Structural Design and Analysis of Hit-To-Kill Projectile

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Abstract

This paper introduces the very first step on the development of a guided ammunition system. It presents high level physics based simulations of a guided 60-mm projectile system, which intention is to enable the sub-projectile to hit and kill an incoming hostile missile at an extended range within a very limited time frame. The projectile requires a very high muzzle exit velocity in order to carry out the mission. Due to high inertia loads derived from immense breech pressure, understanding the survivability of the projectile system during launch becomes very important. The structural system of interest includes sub-projectile body, sabot, penetrator and electronics. This study focuses on overall projectile system configuration design and addresses the concern of structural integrity among components due to propellant pressure forces. LS-DYNA, a popular transient dynamics finite element program, will be adopted to perform in-bore dynamic analysis.

The topology of the projectile was initiated based on gun barrel specifications and certain aerodynamics characteristics. Preliminary structural design of sabot and sub-projectile was then performed with pseudo-static analysis. Subsequently, a 3-D finite element model was created and validated by LS-DYNA explicit dynamic analysis. A characteristic centerline variation of a gun barrel was also taken into account in the study. From simulation results, the muzzle velocity reached only 85% of target value due to 25% overweight of the launch package. However, the projectile system shall survive according to effective stress responses. No material failure is anticipated through in-bore travel. It should be noted that the structural configuration is not optimal as far as the launch package mass is concerned. In the next development phase, rigorous optimization efforts will be made on the projectile system, particularly sabot component.

Introduction

Researches in high-supersonic guided projectiles that intend to intercept incoming missiles have been of interest in recent years. Examples, such as in-bore dynamic responses of projectiles to two distinct types of propellants, validation of steering forces generated by control pins for medium-caliber munitions, cavity design around fin area to achieve desired aerodynamic forces, enhancements in embedded electronics for better guidance, etc. are available in the literatures [1-4]. This paper presents the very first step on the development of a guided ammunition system, which is to perform preliminary structural design and analysis for the launch package. The guided ammunition system was initiated to hit and destroy hostile projectiles with high accuracy at an extended range in a very short time frame. The launch package of study that supports the mission includes all payload, sabot and projectile. With high launch acceleration, interactions among these components must be understood. The focus of the report falls on the design of the projectile system such that the structural integrity can hold in the launch.

The topology of the hit-to-kill projectile was first laid out based on gun barrel specifications and certain aerodynamics characteristics. The projectile came with a windscreen and a penetrator in the front, having an ogive length and radius of 70.5 mm and 1,380 mm, respectively. Four fins for stabilization were embedded in the tail with fin span of 50 mm. Detailed fin configuration that had no structural significance was ignored. The projectile had a total length of 316.7 mm from nose to tail and an outer diameter of 23.5 mm. A 70-caliber smooth gun tube with an inner diameter of 60 mm was used to fire the projectile. The actual in-bore travel distance was 3,840 mm. For clarification, a cross-sectional view of the system before launch is given in Figure 1. The forcing cone and breech areas are excluded from the display. The projectile system was subjected to a peak breech pressure of as high as 470 MPa generated by the combustion of M2 propellant. It is assumed that the charge mass was equivalent to the mass of the launch package. Consequently, approximately 2/3 of the breech pressure was applied onto the projectile system. The task here was to determine the wall thickness of the projectile body such that it can withstand the loading. A preliminary calculation on pseudo-static analysis suggests a thickness of 4 mm be required to yield allowable hoop and radial stresses.

Methodologies for forecasting sabot for projectile systems have been under research for decades [5-6]. The design of sabot heavily depends on different type of propulsion systems. In the study, a conventional double-ramp sabot shall be appropriate for a solid propellant gun. Generally speaking, the sabot serves four purposes: supporting the projectile during high acceleration of launch, guiding the projectile along the center of gun barrel, sealing the gun tube to high-pressure propellant gas, and discarding smoothly after muzzle exit. It is understood that the length of sabot which supports a kinetic energy projectile is a major factor affecting the structural integrity. By applying limit state theorem, the fore and aft unsupported projectile length can be determined to avoid axial stress exceeding allowable value. As for the interface between sabot and projectile, i.e. grooves in actual design, a great deal of force transfer would take place by means of equivalent shear stresses. The modeling of grooves is not addressed in the paper. Instead, friction type of surface-to-surface contact is assumed in the study.

It should be pointed out that experimental validation will be performed later this year to compare with simulation results. A preliminary design from the study will serve as a blueprint for the

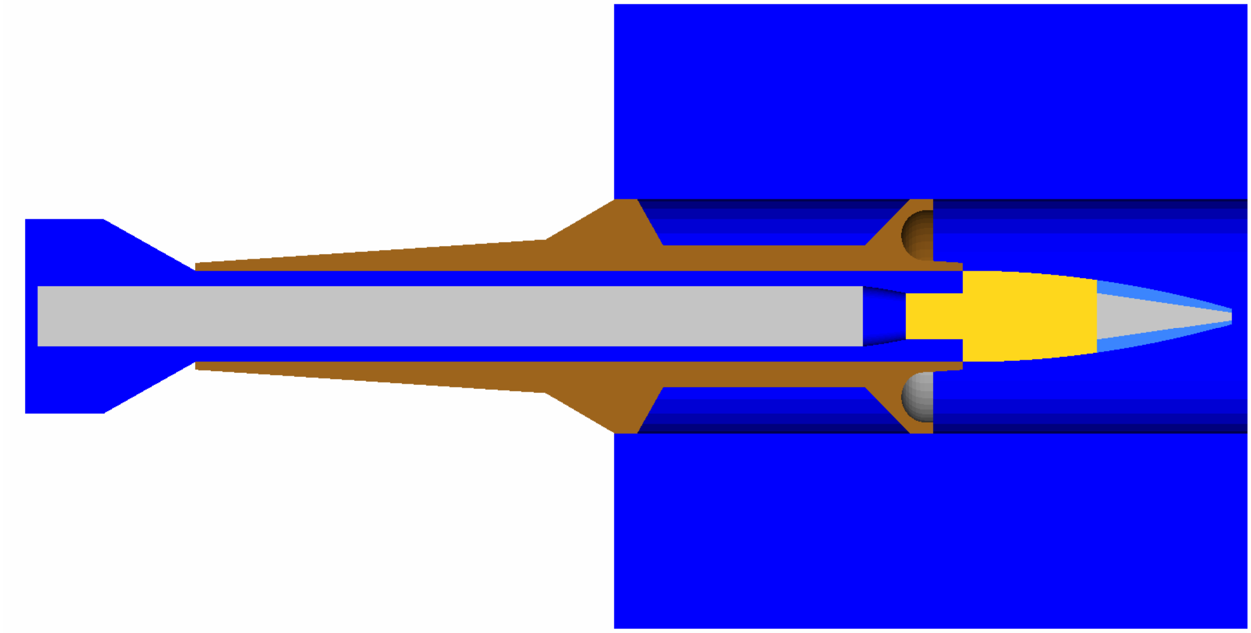

Figure 1. Cross-sectional view of the hit-to-kill projectile system

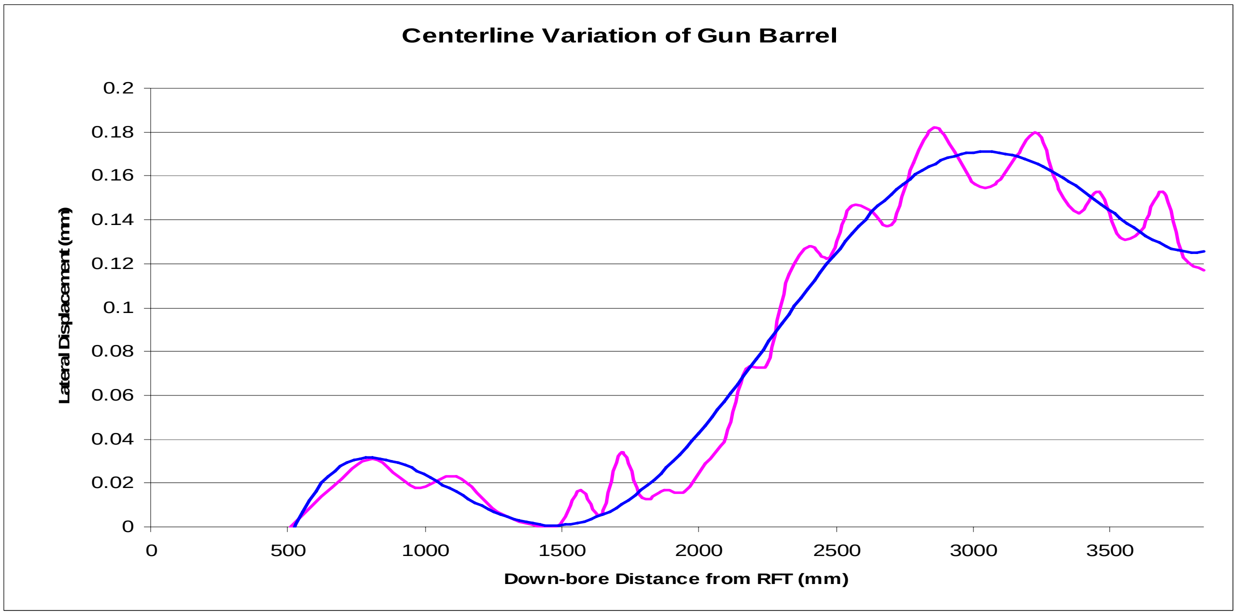

Figure 2. Characteristic centerline variation of a gun barrel

testing. U.S. Army Research Laboratory (ARL) will conduct the experimental shooting. Nevertheless, the gun tube to be used would not be delivered to the facility until the paper was due. The actual centerline variation of the gun barrel could not be measured in time. However, to account for the influence of gun barrel centerline curvature, the author employed a characteristic centerline variation provided by Dr. Bundy [7] in the study. The lateral displacement along down-bore distance from rear face of tube is shown in Figure 2. For gun modeling purpose, the curve was fitted with a high-order polynomial as shown. This paper will be comparing the velocity and stress responses with the gun barrel without centerline variations. Overall, a target muzzle velocity of 1,650 m/s was pursued in the design.

Modeling and Analysis

This article used a full-scale 3-D finite element model as shown in Figure 3 to represent the launch package. As prescribed, the package consisted of projectile body, penetrator, windscreen, fins and sabot. The physical and mechanical properties of the system are given in Table 1. Isotropic elastic material, i.e. material type 1 in LS-DYNA [8], was assumed throughout the model. The model included a total of 237,232 8-node Hexahedron solid elements with 231,456 nodes. Surface-to-surface contact was adopted to model the bore-sabot, sabot-sabot and sabot-body interfaces. A number of different static friction coefficients were applied for the bore-sabot interface and the results were compared. It is assumed that the friction is dependent on the relative velocity and pressure between the two objects. A high coefficient of 0.9 for the sabot-body interface was employed to simulate force transfer by grooves. Contact surface among four pieces of sabot was specified to avoid element overlapping. Default values for the contact parameters were used on the aspect. Figure 4 displays in-bore base pressure, which was derived from IBHVG2 output based on 1.3 liter gun chamber and 1 kg launch mass. All surfaces of the projectile system in the chamber area were subjected to the pressure load.

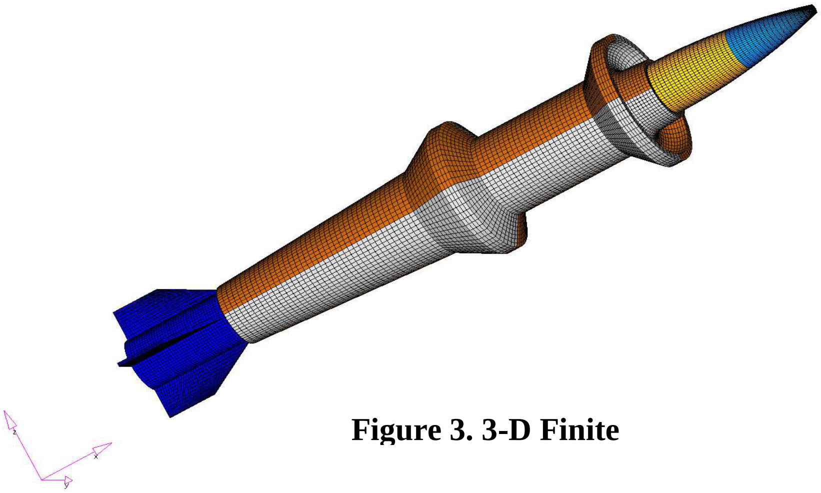

Figure 3. 3-D Finite

Table 1. Physical and Mechanical Properties of the Hit-To-Kill Projectile System

Part No.	Part Name	Material	Density (kg/mm^3)	Elastic Modulus (MPa)	Poisson's Ratio	Weight (kg)
1	Bore	Steel	7.75E-06	1.96E05	0.28	-
2	Body & Fin	Steel	7.75E-06	1.96E05	0.28	5.03E-01
3	Penetrator	Tungsten	1.80E-05	3.65E05	0.28	2.71E-01
4	Windscreen	Aluminum	3.60E-06	6.90E04	0.33	9.51E-03
5	Sabot	Aluminum	3.60E-06	6.90E04	0.33	4.07E-01
6	Cavity	Electronics	7.10E-07	1.00E04	0.35	4.85E-02

This paper studied three different structural configurations as follows: Case I: the projectile body

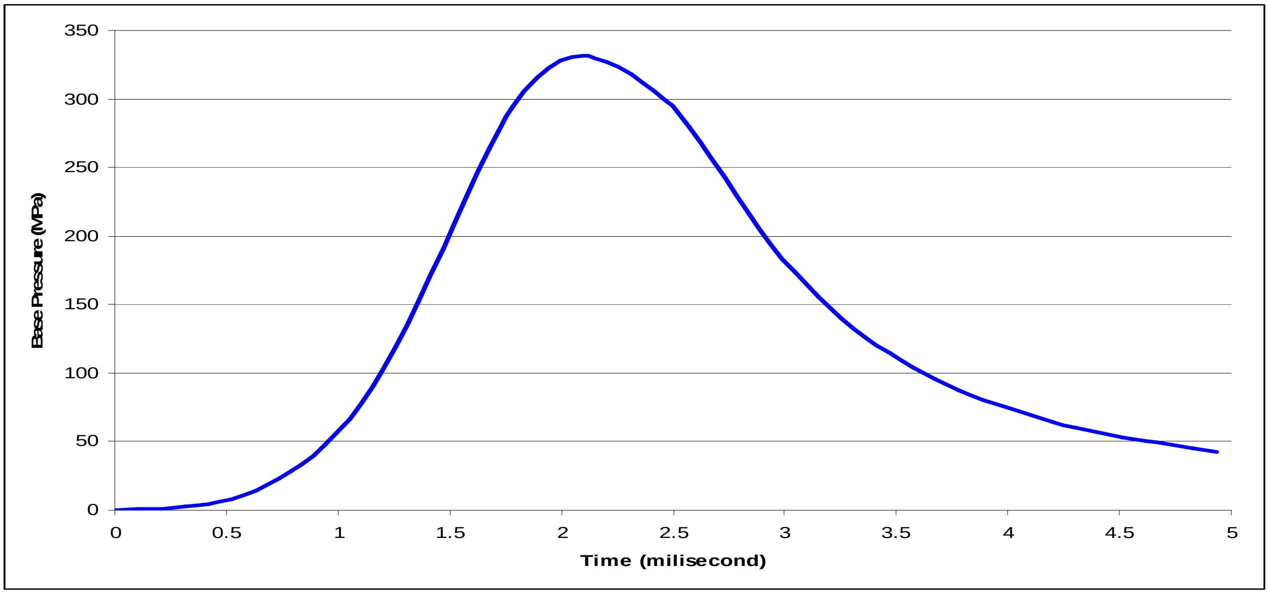

Figure 4. Time History of In-Bore Base Pressure

possessed a uniform thickness of 4 mm and the fore ramp of sabot was flat in the middle area as given in Figure 1; Case II: the body had a thickness of 5 mm in the front half and 4 mm in the tail portion, and sabot stayed the same as Case I; Case III: the body remained the same condition as Case I but the sabot had a taper all the way for the fore ramp. LS-DYNA explicit dynamic analyses were performed on Linux Networx Evolocity II cluster, JVN, at the ARL High Performance Computing Center. Each analysis took approximately five hours of CPU time on 16-thread parallel execution. Database Binary D3plot was requested at 0.1 ms interval. The analysis for Case I yielded a total of 5.0 ms in-bore travel time as shown in Figure 5. The muzzle exit velocity reached around 1,500 m/s as indicated in Figure 6. The in-bore velocity curve was in line with base pressure history, where the maximum acceleration took place at 2.1 ms after ignition.

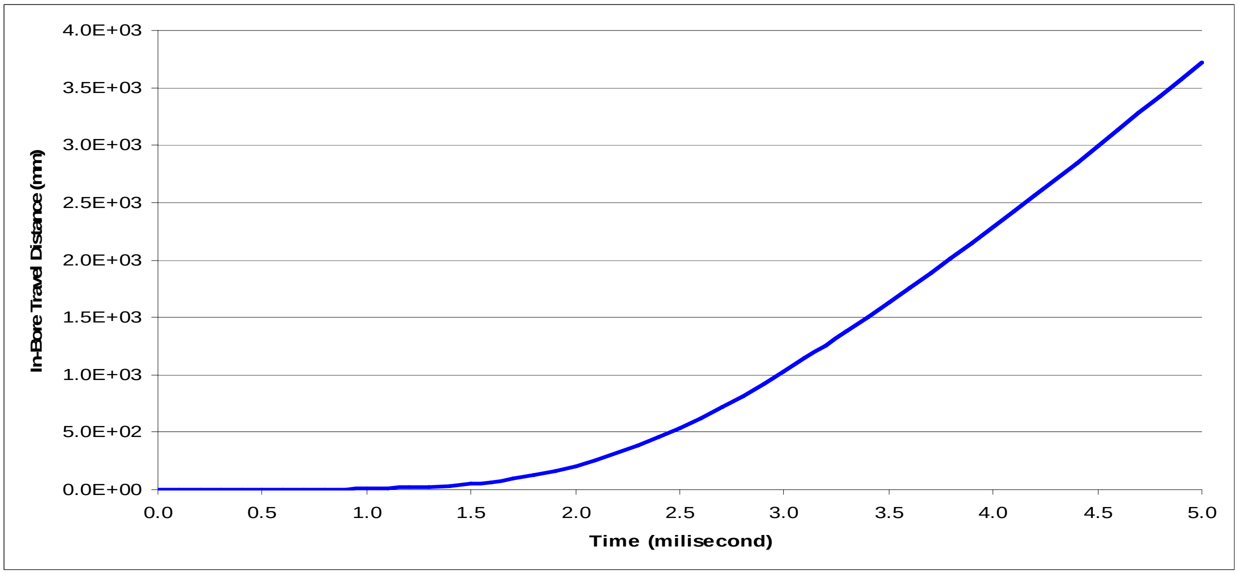

Figure 5. In-Bore Travel Time vs. Travel Distance

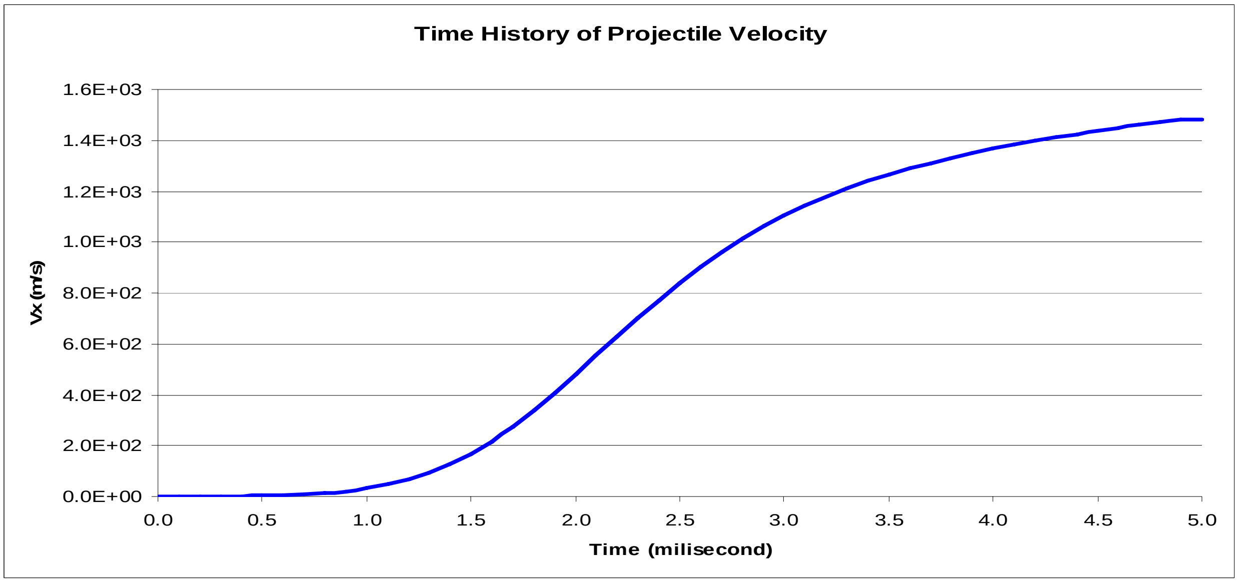

Figure 6. Time History of Projectile In-Bore Velocity

Table 2. Various Responses of the Projectile System to Different Weights of the Launch Package

	Case I	Case II	Case III
Total weight (kg)	1.239	1.269	1.375
In-bore travel distance (mm) at 5 ms from ignition	3721	3514	3351
Projectile velocity (m/s) at 5 ms	1492	1398	1345
Peak acceleration (kgee's) at 2.1 ms	76	74	70
Peak von Mises Stress (MPa) at 2.1 ms	1210	985	1035

The total weights of the launch package for Case I, II and III were 1.239 kg, 1.269 kg and 1.375 kg, respectively. The analysis results are summarized in Table 2. Given the loading history and duration of 5 ms in Figure 4, the Case I projectile traveled a distance of 3,721 mm, close to gun muzzle, with a peak velocity of around 1,500 m/s. The maximum acceleration of 76 k gee's took place at 2.1 ms from firing which incurred a peak von Mises stress of 1,210 MPa. The maximum stress occurred at the projectile body area between bore-rider and bulkhead as shown in Figure 7(a). Significant compression stresses were attributed to the pressure from sabot bulkhead. Considering 17-4 PH steel material with H925 conditions treatment, which possesses a yielding strength of 1,070 MPa, the Case I projectile was predicted to fail accordingly.

Case II which increased the wall thickness by 1 mm was developed to alleviate stress magnitude in the fore ramp area. Figure 7(b) displays the contours of von Mises stress response. As a result, the peak stress was reduced to 985 MPa. No permanent deformation was anticipated. However, due to the addition of mass by 30 g, the in-bore travel distance, peak velocity and maximum acceleration turned out to be 3,514 mm, 1,398 m/s and 74 k gee's, respectively. In order to reach a target muzzle velocity of 1,650 m/s, the breech pressure would need to be magnified, which might result in re-adjustment of the structural configuration. Understandably, an iterative design and analysis process would be required.

Instead of increasing the thickness of the projectile body, Case III was to augment sabot, i.e. making fore ramp all the way to bore-rider, so that it could absorb more of the stresses and uniform the stress distribution due to increasing stiffness ratio between sabot and projectile. The configuration changes along with stress response contours are shown in Figure 7 (c), which led to a reduction of von Mises stress to 1,035 MPa from 1,210 MPa. The decrease in stress would prevent the steel material from yielding. Note that this alteration added significant mass on the system. The in-bore travel distance, peak velocity and peak acceleration were all lowered to 3,351 mm, 1,345 m/s and 70 k gee's, respectively. Therefore, a tradeoff was seen between free space for electronics and sabot mass.

The tungsten joint between penetrator and body exhibited a high effective stress of 700 MPa as shown in Figure 8. However, the stress level was below its material strength. The aluminum windscreen and sabot appeared to have stress responses lower than the yield strength as well. Due to long duration of pressure load, the effect of wave propagation was not significant.

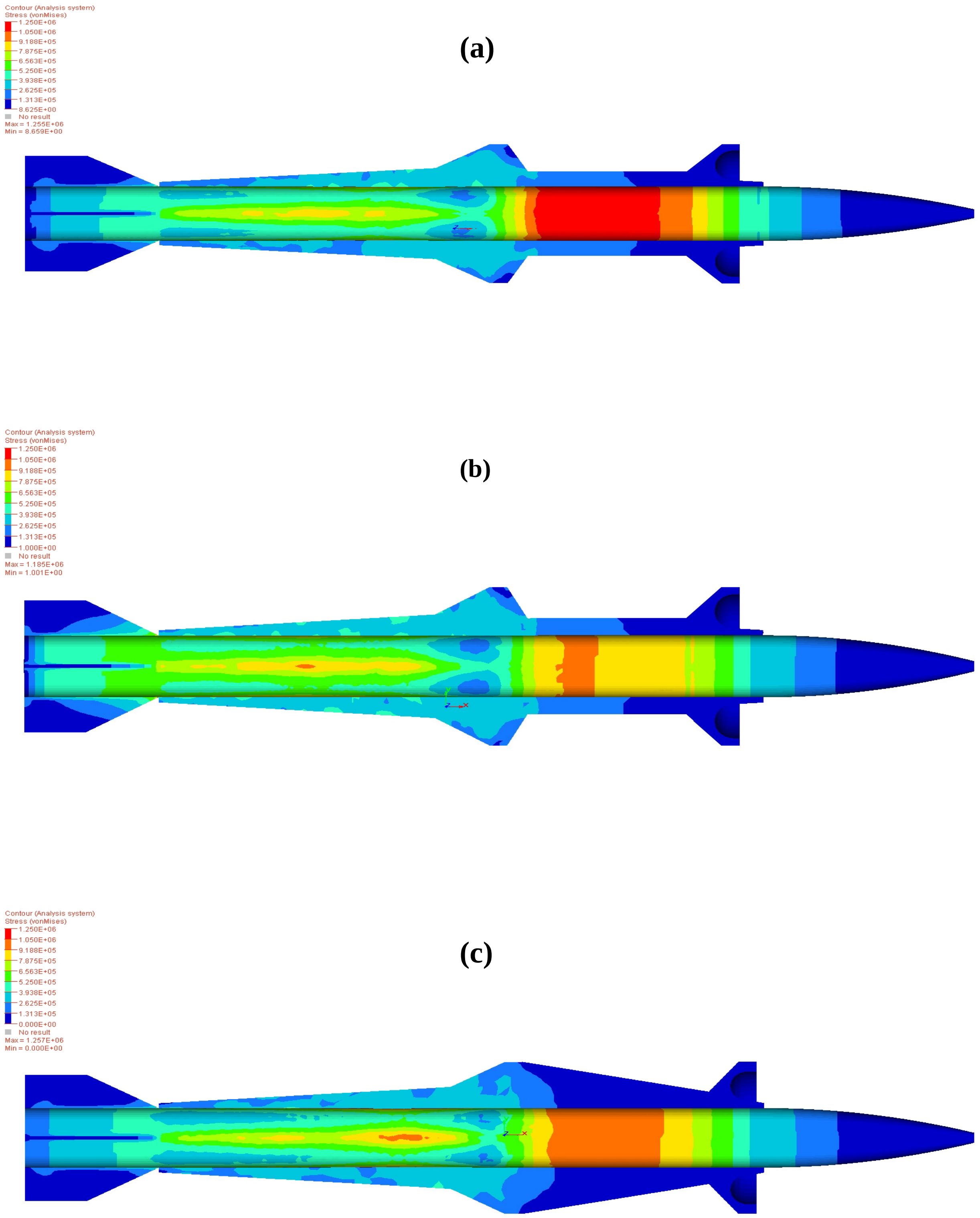

Figure 7. Contours of von Mises Stress Response at 2.1 ms from Ignition for (a) Case I (b) Case II and (c) Case III

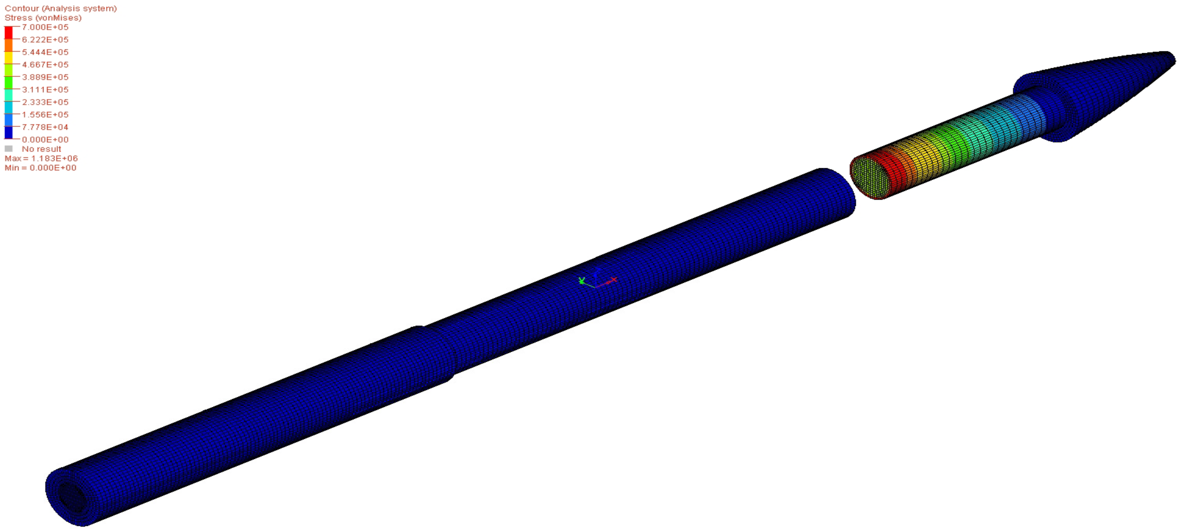

Figure 8. Effective Stress Response of Inner Components

To prevent propellant pressure loss during launch, obturator was used to isolate projectile from the bore of the gun barrel. Five different friction coefficients, i.e. 0.0, 0.1, 0.2, 0.3 and 0.5 for the sliding contact were used to investigate the influence on the velocity and stress responses. The results indicated that the differences in the responses among the coefficients of friction were marginal. However, the friction for the interface between sabot and projectile must be sufficiently high in order to simulate force transfer and be able to move the projectile along. From simulation results, 0.5 shall be good. No response significance was found for the friction coefficient greater than the number.

It is known that barrel centerline curvature influences the location of projectile shot impacts. In addition to investigating projectile responses to configuration changes, this paper also studied how the barrel with centerline variations would affect in-bore projectile movements. Two types of barrels, one with perfectly straight centerline and another with characteristic centerline variation as provided in Figure 2, were used. The Y movements of the projectile, i.e. up and down direction, at the nose while traveling in the barrels were captured and compared in Figure 9. It can be seen that the projectile started balloting at 1.2 ms from ignition for both cases. The results indicated that in-bore Y displacement with centerline variation underwent as much as 0.22 mm, five times larger than that with perfectly straight barrel. Therefore, caution must be taken when considering gun manufacturing error since the muzzle exit yaw and pitch movements play a vital role in aerodynamics stability.

Summary

Preliminary structural design and analysis of a hit-to-kill projectile was initiated as the first step in the development process of a guided ammunition system. The launch package was required to have fairly high muzzle exit velocity in order to carry out its mission. It started with a pre-determined outer configuration based on gun barrel specifications and certain aerodynamics characteristics. The system of study included gun barrel, sabot, projectile body, tungsten nose, fin and windscreen. A total of 22 components along with six different material properties were

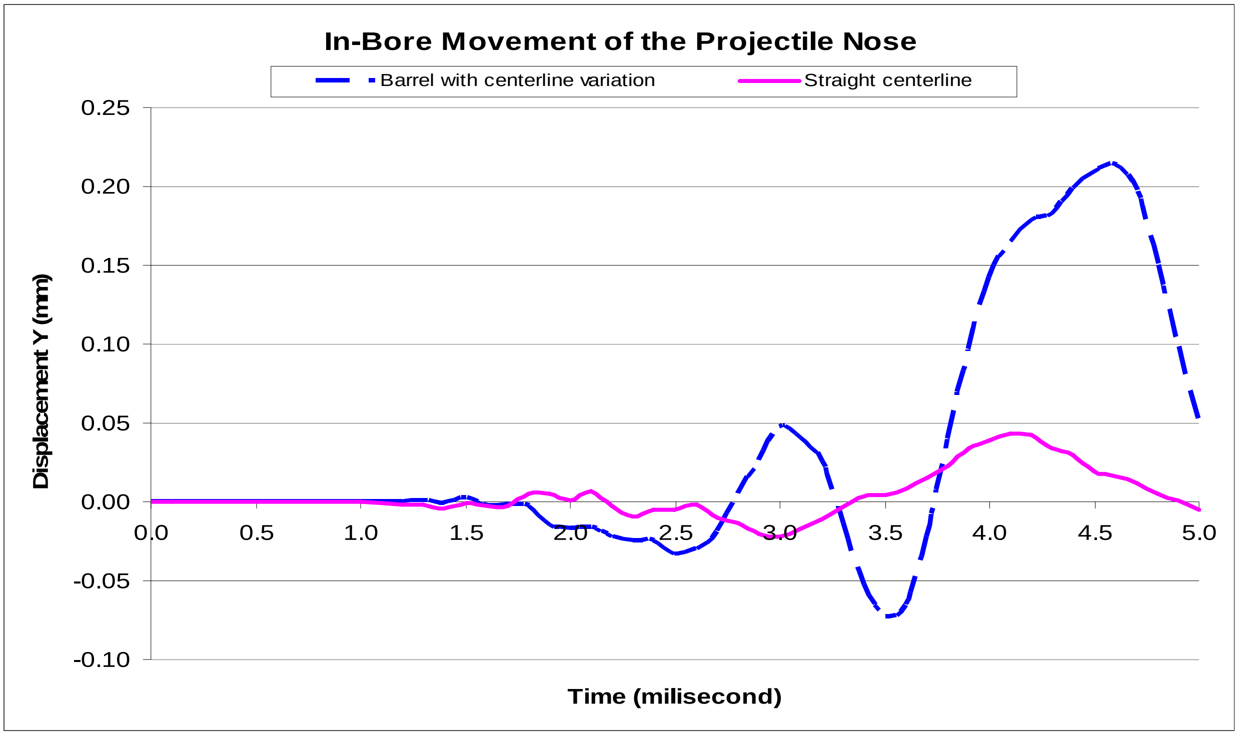

Figure 9. Comparison of In-Bore Movements with and without Centerline Variation

created and assembled for finite element analysis. LS-DYNA computer code was utilized to investigate the hit-to-kill projectile dynamic behavior. The simulation results will be validated by experimental tests which will be conducted later at the U.S. Army Research Laboratory.

Three different structural configurations were studied. The projectile which had a uniform wall thickness of 4 mm with flat fore ramp component (lighter sabot) encountered yielding failure. It would not survive on the launch without altering sabot so that the sabot can transfer forces to the projectile more uniformly. However, the alteration significantly increased the total mass of the launch package which considerably impaired muzzle velocity. Alternatively, the author proposed to reinforce the projectile body by augmenting the thickness in the fore ramp area. Nevertheless, it would lead to more constraint on the installation of inner material. Note that the time-dependent breech pressure used in this study was derived based on empty gun chamber. More accurate measurement by actual case volume shall be undertaken.

In addition, the variations of a characteristic gun barrel centerline were taken into account in the study. The effect of centerline variations was found to be significant on the projectile in-bore movements. The gun barrel to be used for experimental shooting would be carefully measured upon delivery. The actual variations would be utilized in later simulations for better prediction. In the final, the muzzle velocity from the study did not reach the target value. The total mass of the launch package required certain reduction from the preliminary design. Rigorous optimization efforts would be made, particularly on the sabot component.

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