart a rotation on the projectile to simulate the effect of rifling. Through experimentation with these different
techniques, it was determined that applying a torque to the rotating band most closely resembled the actual rotation of the projectile. Based on the experimental data available, two other methods were considered to rotate the projectile. One of these methods used a rotational displacement boundary condition that forced the projectile to rotate from zero to 1.62 revolutions as it exited the gun tube in 12.05 msec. A second method was also a boundary condition, but it applied a known angular velocity curve to the projectile. Neither of these cases gave an acceptable result, since the projectile experienced balloting 300% greater than the nominal model and test results. A possible cause for this difference could be that the boundary conditions are forcing the projectile to follow a given path, while the applied load (Torque) allows the projectile to move more freely.

The torque, $T$, applied to the rotating band is the product of the polar moment of inertia, $I$, of the projectile and its angular acceleration, $\alpha$, (Carlucci and Jacobson, 2008).

$$T = I \alpha$$

(1)

The polar moment of inertia can be taken from the model, so that leaves only one unknown, which is the angular acceleration, $\alpha$.

The axial force on the projectile is

$$F = p_s A$$

(2)

Where $p_s$ is the base pressure acting on the projectile defined by the Lagrange approximation, $A$, is the bore diameter, and, $c$, is the charge mass.
\[ p_s = p_T \left( \frac{1}{1 + \frac{c}{2m}} \right) \]  \hspace{1cm} (3)

The D’Alembert force is the acceleration force that exactly equals the pressure force

\[ a = \frac{p_s A}{m} \]  \hspace{1cm} (4)

For a spin stabilized projectile, the angular acceleration is proportional to the linear acceleration, \( a \)

\[ \alpha = Ka \]  \hspace{1cm} (5)

Then

\[ \alpha = K \frac{p_s A}{m} \]  \hspace{1cm} (6)

\( K \) has units of \( \text{length}^{-1} \) and depends on the twist of the rifling, \( n \), (calibers of travel per turn), and the bore diameter, \( d \)

\[ K = \tan \theta = \frac{2\pi}{nd} \]  \hspace{1cm} (7)

\( \theta \) is the angle between the circumferential twist distance and the axial distance. Thus, the angular acceleration from Equations (6) and (7) can be calculated with the total pressure, \( p_t \), area of the bore, \( A \), mass of the projectile, \( m \), twist of the rifling, \( n \), (calibers of travel per turn), and the bore diameter, \( d \), giving:

\[ \alpha = \frac{2\pi}{nd} \frac{p_t A}{m} \]  \hspace{1cm} (8)
This leaves one unknown, the total pressure, which is the base pressure minus resistive pressure to be determined. The resistive pressure is not known but can be estimated using PRODAS, a lumped-parameter, interior ballistic computer code. The process was to create a model in PRODAS that outputs the same pressure-time curve as the experimental data. One of the parameters that PRODAS calculates is the empirically derived resistive pressures as plotted in Figure 26. Therefore, the total pressure could be derived from PRODAS. The resistive pressure in PRODAS is based on empirical measurements gained through strain gages mounted on the outside of the gun tube. Resistive pressure is not pressure in the true sense but is the resistive forces normalized by the bore area. These forces include the engraving force and friction.

Figure 26  Base, Resistive and Total Pressures as calculated by PRODAS
Once the total pressure was found, the angular acceleration was calculated using Equation (8). Then, substituting Equation (8) back into Equation (1), a function for torque vs time was determined as shown in Equation (9) and Figure 27.

\[ T = I \frac{2\pi Ap}{nd m} \]  

(9)

Where the units for torque are as follows,

\[ T = \left[ \text{lbf} \cdot \text{s}^2 \cdot \text{in} \right] \left[ \text{in} \right] \left[ \text{lb} \right] \left[ \text{lb} \cdot \text{ft} \right] \left[ \text{in} \right] = \text{lb} \cdot \text{in} \]

![Figure 27  Derived Torque vs Time](image)

**5.6 MODEL OUTPUT**

Once the model was assembled and boundary conditions, loads, and constraints had been applied, the simulated output data had to be validated against the experimental results. The experimental data available were acceleration data in the axial and both radial directions from the nose of the projectile. Initially, the model was set up to record history data in the fuze of the projectile by defining
nodes at the center and at two radial directions 90 degrees apart at the base of the fuze. The axial accelerations closely matched the experimental results but the radial accelerations were centered on the 0-acceleration line. The radial experimental data rolls off the 0-acceleration line and is offset due to the rotation of the projectile as it travels through the gun tube. Simply put, the nodes of interest were following a global coordinate system as the projectile rotated. Thus, the model was not consistent with the OBR data, which shows this bias due to spin because the radial accelerometers are intentionally mounted off the centerline.

To fix this problem, an accelerometer connector was connected to a shell element that was attached to the base of the fuze (Figure 28). This allowed the shell element to get more than the three Degrees of Freedom (DOFs) per node than the eight node brick elements allow. The accelerometer connectors were attached in the “2” and “3” directions. The location was the same as the DFuze 0.477 inches from the centerline of the fuze. As can be seen in the results chapter, these radial accelerations better match the experimental data. In addition, the accelerometer connectors better mimic the way the DFuze would record acceleration data, because they record the data in a local coordinate system that rotates with the projectile.
5.7 ENGRAVING AND RIFLING IN ABAQUS

A projectile undergoes a high pressure resistance as it begins its travel down the gun tube as shown in Figure 27. This resistance is due to the engraving that the rotating band undergoes as it is forced into the rifling of the gun tube. The M284 cannon has a rifled diameter of 6.1 inches but the grooves are 6.2 inches in diameter. However, the model used for this research is representative of a smooth bore gun tube with an internal diameter of 6.1 inches. Several attempts were made in ABAQUS to model a fully rifled gun tube that would engrave the rotating band. However, the current modeling techniques and computation power would not allow a model to output results that were comparable to the experimental data in the time needed to complete this research.
The rifled and engraved model included an additional step before the two loads were applied. This step simulated the ramming of a projectile. It was needed to force the outer diameter (6.22 in) of the rotating band into the forcing cone and rifling (6.1 in). In this model, the rotating band was not shaved, and because element deletion was needed to correctly simulate engraving, the rotating band needed a very fine mesh. Once the projectile was rammed the pressure and gravity loads were applied to the model in the same manner as the afore mentioned models. This model consisted of 3.5 million DOFs and took approximately 15 days using 128 processors to run. After several iterations, the rotating band mesh was modified such that the mesh was the same as the channel that the rifling would cut into the band. Essentially this method, pre-meshed the engraved portion of the rotating band. Even though the engraving event was successful, the projectile would come to a rest after 60 inches of travel in 12.5 ms.

Since the rifling and engraving technique was not successful, this analysis used a smooth bore gun tube design. As will be seen in the following chapter, this technique more than adequately represents the interior ballistic dynamics of a projectile and gun tube. However, a few factors had to be modified in order for this to succeed. First, the gun tube had to be made into a solid interior surface with an inner diameter of 6.1 inches. In addition, since the model did not include engraving, the rotating band had to be matched to the same diameter as the gun tube to simulate the correct bearing loads. As stated above in the computation of torque, the engraving forces were included in the resistive pressure as well as the
friction as the projectile travels down the gun tube. Thus, the torque and pressure curves applied in this model implicitly take into account the engraving and other resistive forces.
CHAPTER 6: MODEL VALIDATION

The experimental data from the M795 fired from a M284 cannon at PIMP +5% was used not only as input to the 3D Finite Element Model (FEM), but also used as a baseline for comparison to see how closely the model matched the experimental data. The comparison between the model and experimental data is defined at the front of the projectile. Validation of this analysis requires the system response and structural transform function to match test data. The data recorded from the model closely matched the experimental data as shown in Table 3. At muzzle exit, the analysis is 1 m/s greater than the experimental data, which accounts for the faster exit time. In addition, the slower rotational velocity of the model accounts for less rotation.

Table 3 Experimental and Model Data Check

<table>
<thead>
<tr>
<th></th>
<th>Muzzle Exit</th>
<th>Rotational Velocity</th>
<th>Gun Tube Travel (199.5in)</th>
<th>Rotation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental</td>
<td>830 m/s</td>
<td>267 Hz</td>
<td>12.06 msec</td>
<td>1.62 rev</td>
</tr>
<tr>
<td>FE Model</td>
<td>831 m/s</td>
<td>263 Hz</td>
<td>12.04 msec</td>
<td>1.61 rev</td>
</tr>
</tbody>
</table>

The basic launch data can be seen to match the experimental data well. This is necessary in order to meet the true goals of this research, which is characterization of projectile dynamics. The dynamics of the projectile during launch is the main concern. The accuracy of the model can be assessed by comparison of the axial and radial accelerations to the experimental data. Model output data generally contains high frequency noise, an artifact of the explicit solver’s calculation method, which obscures the true results. This data must be
filtered before a proper comparison with experiment can be made. This analysis used a Chebyshev filter with a cutoff frequency of 2,000 Hz. Both the experimental data and model data were passed though this low pass filter in order to put the two in the same context. A cutoff frequency of 2,000 Hz was used to filter out the noise, yet retain valid data. MathCAD with a software toolbox called Kornucopia was used to do the post processing of the model data. Kornucopia was specifically designed to perform digital signal processing. 2,000 Hz is used as the cutoff frequency for all data processing. This frequency is typically accepted as a cutoff for experimental validation of dynamic mechanical systems, except in rare instances.

The axial accelerations between the model and the experimental data correlate well as shown in Figure 29. The curves do not differ by more than 250 Gs, which is less than 2%.

![Figure 29 Axial Acceleration: Model and Experimental](image)
The radial accelerations, however do not match as well as shown in Figure 30. Although the two curves generally have the same magnitudes, frequencies and follow the same general trend through muzzle exit. Balloting or radial accelerations in general are harder to match to the experimental data due to their more random nature. Axial accelerations are less sensitive to unknowns than radial accelerations. What is meant by this is that model data is ideal data whereas the experimental data could contain errors or circumstances that are unknown. For example, the projectile that was fired could have had a projectile whose CG was not on the centerline or the projectile was improperly rammed. In most experiments the projectile’s CG is not measured.

Figure 30  Radial Acceleration: Model and Experimental

Another check to ensure there are no significant errors in either the model or experimental data is to double integrate the axial acceleration with respect to time and compare the results to the positional data. Ideally, the curves should
match which confirms if there are any errors in the data or if filtering the data caused any valid data to be lost. The double integration produced a displacement curve that matched the expected result of the projectile displacing 199.5 inches in 12.05 msec as shown in Figures 31 and 32.

Figure 31  Double Integration of Model Data

Figure 32  Double Integration of Experimental Data
The comparisons between the experimental data and the model suggest a good correlation. Now validated, the model was used as the baseline for comparisons in the results section.
CHAPTER 7: MODEL VARIATIONS AND PARAMETERS

Recall two different cases of the gun tube were used in this analysis, a 0 degree QE and 70 degree QE. The gun tube in the baseline model and in the experimental data were considered new gun tubes. This means the inner diameter of the gun tube is 6.1 inches and is considered a 1\textsuperscript{st} Quartile gun tube. As the tube becomes worn the inner diameter increases. When the gun tube nears the end of its expected life, it is considered a 4\textsuperscript{th} Quartile gun tube. This research not only looks at the 1\textsuperscript{st} Quartile gun tubes at 0 and 70 degrees QE, but also includes a 4\textsuperscript{th} Quartile gun tube with a inner diameter of 6.197 inches. This leads to four different scenarios for the model; 0 degrees QE, 1\textsuperscript{st} Quartile; 70 degrees QE, 1\textsuperscript{st} Quartile; 0 degrees QE, 4\textsuperscript{th} Quartile; and 70 degrees QE, 4\textsuperscript{th} Quartile.

To look further into the effects of balloting, other parameters of the projectile and variations thereof need to be explored. These variations include CG axial forward (plus) and reward (minus) with the constant mass, wheel base length increase (plus) and decrease (minus) with the constant mass, band location forward (plus) and rearward (minus) with the constant mass, length of the projectile (short and longer) and CG radial offset with the constant mass. Figure 33 and Table 4 describe the parameters and variations thereof that were used. Tactical M795 HE projectiles weigh approximately 103.5 lbs. Table 3 shows that the nominal projectile in the model weighs 101.5 lbs. The weight in the table represents the weight of the projectile without a fuze (1.4 lbs) and a rotating band (0.6 lbs) while the 103.5 lbs represents a fuzed round with a rotating band.
Table 4  Model Parameters and Variations

<table>
<thead>
<tr>
<th>Parameter</th>
<th>CG</th>
<th>Wheel Base</th>
<th>Band Location</th>
<th>Length</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Variation</td>
<td>(in)</td>
<td>(in)</td>
<td>(in)</td>
<td>(in)</td>
<td>(lbs)</td>
</tr>
<tr>
<td>Nominal</td>
<td>11.31</td>
<td>5.33</td>
<td>2.029</td>
<td>29.40</td>
<td>101.5</td>
</tr>
<tr>
<td>CG Axial-Minus</td>
<td>10.65</td>
<td>5.33</td>
<td>2.029</td>
<td>29.40</td>
<td>101.5</td>
</tr>
<tr>
<td>CG Axial-Plus</td>
<td>11.96</td>
<td>5.33</td>
<td>2.029</td>
<td>29.40</td>
<td>101.5</td>
</tr>
<tr>
<td>Wheel Base-Minus</td>
<td>11.31</td>
<td>4.97</td>
<td>2.029</td>
<td>29.40</td>
<td>101.5</td>
</tr>
<tr>
<td>Wheel Base-Plus</td>
<td>11.31</td>
<td>5.90</td>
<td>2.029</td>
<td>29.40</td>
<td>101.5</td>
</tr>
<tr>
<td>Band Loc-Minus</td>
<td>11.31</td>
<td>5.33</td>
<td>1.800</td>
<td>29.40</td>
<td>101.5</td>
</tr>
<tr>
<td>Band Loc-Plus</td>
<td>11.31</td>
<td>5.33</td>
<td>2.300</td>
<td>29.40</td>
<td>101.5</td>
</tr>
<tr>
<td>Body Long</td>
<td>11.54</td>
<td>5.33</td>
<td>2.029</td>
<td>30.90</td>
<td>102.7</td>
</tr>
<tr>
<td>Body Short</td>
<td>11.14</td>
<td>5.33</td>
<td>2.029</td>
<td>28.04</td>
<td>100.7</td>
</tr>
<tr>
<td>CG Radial Offset (0.148)</td>
<td>11.31</td>
<td>5.33</td>
<td>2.029</td>
<td>29.40</td>
<td>101.5</td>
</tr>
</tbody>
</table>

Normally each variation only has one modified parameter. That is not the case for the projectile length variation, because the density was not changed. The CG and mass of the projectile changed as material was taken out and added to the nose of the projectile to make it shorter and longer. The CG axial variation was modified by moving the CG closer to the base (minus) or further from the base.
(plus). The wheel base variation was modified by moving the forward bourrelet forward (plus) and back to the base (minus). The band location variation was modified by moving the band location measured from the base of the projectile to the seat of the rotating band, towards the base (minus) and further away (plus). The CG radial offset variation was modified by changing the TNT density in the radial direction without changing the overall mass. These dimensions can be seen in Table 3.

There are four different gun tube configurations and ten different projectile variations. Each gun tube configuration therefore has ten projectile cases. Thus, forty different iterations were run with this model (Appendix C-F).
CHAPTER 8: 3D FINITE ELEMENT MODEL RESULTS

The 3D FE model was used to simulate a projectile, of various configurations fired in a gun tube, at various conditions in order to analyze the internal dynamics of the projectile. Forty different cases were run, consisting of four different gun tube configurations and ten different projectile variations. The axial acceleration results from all forty runs were compared and all forty axial acceleration curves were almost identical. This was an expected result because the parameters that were modified should not have affected the axial accelerations greatly. Because they were similar, they will not be presented in the results section, but can be found in Appendix B-F for all four gun tube configurations. The only exception was the body length variations. Since these two variations had different masses, the axial accelerations were slightly different than the rest of the model. This was as expected as the lower mass projectile experienced increased acceleration and the heavier projectile experienced decreased acceleration as compared to the baseline. This section will focus on the radial accelerations, comparing each variation to the nominal case of the appropriate gun tube configuration to determine which parameters and variations thereof affect balloting. Also, the results from the 1st Quartile gun tubes and the 4th Quartile gun tubes were very similar to each other and followed the same trends. A complete listing of the results can be found in Appendix C-F.
8.1 NOMINAL GUN TUBE COMPARISON

The first conditions to be compared were the different gun tube configurations to determine how firing at different elevations affects balloting. The higher elevation gun tube at 70 degrees has slightly less magnitude in balloting than the 0 degree gun tube as shown in Figure 34. The projectiles start out similarly, but around 8 msec the 0 degree elevation tube has increased the magnitude of balloting. As the projectile nears muzzle exit, the increase in balloting is more prominent and easily discernable. This trend is consistent in the 4th Quartile gun tube configurations.

![Figure 34 Radial Acceleration: 0 and 70 Degree Elevation](image)

8.2 CG AXIAL VARIATION COMPARISON

CG axial variation was achieved by moving the CG from the nominal position closer to base of the projectile and by moving the CG further from the base of the projectile. As the CG moved further from the base of the projectile, the
magnitude of the balloting increased as shown in Figures 35-37. As the CG is moved closer to the base of the projectile, the magnitude of balloting is decreased. As the projectile reaches muzzle exit, the magnitude of balloting in the CG axial plus variation nearly doubled that of the nominal case as shown in Figure 36.

Figure 35  Radial Acceleration: Axial Minus and Nominal

Figure 36  Radial Acceleration: Axial Plus and Nominal
8.3 WHEEL BASE VARIATION COMPARISON

The wheel base variations were modified by moving the forward bourrelet. The forward bourrelet was moved rearward toward the base (minus) and was moved forward toward the nose (plus). The wheel base minus variation is close to the radial acceleration curve of the nominal case as seen in Figure 38. The wheel base plus variation has slightly less balloting than the nominal or minus configuration. The decrease in magnitude of balloting near muzzle exit is slightly more pronounced than the rest of the curve. This is consistent in all four gun tube configurations.
8.4 BAND LOCATION VARIATION COMPARISON

The band location variation was modified by moving the band seat closer to the base of the projectile and moving the band seat further from the base of the projectile. There is little difference in the band location plus variation and the band location minus variation in terms of magnitude of balloting as seen in Figure 39. This is consistent in all four gun tube configurations.
8.5 PROJECTILE BODY LENGTH VARIATION COMPARISON

The body length variation was modified by removing and adding length to the ogive of the projectile. These results are consistent with the CG axial variation, and the balloting performed in much the same manner. The shorter projectile, which had a CG closer to the base as seen in Figures 40-42 has decreased balloting. The longer projectile, which has a CG further from the base, had increased balloting.
Figure 40  Radial Acceleration: Body Short and Nominal

Figure 41  Radial Acceleration: Body Long and Nominal
8.6 CG RADIAL OFFSET VARIATION COMPARISON

The CG radial offset was 0.148 inches in the “3” direction. The TNT density was increased in the top half of the projectile and decreased in the bottom half of the projectile until the correct mass and offset was obtained. This variation clearly has the most dramatic effect (Figures 43 and 44). From first motion, the balloting has a greater magnitude. Toward muzzle exit, the balloting completely departs from the nominal curve. Also near muzzle exit, the projectile is seen to severely impact into the gun tube wall. Figure 44 shows more clearly than the other cases the phase lag in the accelerations recorded by the perpendicular accelerometer connectors. The CG radial offset causes a faster balloting frequency than observed in the other variations. This could be one reason the out of phase frequencies are more prominent in the CG radial offset variation.
This trend is consistent in all four gun tube configurations. This was an expected result as it confirms what many engineers took as a rule of thumb about requiring the CG to lie on the centerline of the projectile. This balloting caused by this parameter could be the major contributor to many electronic components failing in mechanical ways.
CHAPTER 9: SUMMARY OF RESULTS, CONCLUSIONS AND RECOMMENDATIONS

The research into the effects of balloting has resulted in the development of a 3D FE model that simulates the firing of a projectile in a gun tube.

9.1 3D FE MODEL VALIDATION

1. A 3D FE model that simulates the firing of a projectile in a gun tube that can be used to analyze the internal dynamics has been developed and validated.

2. Features of the model include:
   a. The ability to be tailored to accommodate different cannons and projectiles. The model is easily modified to switch out components as necessary.
   b. Given the current configuration of the model, the architecture of the model allows individual runs to be made in less than an hour.
   c. The inputs to the model include pressure and torque with respect to time. The model can be easily modified to fire any propelling charge that is desired. This is done by modifying the pressure and torque curves.
   d. Outputs of the model include rotational and translation displacements and velocity as well as axial and radial accelerations. The model can be tailored to change the output parameters by modifying the history output fields in ABAQUS.
3. With regard to muzzle velocity, rotation, rotational velocity, displacement and muzzle exit time, the comparison between the 3D FE model and the experimental data is excellent.

4. With regard to axial accelerations, the 3D FE model and the experimental data have a good correlation with a maximum difference of less than 2%.

5. With regard to radial accelerations, the 3D FE model and experimental data correlates and generally follows the same magnitudes frequencies and trend, but does contain some differences. These differences can probably be attributed to unknown errors that might have been present during the test, such as unknown projectile mass properties and CG location. However, the general trends and magnitudes of the curves are in good enough agreement to consider the model valid.

6. With regard to aliasing or errors in data, the double integration of the axial acceleration with respect to time closely correlates to the 3D model and experimental data expected displacements. The in bore travel distance of 199.5 inches was traveled in 12.05 msec, which closely matches both the integrated data and the measured data.

**9.2 3D FE MODEL RESULTS**

1. With regard to the nominal projectile and the four gun tube conditions, the results show a slight increase in balloting when the projectile is fired from a gun tube at 0 degrees elevation. This is expected as the gravity vector is
entirely in the negative “3” direction when the gun tube is at 0 degrees elevation. While at 70 degrees elevation, most of the gravity vector is in the negative "1" direction and only partially in the negative “3” direction causing the projectile to react against gravity. The same trend was present in the 4th Quartile gun tube configurations.

2. With regard to the CG axial variation, the results show that as the CG moves closer to the base of the projectile, the magnitude of the balloting decreases. Conversely, as the CG moves further away from the base of the projectile, the magnitude of the balloting increased. The same trend was present in all gun tube configurations.

3. With regard to the wheel base variation, the results show a slight decrease in the magnitude of balloting when the wheel base was increased. The same trend was present in all gun tube configurations.

4. With regard to the band location variation, the results show little difference in magnitude of balloting from the nominal case. The same trend was present in all gun tube configurations.

5. With regard to the projectile body length variation, the results show the same trend as did the CG axial variation. As the CG moves closer to the base of the projectile, the magnitude of the balloting decreases. As the CG moves further away from the base of the projectile, the magnitude of the balloting is increases. The same trend was present in all gun tube configurations.
6. With regard to the CG radial offset, the results show that this variation was the most significant and produced the most dramatic change in magnitude of balloting. As the projectile begins travel, there is an immediate increase in balloting of the projectile. This increase in balloting follows the projectile throughout its travel. As the projectile approached muzzle exit, the magnitude of balloting increased so much that it departed completely from the nominal curve. In addition, the balloting exhibited on the projectile appeared at a higher frequency than during any other variations. It should be noted that very close to muzzle exit, the projectile impacts the gun tube wall violently.

9.3 CONCLUSIONS

With regard to the 3D FE model and the experimental data, the results for the baseline corresponded excellently in most key categories. Only in the radial directions are there any appreciable discrepancies, but the curves have a close enough fit and follow the same trend that the model is still considered valid.

It is evident that the CG radial offset variation is the most significant contributor to balloting. This is followed by the CG axial variation and the projectile body variation, followed by the wheel base length and lastly the band location.

9.4 RECOMMENDATIONS

This research developed a tool for design engineers to improve their understanding of the highly dynamic response of projectiles during gun launch.
The 3D FE model has been developed to simulate the firing of a projectile in a gun tube to understand the interior ballistic dynamic responses. The model can accommodate different cannons and different projectiles as well as various propelling charges. The one aspect that needs to be further researched is the engraving event and subsequent rotating caused by rifling. This may now be possible with the new Coupled Eulerian-Lagrangian technique that ABAQUS has recently added to the software.

To fully calibrate this model, more data needs to be collected on the M795 projectile as well as other projectiles. This data would need to include all firing zones. This would give good confidence to the predictive nature of this tool under all circumstances.

This research was designed to study the parameters that affect balloting to help engineering understand and better design projectiles to minimize projectile failures. The most important parameter that must be considered is to ensure the CG is not offset radially. The CG must be as close to the centerline of the projectile as possible. Tolerances must be held tight and inspected to ensure that they are correct. The other parameters should be considered in developing a new projectile as well to minimize balloting. Although beyond the scope of this research, these parameters should be combined in a design of experiments to see if they affect each other. By analyzing combinations of these parameters, an engineer should be able to minimize the balloting on any new projectiles.
REFERENCES


APPENDIX A: 3D FE MODEL PARTS

Each of the parts that were used in this research are shown in this Appendix. The M284 cannon assembly consisted of the gun tube and three subcomponents; the breech, bore evacuator, and the muzzle brake. The M795 projectile assembly consisted of the body and three subcomponents; the fuze, shaved band, and the shell element. The TNT inside the body was not modeled as a separate part. The body was partitioned and the TNT regions were given different material properties.
Figure 45  M284 Cannon Assembly:  Gun Tube

Figure 46  M284 Cannon Assembly:  Mock Muzzle Brake
Figure 47  M284 Cannon Assembly: Bore Evacuator

Figure 48  M284 Cannon Assembly: Mock Breech
Figure 49  M795 Projectile: Body with TNT

Figure 50  M795 Projectile: Body
Figure 51  M795 Projectile: Fuze

Figure 52  M795 Projectile: Shaved Rotating Band
Figure 53  M795 Projectile: Shell Elements
APPENDIX B: EXPERIMENTAL
DATA FILTERED AT 2,000 HZ

The results for the experimental data using a Chevyshev low pass filter are included in this Appendix. These graphs include the accelerations in the axial and both radial directions.
Figure 54  Experimental Data M284/M795 PIMP+5% Axial

Figure 55  Experimental Data M284/M795 PIMP+5% Radial 1

Figure 56  Experimental Data M284/M795 PIMP+5% Radial 2
Appendix C includes the results for the FE Model at 0 degrees QE, 1st Quartile gun tube using a Chevyshev low pass filter at 2,000 Hz. These graphs include the accelerations in the axial and both radial directions for all parameters and variations. They are listed in the following order:

1. Nominal
2. CG Axial Minus
3. CG Axial Plus
4. Band Location Minus
5. Band Location Plus
6. Projectile Body Long
7. Projectile Body Short
8. Wheel Base Minus
9. Wheel Base Long
10. CG Radial Offset
Figure 57  0 Degrees QE 1st Quartile, Nominal, Axial

Figure 58  0 Degrees QE 1st Quartile, Nominal, Radial 1

Figure 59  0 Degrees QE 1st Quartile, Nominal, Radial 2
Figure 60  0 Degrees QE 1\textsuperscript{st} Quartile, CG Axial Minus, Axial

Figure 61  0 Degrees QE 1\textsuperscript{st} Quartile, CG Axial Minus, Radial 1

Figure 62  0 Degrees QE 1\textsuperscript{st} Quartile, CG Axial Minus, Radial 2
Figure 63  0 Degrees QE 1st Quartile, CG Axial Plus, Axial

Figure 64  0 Degrees QE 1st Quartile, CG Axial Plus, Radial 1

Figure 65  0 Degrees QE 1st Quartile, CG Axial Plus, Radial 2
Figure 66  0 Degrees QE 1st Quartile, Band Location-Minus, Axial

Figure 67  0 Degrees QE 1st Quartile, Band Location-Minus, Radial 1

Figure 68  0 Degrees QE 1st Quartile, Band Location-Minus, Radial 2
Figure 69  0 Degrees QE 1st Quartile, Band Location-Plus, Axial

Figure 70  0 Degrees QE 1st Quartile, Band Location-Plus, Radial 1

Figure 71  0 Degrees QE 1st Quartile, Band Location-Plus, Radial 2
Figure 72  0 Degrees QE 1st Quartile, Body-Long, Axial

Figure 73  0 Degrees QE 1st Quartile, Body-Long, Radial 1

Figure 74  0 Degrees QE 1st Quartile, Body-Long, Radial 2
Figure 75  0 Degrees QE 1st Quartile, Body-Short, Axial

Figure 76  0 Degrees QE 1st Quartile, Body-Short, Radial 1

Figure 77  0 Degrees QE 1st Quartile, Body-Short, Radial 2
Figure 81  0 Degrees QE 1st Quartile, Wheel Base-Plus, Axial

Figure 82  0 Degrees QE 1st Quartile, Wheel Base-Plus, Radial 1

Figure 83  0 Degrees QE 1st Quartile, Wheel Base-Plus, Radial 2
Figure 84  0 Degrees QE 1st Quartile, CG Radial Offset, Axial

Figure 85  0 Degrees QE 1st Quartile, CG Radial Offset, Radial 1

Figure 86  0 Degrees QE 1st Quartile, CG Radial Offset, Radial 2
APPENDIX D: FE MODEL RESULTS
70 DEGREES QE 1ST QUARTILE GUN
TUBE FILTERED AT 2,000 HZ

Appendix D includes the results for the FE Model at 70 degrees QE, 1st Quartile gun tube using a Chevyshev low pass filter at 2,000 Hz. These graphs include the accelerations in the axial and both radial directions for all parameters and variations. They are listed in the following order:

1. Nominal
2. CG Axial Minus
3. CG Axial Plus
4. Band Location Minus
5. Band Location Plus
6. Projectile Body Long
7. Projectile Body Short
8. Wheel Base Minus
9. Wheel Base Long
10. CG Radial Offset
Figure 87 70 Degrees QE 1st Quartile, Nominal, Axial

Figure 88 70 Degrees QE 1st Quartile, Nominal, Radial 1

Figure 89 70 Degrees QE 1st Quartile, Nominal, Radial 2
Figure 90  70 Degrees QE 1st Quartile, CG Axial-Minus, Axial

Figure 91  70 Degrees QE 1st Quartile, CG Axial-Minus, Radial 1

Figure 92  70 Degrees QE 1st Quartile, CG Axial-Minus, Radial 2
Figure 93  70 Degrees QE 1st Quartile, CG Axial-Plus, Axial

Figure 94  70 Degrees QE 1st Quartile, CG Axial-Plus, Radial 1

Figure 95  70 Degrees QE 1st Quartile, CG Axial-Plus, Radial 2
Figure 96  70 Degrees QE 1st Quartile, Band Location -Minus, Axial

Figure 97  70 Degrees QE 1st Quartile, Band Location -Minus, Radial 1

Figure 98  70 Degrees QE 1st Quartile, Band Location -Minus, Radial 2
Figure 99  70 Degrees QE 1st Quartile, Band Location -Plus, Axial

Figure 100  70 Degrees QE 1st Quartile, Band Location -Plus, Radial 1

Figure 101  70 Degrees QE 1st Quartile, Band Location-Plus, Radial 2
Figure 102 70 Degrees QE 1st Quartile, Body-Long, Axial

Figure 103 70 Degrees QE 1st Quartile, Body-Long, Radial 1

Figure 104 70 Degrees QE 1st Quartile, Body-Long, Radial 2
Figure 105  70 Degrees QE 1st Quartile, Body-Short, Axial

Figure 106  70 Degrees QE 1st Quartile, Body-Short, Radial 1

Figure 107  70 Degrees QE 1st Quartile, Body-Short, Radial 2
Figure 108  70 Degrees QE 1st Quartile, Wheel Base-Minus, Axial

Figure 109  70 Degrees QE 1st Quartile, Wheel Base-Minus, Radial 1

Figure 110  70 Degrees QE 1st Quartile, Wheel Base-Minus, Radial 2
Figure 111  70 Degrees QE 1st Quartile, Wheel Base-Plus, Axial

Figure 112  70 Degrees QE 1st Quartile, Wheel Base-Plus, Radial 1

Figure 113  70 Degrees QE 1st Quartile, Wheel Base-Plus, Radial 2
Figure 114  70 Degrees QE 1st Quartile, CG Radial Offset, Axial

Figure 115  70 Degrees QE 1st Quartile, CG Radial Offset, Radial 1

Figure 116  70 Degrees QE 1st Quartile, CG Radial Offset, Radial 2
Appendix E includes the results for the FE Model at 0 degrees QE, 4th Quartile gun tube using a Chevyshev low pass filter at 2,000 Hz. These graphs include the accelerations in the axial and both radial directions for all parameters and variations. They are listed in the following order:

1. Nominal
2. CG Axial Minus
3. CG Axial Plus
4. Band Location Minus
5. Band Location Plus
6. Projectile Body Long
7. Projectile Body Short
8. Wheel Base Minus
9. Wheel Base Long
10. CG Radial Offset
Figure 117  0 Degrees QE 4\textsuperscript{th} Quartile, Nominal, Axial

Figure 118  0 Degrees QE 4\textsuperscript{th} Quartile, Nominal, Radial 1

Figure 119  0 Degrees QE 4\textsuperscript{th} Quartile, Nominal, Radial 2
Figure 120  0 Degrees QE 4\textsuperscript{th} Quartile, CG Axial-Minus, Axial

Figure 121  0 Degrees QE 4\textsuperscript{th} Quartile, CG Axial-Minus, Radial 1

Figure 122  0 Degrees QE 4\textsuperscript{th} Quartile, CG Axial-Minus, Radial 2
Figure 123  0 Degrees QE 4th Quartile, CG Axial-Plus, Axial

Figure 124  0 Degrees QE 4th Quartile, CG Axial-Plus, Radial 1

Figure 125  0 Degrees QE 4th Quartile, CG Axial-Plus, Radial 2
Figure 126  0 Degrees QE 4th Quartile, Band Location-Minus, Axial

Figure 127  0 Degrees QE 4th Quartile, Band Location-Minus, Radial 1

Figure 128  0 Degrees QE 4th Quartile, Band Location-Minus, Radial 2
Figure 129  0 Degrees QE 4th Quartile, Band Location-Plus, Axial

Figure 130  0 Degrees QE 4th Quartile, Band Location-Plus, Radial 1

Figure 131  0 Degrees QE 4th Quartile, Band Location-Plus, Radial 2
Figure 132  0 Degrees QE 4th Quartile, Body-Long, Axial

Figure 133  0 Degrees QE 4th Quartile, Body-Long, Radial 1

Figure 134  0 Degrees QE 4th Quartile, Body-Long, Radial 2
Figure 135  0 Degrees QE 4\textsuperscript{th} Quartile, Body-Short, Axial

Figure 136  0 Degrees QE 4\textsuperscript{th} Quartile, Body-Short, Radial 1

Figure 137  0 Degrees QE 4\textsuperscript{th} Quartile, Body-Short, Radial 2
Figure 138  0 Degrees QE 4\textsuperscript{th} Quartile, Wheel Base-Minus, Axial

Figure 139  0 Degrees QE 4\textsuperscript{th} Quartile, Wheel Base-Minus, Radial 1

Figure 140  0 Degrees QE 4\textsuperscript{th} Quartile, Wheel Base-Minus, Radial 2
Figure 141  0 Degrees QE 4\textsuperscript{th} Quartile, Wheel Base-Plus, Axial

Figure 142  0 Degrees QE 4\textsuperscript{th} Quartile, Wheel Base-Plus, Radial 1

Figure 143  0 Degrees QE 4\textsuperscript{th} Quartile, Wheel Base-Plus, Radial 2
Figure 144  0 Degrees QE 4\textsuperscript{th} Quartile, CG Radial Offset, Axial

Figure 145  0 Degrees QE 4\textsuperscript{th} Quartile, CG Radial Offset, Radial 1

Figure 146  0 Degrees QE 4\textsuperscript{th} Quartile, CG Radial Offset, Radial 2
APPENDIX F: FE MODEL RESULTS
70 DEGREES QE 4th QUARTILE GUN
TUBE FILTERED AT 2,000 HZ

Appendix F includes the results for the FE Model at 70 degrees QE, 4th Quartile gun tube using a Chevyshev low pass filter at 2,000 Hz. These graphs include the accelerations in the axial and both radial directions for all parameters and variations. They are listed in the following order:

1. Nominal
2. CG Axial Minus
3. CG Axial Plus
4. Band Location Minus
5. Band Location Plus
6. Projectile Body Long
7. Projectile Body Short
8. Wheel Base Minus
9. Wheel Base Long
10. CG Radial Offset
Figure 147 70 Degrees QE 4th Quartile, Nominal, Axial

Figure 148 70 Degrees QE 4th Quartile, Nominal, Radial 1

Figure 149 70 Degrees QE 4th Quartile, Nominal, Radial 2
Figure 150  70 Degrees QE 4th Quartile, CG Axial-Minus, Axial

Figure 151  70 Degrees QE 4th Quartile, CG Axial-Minus, Radial 1

Figure 152  70 Degrees QE 4th Quartile, CG Axial-Minus, Radial 2
Figure 153  70 Degrees QE 4th Quartile, CG Axial-Plus, Axial

Figure 154  70 Degrees QE 4th Quartile, CG Axial-Plus, Radial 1

Figure 155  70 Degrees QE 4th Quartile, CG Axial-Plus, Radial 2
Figure 156  70 Degrees QE 4th Quartile, Band Location-Minus, Axial

Figure 157  70 Degrees QE 4th Quartile, Band Location-Minus, Radial 1

Figure 158  70 Degrees QE 4th Quartile, Band Location-Minus, Radial 2
Figure 159  70 Degrees QE 4th Quartile, Band Location-Plus, Axial

Figure 160  70 Degrees QE 4th Quartile, Band Location-Plus, Radial 1

Figure 161  70 Degrees QE 4th Quartile, Band Location-Plus, Radial 2
Figure 162 70 Degrees QE 4th Quartile, Body-Long, Axial

Figure 163 70 Degrees QE 4th Quartile, Body-Long, Radial 1

Figure 164 70 Degrees QE 4th Quartile, Body-Long, Radial 2
Figure 165  70 Degrees QE 4\textsuperscript{th} Quartile, Body-Short, Axial

Figure 166  70 Degrees QE 4\textsuperscript{th} Quartile, Body-Short, Radial 1

Figure 167  70 Degrees QE 4\textsuperscript{th} Quartile, Body-Short, Radial 2
Figure 168  70 Degrees QE 4\textsuperscript{th} Quartile, Wheel Base-Minus, Axial

Figure 169  70 Degrees QE 4\textsuperscript{th} Quartile, Wheel Base-Minus, Radial 1

Figure 170  70 Degrees QE 4\textsuperscript{th} Quartile, Wheel Base-Minus, Radial 2
Figure 171  70 Degrees QE 4th Quartile, Wheel Base-Plus, Axial

Figure 172  70 Degrees QE 4th Quartile, Wheel Base-Plus, Radial 1

Figure 173  70 Degrees QE 4th Quartile, Wheel Base-Plus, Radial 2
Figure 174  70 Degrees QE 4\textsuperscript{th} Quartile, CG Radial Offset, Axial

Figure 175  70 Degrees QE 4\textsuperscript{th} Quartile, CG Radial Offset, Radial 1

Figure 176  70 Degrees QE 4\textsuperscript{th} Quartile, CG Radial Offset, Radial 2