Rifles In-Bore Finite Element Transient Analysis

S. Deng , H. K. Sun, and Chung-Jung Chiu

Abstract**—T**his research used nonlinear transient Finite element method to simulate 5.56 mm rifle bullet's behavior inside barrel due to chamber pressure after being fired. The in-bore process of rifles is a multi-physical and complex topic because the action time is brief; usually counts in scale of millisecond, and propellant produces high temperature and high pressure gas during burning process. These factors keep in-bore behavior of bullet difficult to simulate in the past. This research first using solid element to discretize bullet and barrel including throat and rifling, then put the bullet inside barrel at the position of throat to be the finite element model. For the chamber pressure, this research using Vallier-Heydenreich method to formulate and using it as the input loading. The material of finite element model is set the type of isotropic elastic with failure. When start simulate, the bullet is compressed by rifling and moving forward with spin through out the barrel. In this simulation, one can not only collect the stress and strain of the barrel and bullet, but the velocity and rotation of the bullet. This research also compared the bullet muzzle velocity with experiment data, which indicate the accuracy less than 2%. The simulation of this research can save lots of time when design barrels of small arms in the future.

Keywords**—** interior ballistics, finite element method, transient analysis.

I. INTRODUCTION

BALLISTICS can be divided into interior ballistics, exterior ballistics, and terminal ballistics. Interior ballistics involves examining the chamber pressure, trajectory, and velocity of projectiles launched by propellants until outside the muzzle of a gun. The interior ballistic theory can be used to estimate ballistic characteristics according to weapon system design parameters, or to design new weapon systems under specific conditions, such as muzzle velocities.

Ballistics research usually entails experimental tests requiring considerable manpower, materials, and time. The purpose of such tests is to derive empirical or semi-empirical formulas that can facilitate system design, manufacture, and operation. The drawback of this method is the high cost, long development time, and the result may not be suitable for every system. Unlike traditional trial-and-error methods or, depending on the research modes of experienced engineers, computer-aided engineering (CAE) techniques have excellent numeric, visible, and reappearance attributes that can help engineers design and develop a new system efficiently. Today, CAE is accepted and widely used in many fields and has become an essential tool in contending with difficult measurement experiments and instant reaction phenomenon analyses, such as those encountered in ballistics research.

Extensively used in massive quantities, rifles have become the basic weapon of infantry. Although breech-loading rifles were invented hundreds of years ago, thoroughly mastering the in-bore reaction that remains elusive. In recent years, numerous research institutes and scholars have conducted experiments and numerical analyses in interior ballistics [1–9]. Previous research has simplified the analysis using mainly a partial or two-dimensional model. Furthermore, some detailed parameters and conditions are unpublished. Hence, this study developed a simple, efficient, and accurate process, which can be applied to small-caliber systems, to calculate the kinetic in-bore performance of both the barrel and bullet.

II. ANALYSIS PROCESS

This article uses nonlinear finite element methods to simulate in-bore kinetic motions. The complete analysis process is introduced as follows (see Fig. 1).

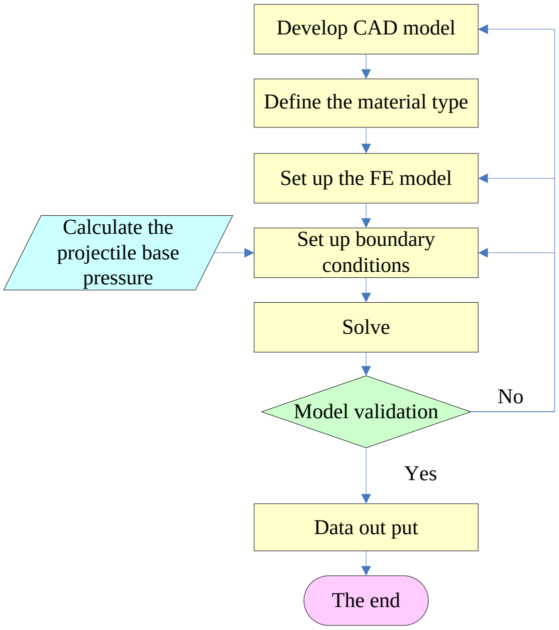

Fig. 1 Analysis process

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Step1. Develop the computer-aided design (CAD) model:

First, develop the complete realistic virtual rifled barrel/bullet model. The barrel includes three-dimensional riflings, and the bullet is composed of a core and jacket. The basic parameters of the model are referenced in Table 1. The subsidiary parts and detailed geometric characteristics that do not affect the numerical results are neglected or simplified to reduce the computation time. The finished CAD model is shown in Figure 2.

TABLE I
Listing of The Rifle Parameters

Target	Items	Parameters
5.56 mm Rifle	caliber (mm)	5.56
	muzzle velocity (m/sec) (measured form experiments)	840
	quantity of riflings	6
	mass of bullets (g)	7.4

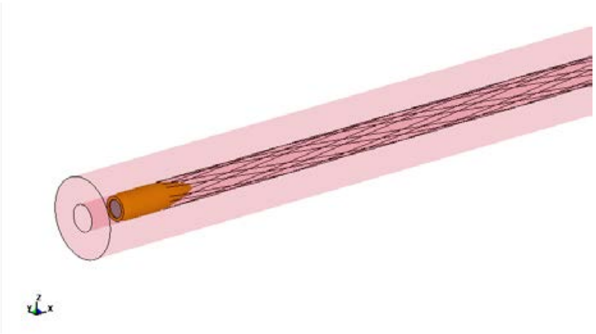

Fig. 2 Graphic of the CAD model

Step2. Define the material type:

The material type in this research is set to isotropic elastic-plastic with failure[10]. The barrel is an AISI 3040 high-alloy steel and the bullet jacket and core is a UNS C22000 copper alloy and lead antimony alloy, respectively. The material parameters [11], [12] details are presented in the following table:

TABLE II
Listing of The Material Parameters

Parts / Items	Barrel	Bullet	
		Jacket	Core
material type	AISI 3040 steel	UNS C22000 copper alloy	lead antimony alloy
density（g/cm^3）	7.85	8.8	11.04
shear modulus（GPa）	80	44	4.93
yield stress （MPa）	1165	83	37.9
plastic hardening modulus （MPa）	736	479.2	65.86
bulk modulus（GPa）	156.19	99.3	29.17

Step3. Set up the finite element (FE) model:

Import the CAD model into the FE analysis software, and plan the grid and mesh the model. The purpose of grid planning is to define the mapped mesh, control and improve the quality of elements, and decrease the element quantities. This process can improve the velocity analysis and economize the calculation time. For example, a free mesh barrel is composed of 2,765,970 elements, whereas a mapped mesh barrel is composed of only 418,344 elements in the same mesh scale (a total reduction of 2,347,626 or 84.88% elements). Hence, we use mapped mesh to discretize the key structures in this research.

TABLE III
Comparison of Barrel Element Quantity Using Different Mesh Types

Items	Barrel	
mesh type	free mesh	mapped mesh
element type	tetrahedron	hexahedral
element quantity	2,765,970	418,344
element quantity difference	-2,347,626（-84.88%）	

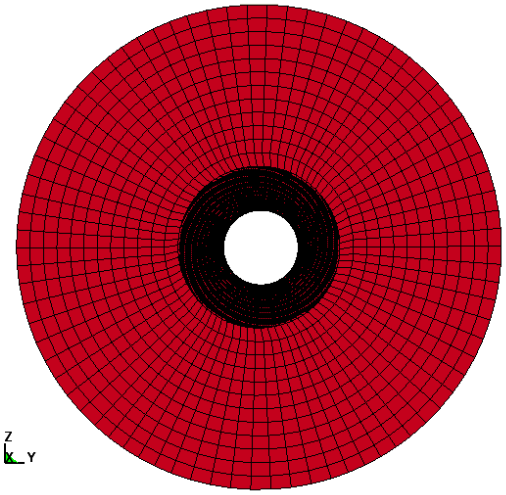

Fig. 3 Picture of the barrel FE model (Front View)

The copper alloy jacket and lead antimony alloy core of the bullet consist of 28,528 and 17,875 solid elements, respectively. Fig. 4 shows the finite element meshes for the bullet.

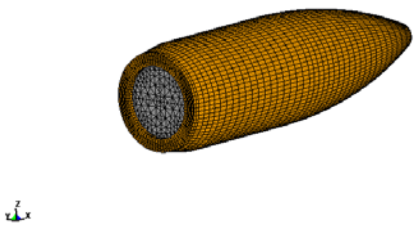

Fig. 4 Picture of the bullet FE model

Step4. Calculate the projectile base pressure:

The average chamber pressure history $p(t)$ can be assessed according to specific parameters such as barrel length, bullet types, and propellant mass, by using the Vallier-Heydenreich empirical formula [13]. The chamber gas pressure is not uniform, whereas the chamber base gas has the lowest average velocity but a higher pressure level. Conversely, the projectile base gas trails the bullet and with a higher velocity but lower pressure. The relationship between projectile base pressure and average pressure [14] is

$$p=\left(1+\frac{m_y}{3\varphi_1 m_D}\right)p_D \qquad (1)$$

where m_y is the propellant mass, m_D is the bullet mass, and φ_1 is the bullet mass coefficient. The projectile base pressure is 87.4% of the average pressure from “(1).” Additionally, this analysis does not consider the primer time to reduce the analysis time. The projectile base pressure history in this case is shown as Fig. 5.

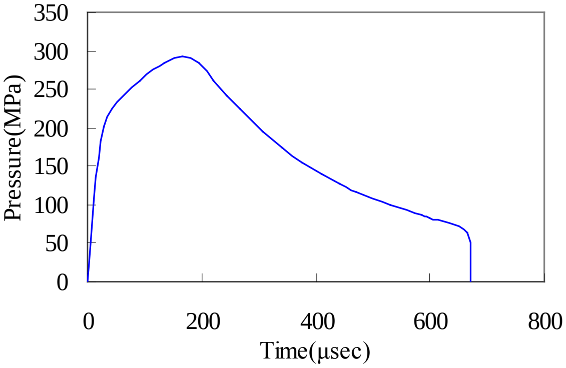

Fig.5 Projectile base pressure time diagram

Step5. Set up boundary conditions:

Reasonable initial and boundary conditions such as fixing, loading, and contact are set according to the rifle’ s operation principle. For example, the front and rear portions of the barrel are fixed to prevent motion; the back face of the bullet is loaded with a time-dependent distribution force (computed during Step 4) to simulate the chamber gas acting on the bullet. Between the jacket and core of the bullet is surface-to-surface contact. Finally, the relationship between the projectile’s external surface and the barrel’ s internal surface is eroding contact.

Step6.Solve:

This research uses the explicit dynamic finite element analysis simulation code, LS-Dyna, as the numerical solver.

Step7. Model validation:

This research uses the muzzle velocity as the validation criterion. The rifle’s real test muzzle velocity is 840 m/s, whereas the calculated numerical result is 848.96 m/s (1.07% difference). This comparison between experiment and numerical data indicates that the simulation is credible.

Step8. Data output

III. BULLET KINEMATIC ANALYSIS

The numerical simulation shows us that the bullet is pushed forward by the chamber pressure to move along the barrel’s axis. The projectile is compressed causing plastic deformation and guided to spin by riflings. The curve shown in Fig. 6 shows that the bullet movement is miniscule (<1 mm) for the initial 50 µs because of inertial effects before increasing steadily. The traveling time of the projectile from a static position to being outside the muzzle is 664 µs.

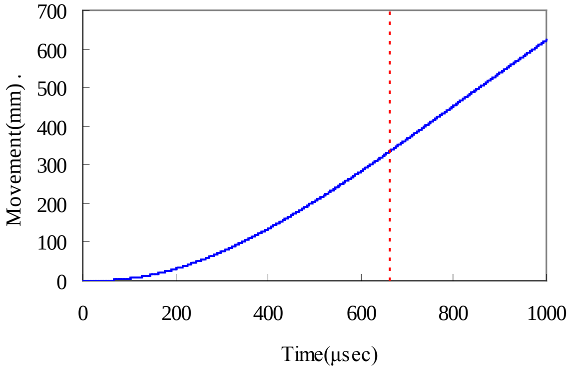

Fig. 6 Bullet movement curve

The analysis indicates that the bullet accelerates during the initial period after firing, although the rate of acceleration diminishes after 167 µs because of a reduction in base pressure. However, the bullet remains in a state of acceleration until it is outside of the muzzle. Finally, the velocity remains steady because air resistance is ignored in this simulation.

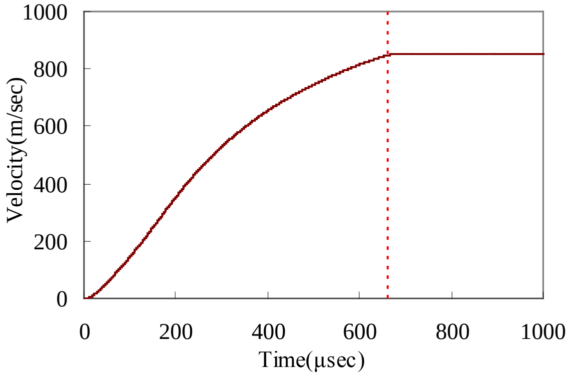

Fig. 7 Plot of the bullet speed curve

Fig. 8 is the acceleration history of the bullet. The rate of acceleration is significantly dependent on the projectile base pressure. The highest value of acceleration is 2.17×10^3 km/s^2 at 163µs. When the bullet is outside of the barrel, the materials lose lecture constriction and spring back sharply, causing the projectile to vibrate. This vibration diminishes over time.

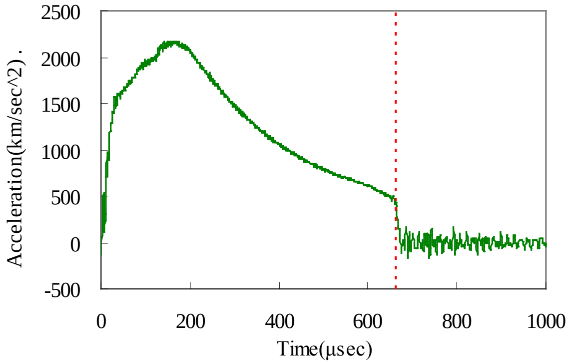

Fig. 8 Plot of the bullet acceleration curve

Spin velocity is another crucial parameter for exterior ballistics because it affects projectile stability and flight dynamics. The angular velocity history diagram of the bullet (Fig. 9) shows that the projectile moves without rotation through the smooth-bore section. The spin-rate increases rapidly when the bullet slides into the rifling section at 70 μs. The rotational speed is corrected by riflings due to over rotating phenomenon in the beginning of rifling section. The rotational speed increases steadily after 170 μs until the bullet exits the muzzle. The material resilient phenomenon causes the rotating ratio to decrease by approximately 1.78% while the bullet is passing through the muzzle. Finally, the rotational speed does not change obviously during free flight.

This shows that the bullet begins to spin rapidly at the initial rifling section. Therefore, a suitable smooth-bore distance design is crucial to reduce the torque effect. This phenomenon is difficult to replicate using experimental approaches. Conversely, one can analyze the full in-bore kinematic process of bullets by using this analysis.

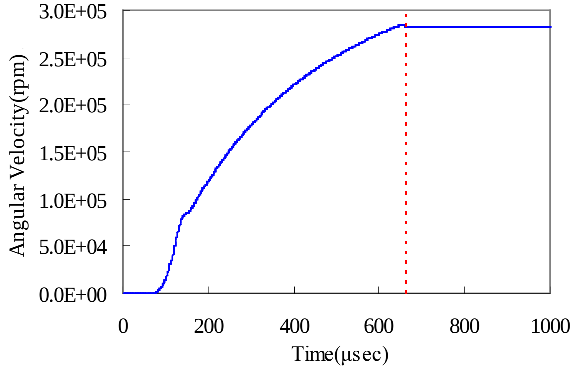

Fig. 9 Plot of the bullet spin curve

IV. STRESS ANALYSIS

Fig. 10 to 14 plot the transient von Mises stress distribution of the bullet at different points during motion. The boat tail region and lecture section that contact the riflings are considered high stress zones during shot travel. High stresses in the rear region are caused by geometric stress concentration. The high lecture part stress is caused by the bullet being compressed by the riflings, which induces plastic deformation or failure. The material spring back effect creates the peak stress when the bullet exits the muzzle. The residual stress tends to decrease and stabilize over time. This analysis can be applied to future projectile design and material selection research.

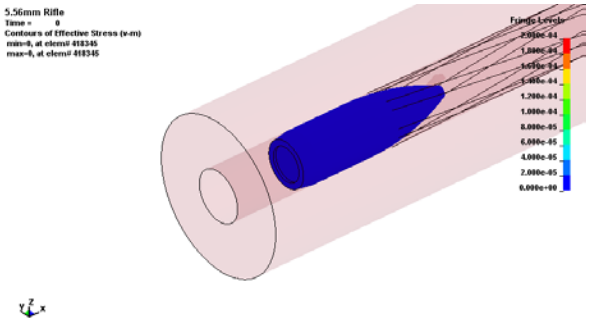

Fig. 10 Projectile stress distributions at time 0

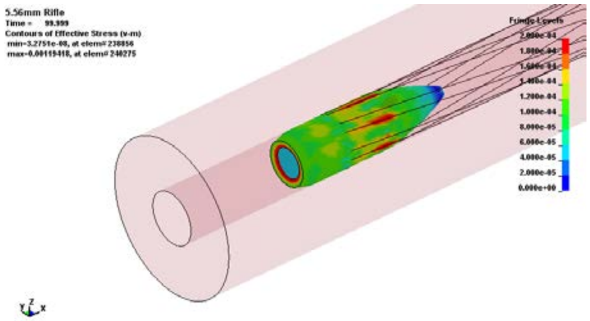

Fig. 11 Projectile stress distributions at time 100μsec

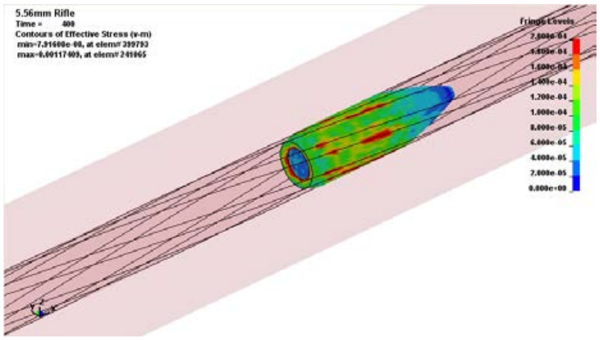

Fig. 12 Projectile stress distributions at time 400μsec

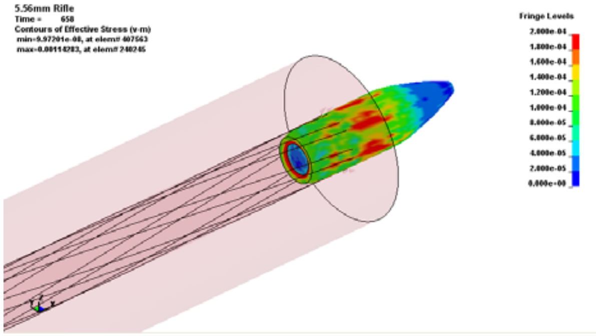

Fig. 13 Projectile stress distributions at time 658μsec

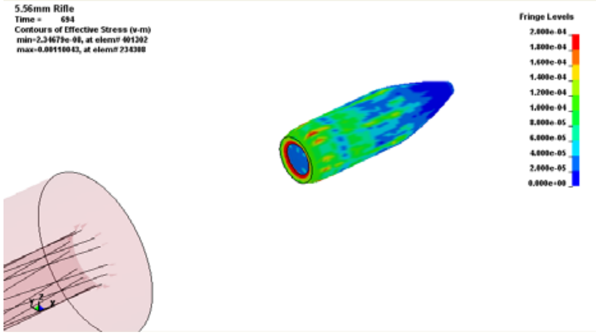

Fig. 14 Projectile stress distributions at time 694μsec

Fig. 15 shows the stress curves diagram. Points A, B, and C are at the initial, medium, and end regions on the land surface, respectively. At the initial regions on the land surface has the higher stress level, and the peak of instant stress is 1170.17 MPa. The medium and muzzle regions' stresses are relatively lower. Additionally, the lands have higher residual stress then the grooves after the projectile travels through. This analysis demonstrates the internal surface treatment of gun barrels is essential.

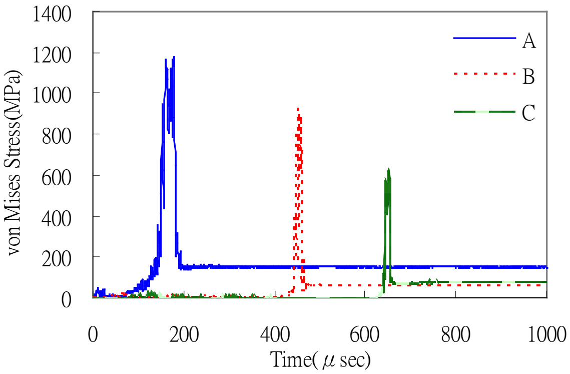

Fig. 15 Stress curves of lands

V. CONCLUSION

This study uses nonlinear transient finite element methods to simulate the in-bore behavior of a 5.56 mm rifle bullet after being fired. The difference in muzzle velocity between the real test and the numerical simulation is only 1.07%; therefore, the analysis is reliable.

This simulation allows the collection of data for the whole shot travel, including movement, velocity, acceleration, rotation, stress, and strain. These useful and essential data are difficult to obtain through real experiments. The simulation of this research can save significant amounts of time for design barrels of small arms in the future.

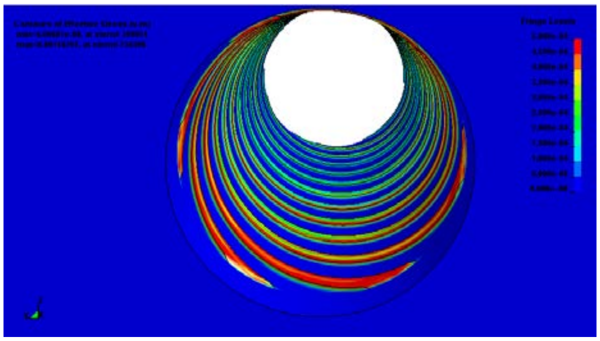

Fig. 16 Residual stress distribution of barrel after shooting

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