Stochastic study of 60-mm gun-projectile responses

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Abstract

Gun propulsion modeling has been under development for many decades. Starting from lumped parameter computer code, then 1D and 2D approaches and finally by multi-dimensional and multi-phase interior ballistics codes, one has been able to estimate in-bore pressure-time history at a fairly accurate level. However, some underlying assumptions among the models exhibit certain levels of uncertainties, for instance: the time-varying friction between obturator and bore surface; the granular shape variations of propellant charges; the packaging deviations of each propellant load, etc. This study was to investigate in-bore responses of a 60-mm projectile subjected to the inherent randomness of propulsion pressures. The pressure-time curve was modeled with 47 Gaussian variables. A total of 100 pressure samples were then generated through Monte Carlo simulation techniques. Subsequently, the time histories of the highest in-bore velocity, peak acceleration and the maximum von Mises stress responses of the projectile were obtained respectively corresponding to each pressure simulation. The goals were to gain more understanding of how the projectile performs in response to the changes of chamber pressures, and how much variation of the responses should be expected from experimental results under normal circumstances. The significance of the random variables on the projectile responses was outlined as well.
Keywords: interior ballistics, 60-mm projectile, IBHVG2, Monte Carlo simulation, stochastic responses.

1 Introduction

The modeling of complex gun propulsion schemes has evolved at a great stride over the past two decades. In the mid 1980s, a lumped-parameter computer code IBHVG2 (Interior Ballistics of High Velocity Gun, version 2), developed by the

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US Army Research Laboratory (ARL, formerly Ballistic Research Laboratory), was available for the calculation of interior ballistic trajectories including time-dependent gas pressure, projectile displacement and velocity [1]. In early 1990s the efforts were extended to 1-D/2-D interior ballistic modeling, where a number of experimental studies have demonstrated space-time-dependent flame spreading processes [2,3]. More details in determining gun distributed pressure field were further taken into account, which led to initial development of next generation model named NGEN [4]. The 3-D, multiphase and computational fluid dynamics based NGEN codes have been used for a number of applications in recent years [5,6]. Nowadays, in-bore pressure-time curve can be estimated at a fairly accurate level.

Nevertheless, there are a few factors that are inherently uncontrollable and exhibit certain level of variations when calculating in-bore pressure history. Some of the examples are time-varying frictions between obturator and bore surface, gun barrel manufacturing tolerance, granular shape variations of propellant charges, packaging deviations of each propellant load, distinctive flame spreading path, changing ambient temperature, etc. Many experimental shootings have demonstrated the pressure variations, where the differences from one shot to another may be attributed to one or more of these factors. Understandably, the shot deviations would become even more apparent at war field. Thus, it is important to study how the performance of a projectile is influenced by the stochastic excitations. The objective of this paper was not to model the random nature of each factor individually. Instead, the variations of all the contributing factors were considered as a whole. A nominal pressure-time curve, where the pressure level at each time step was modeled as a Gaussian variable, was utilized for this study.

2 Description of the 60-mm projectile system

A 60-mm gun projectile was chosen for the study. The projectile possessed a total length of 317 mm from nose to tail and an outer diameter of 23.5 mm in the body. It was equipped 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. Figure 1 illustrates material configuration from a cross-sectional view of the projectile system. The sabot and windscreen cover were composed of 7075-T651 aluminum alloy. Tungsten material was used for the penetrator. The gun barrel, projectile body and fins were modeled with 17-4 PH stainless steel. The inside of its body was divided into two cavity areas. The forward cavity may carry high explosive payload while the rear cavity was designed to accommodate electronic equipments. The projectile was intended to hit and destroy hostile objects, such as mortars, rockets and artillery. Because of the precision-sensitive mission, it becomes vital to investigate the stochastic responses of the projectile system.

A 64-caliber smooth bore gun tube with an inner diameter of 60 mm was used to simulate the projectile firing. The barrel has a total length of 3,840 mm, i.e. in bore travel distance for the projectile. M2 propellants with geometry of 7 perf grain were used for the propulsion. Given a chamber volume of 1.3 liter, a peak breech pressure of 470 MPa was derived from the interior ballistics code IBHVG2. The in-bore structural dynamic analysis of the projectile system except optimized sabot has been previously performed [7]. For computational efficiency in stochastic study, the windscreen and stabilized fins were substituted with equivalent weight such that the center of gravity of the projectile system remained at the same location. The simplification that avoided very fine mesh significantly reduced computational time. The projectile configuration and grids are displayed in Figure 2. This model contained solely hexahedral elements with a total number of 42,984. The entire mass of the projectile system including sabot was approximately 1 kg.

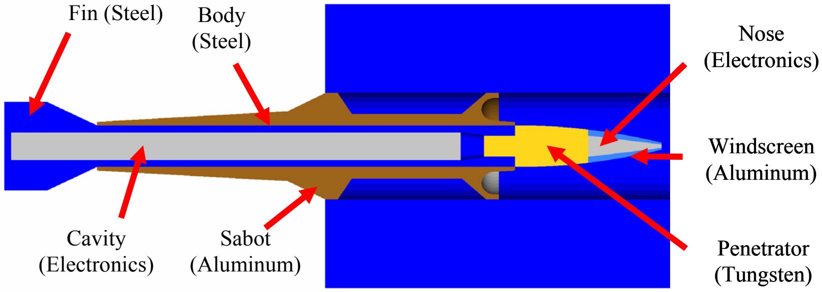

Figure 1: Material configuration of a 60-mm projectile.

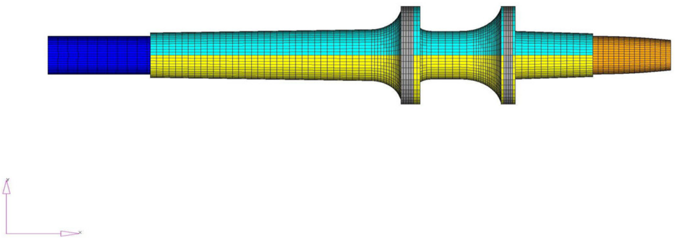

Figure 2: Display of 60-mm projectile geometry and mesh.

3 Stochastic modeling

A nominal base pressure-time curve shown in Figure 3 was adopted for the study. A peak pressure of 315 MPa occurred at 2 ms from ignition and the total pressure duration was 4.7 ms. Given the random nature of pressure generation through propellant burning process, the pressure level at each time step was considered as a normally distributed function. As a result, a total of 47 Gaussian variables were required to represent the profile of the stochastic pressures. This modeling may account for the fact that the measured pressure level of every experimental shot differed even with the same gun, the same cartridge and the same projectile. Because the differentiation was not substantial, a coefficient of variation of 3% for the random variables was employed [8]. Note that no additional energy was imposed on the projectile system as opposed to the original pressure curve since the ensemble mean remained the same.

To better illustrate the pressure deviations, Figure 4 shows the Gaussian distributions of the base pressures at the time steps of 1.8, 1.9 and 2.0 ms from ignition, respectively. It is a local magnified view in the area of Figure 3. The middle line represents the mean value of the pressure, and the lines above and below stand for one standard deviation from the mean. The bell shapes depict the spread of the random variables. In this paper, HyperStudy software [9] was adopted to perform Monte Carlo simulations. A total of 100 samples were generated for each random variable. As a result, 100 design cases, each with a distinctive time-pressure curve, were constituted. The pressure curves for the first three design cases are shown in Figure 5. Due to low values in the initial stage, the variations are not visible because of scale. The uncommon small double-bumps in high pressure area have to be achieved with complex configurations of propellant charges, which is beyond the scope of the paper.

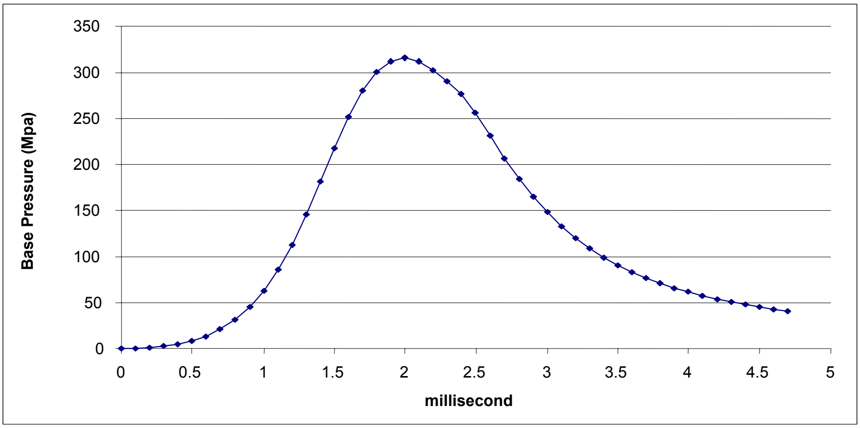

Figure 3: A nominal base pressure-time history.

In terms of sampling distribution, Figure 6 gives a histogram plot for the random variable #20, i.e. the peak pressure at 2 ms travel time. The histogram passed a normality test at 95% confidence level although a bit right skewed is seen on the chart. In addition, the computed sample average was close to the ensemble average of 315 MPa, indicating that the number of 100 samples was sufficient, i.e. a good representation of the pressure profile. Based on the 100 sampled pressures, the whole design cases were solved with LS-DYNA on Linux

Networx Evolocity II cluster, JVN, at the ARL High Performance Computing Center. Each analysis took approximately two hours of CPU time on 8-thread parallel execution. In summary the gun- projectile system was subjected to the described stochastic excitations, the system responses would be stochastic even with a deterministic projectile system.

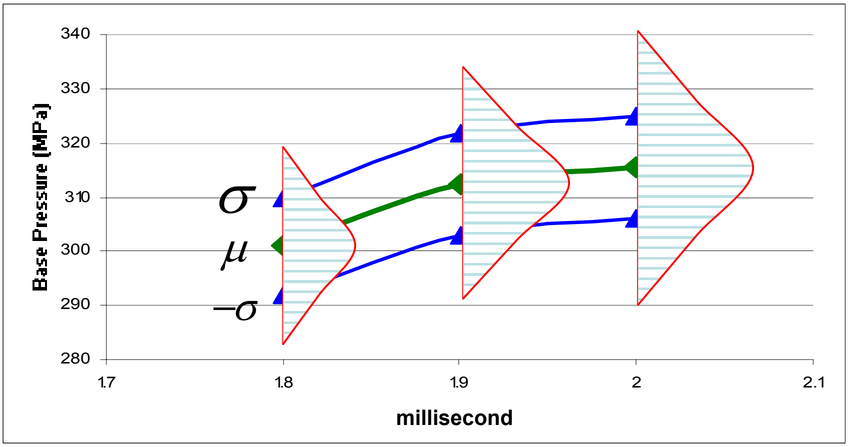

Figure 4: Gaussian distributions of base pressures at the time steps of 1.8, 1.9 and 2.0 ms from ignition, respectively.

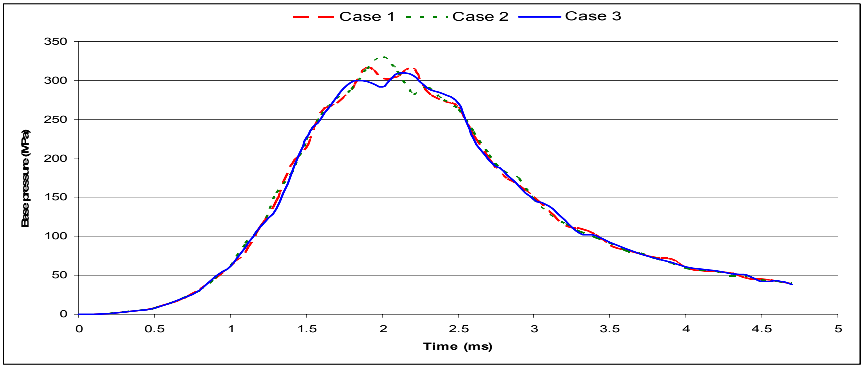

Figure 5: Pressure curves of the first three design cases.

4 Stochastic responses

The dispersion of in-bore projectile responses including peak velocity, peak acceleration, von Mises stress and travel distance, was obtained. The scattering of the values provided insight into what variations and ranges of the projectile responses should be expected even in a normal circumstance. The derived statistical in-bore data are important for the design of the projectile system and may be further utilized for the analysis of exterior ballistics and terminal effect evaluations.

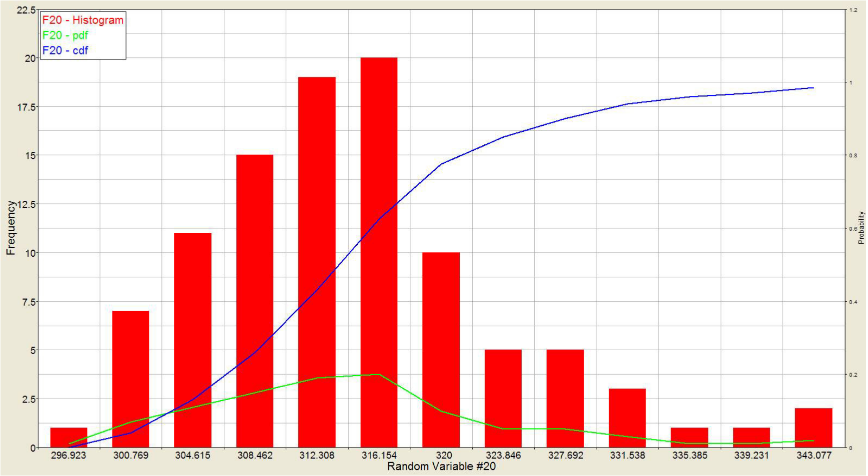

Figure 6: Histogram of random variable #20, i.e. peak pressure distribution.

A histogram of the maximum in-bore velocity is showed in Figure 7. The average and standard deviation of the velocity were approximately 1551 m/s and 12.4 m/s, respectively. Due to a very low coefficient of variation (COV) of 0.8%, most computed data were centralized at the mean. Given an assumption of Gaussian response, which is acceptable in this case, there was a 99.7% likelihood that the axial velocity responses would fall into the range between 1514 m/s and 1588 m/s, i.e. within three standard deviations of the mean.

Figure 8 displays the distribution of peak accelerations. The mean value of the response was 85,000 g. Unlike velocity, the accelerations exhibited high spread, which was because of inconsistent occurrence time, i.e. the peak accelerations occurred at the time step where the peak pressures took place. One can see the time distinction for the peak values of the pressure curves as demonstrated in Figure 5. As a result, the peak accelerations appeared to be a non-Gaussian distribution. In terms of stress responses, a point of the projectile body in which the highest stress happened was selected. The histogram of the von Mises stress distribution of the point with a mean value of 952 MPa is shown in Figure 9. As expected, a wide range and a non-Gaussian distribution of the responses from 894 MPa to 1020 MPa were derived.

The response statistics of the projectile including mean, COV, minimum and maximum values are summarized in Table 1. Note that the acceleration and stress responses had higher COV of 3.1% and 3.0%, respectively. The second order derivatives exhibited equivalent COV level compared with the applied pressure. The displacement response showed a COV of 0.67%, a much smaller

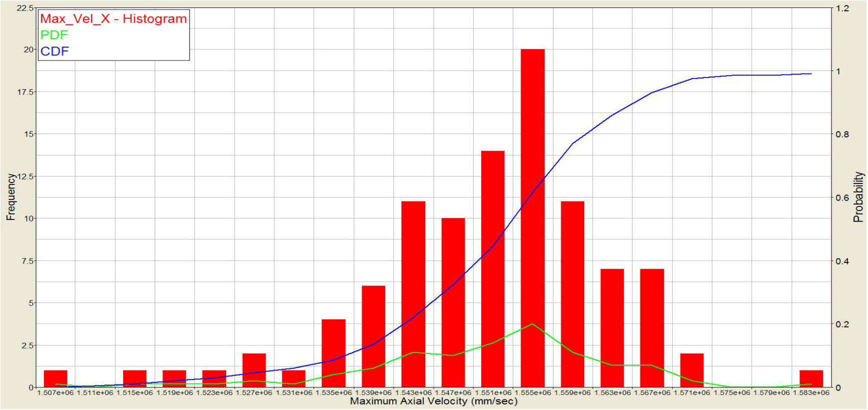

Figure 7: Histogram of maximum axial velocity distribution.

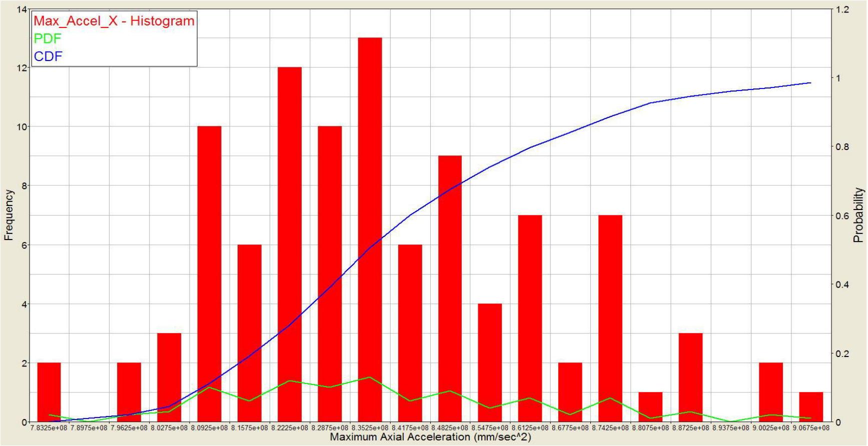

Figure 8: Histogram of peak axial acceleration distribution.

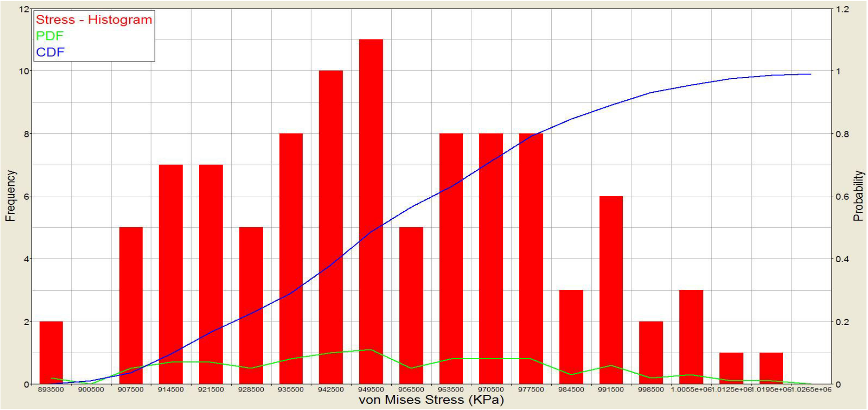

Figure 9: Histogram of peak von Mises stress distribution at projectile body.

Table 1: Response statistics of a 60-mm projectile subject to random excitations.

Response	Mean	Coefficient of Variation	Minimum	Maximum
Peak velocity (mm/s)	1.55×10^6	0.80%	1.506×10^6	1.583×10^6
Peak acceleration (mm/s^2)	8.38×10^8	3.1%	7.80×10^8	9.09×10^8
von Mises stress at projectile body (KPa)	9.52×10^5	3.0%	8.94×10^5	1.02×10^6
Travel Distance (mm)	3770	0.67%	3699	3847

variations as expected. The mean value of the travel distance was 3770 mm with a standard deviation of 25.3 mm. It implies that the time duration of the pressure curve should have been a bit longer than 4.7 ms for the projectile to reach the muzzle. Based on the simulated results, the likelihood to travel through the barrel within the time frame was less than 10%. The discrepancy was probably due to the slight difference in the total mass of the launch package used in computer modeling and IBHVG2.

The relationships among responses were of interest as well in this study. Figure 10 provides the scatter plot of the peak acceleration against the von Mises stress responses. Overall speaking, a positive trend is seen from the plot. However, the level of correlation was not considerably high because the locations where the nodal acceleration and the element stress were obtained were not identical. Another scatter plot that represented the relationships between the maximum axial velocity and the travel distance is given in Figure 11. As anticipated, the data demonstrated a very strong correlation. The relationships should help derive required muzzle velocity given a certain length of gun barrel. It should be noted that having scatter plots between random variables and responses are not very meaningful because the 47 random variables were not completely independent in terms of their contributions to the total responses. No clear pattern was found between any instant pressure variable and any of the projectile responses.

5 Summary

A pressure-time curve that consisted of 47 data points was adopted for the stochastic study. The pressure at each data point was considered as a normally distributed variable. The variations of the pressure were used to account for the uncertainties from a number of inherently uncontrollable factors that are associated with propulsion thrust generation. A slight 3% coefficient of variations for each random variable was employed to support the evidence that the dispersion of in-bore projectile responses exists in daily experimental shooting even with the same gun, the same cartridge and the same projectile system.

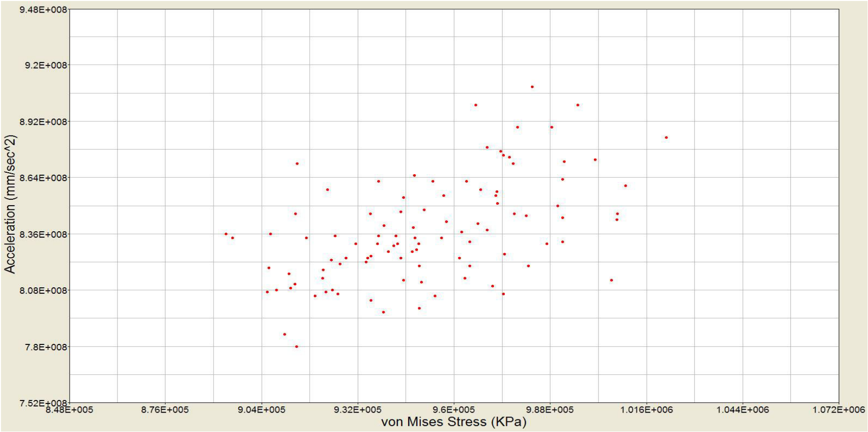

Figure 10: Scatter plot of von Mises stress vs. maximum acceleration.

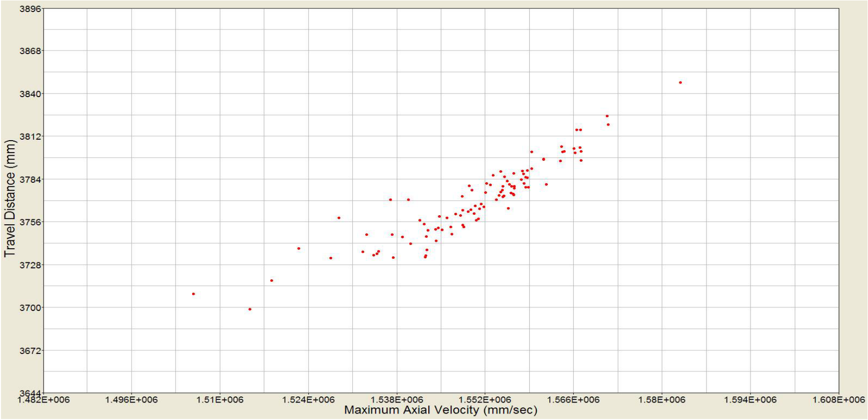

Figure 11: Scatter plot of maximum axial velocity vs. total travel distance.

A deterministic 60-mm projectile system and a 64-cal smooth bored gun were used. The composite projectile system was simplified in the nose and fin areas in order to increase computational efficiency. A total of 100 distinctive pressure curves that consisted of 47 Gaussian variables were created based on Monte Carlo simulation techniques. The corresponding in-bore projectile responses to each pressure sample were then obtained.

Given 95% likelihood, the highest in-bore velocity should fall into the range from 1526 m/s to 1575 m/s, the peak acceleration from 80170 g to 90735 g, the maximum von Mises stress of the projectile body from 894 MPa to 1009 MPa. The variations should serve as a guideline for the design of the 60-mm gun-projectile system. In addition, the computed response ranges should be anticipated from experimental results even under regular shooting environment.

Acknowledgement

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