High Fidelity In-Bore Pressure Modeling

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Abstract

Significant research efforts have been conducted to gain an in-depth understanding of projectile-weapon interactions at the U.S. Army Research Laboratory. The objective of this paper is to increase the fidelity of in-bore modeling and simulations that will facilitate the development of component and system models for U.S. Army weapon systems. Specifically, the in-bore pressure as a projectile travels through a gun tube, which has been known to be spatially and temporally varying distribution, will be programmatically taken into account in finite element analysis of launch dynamics.

A computer program that embeds IBHVG2 Interior Ballistics code was implemented to automate the process. This tool can apply a substantial number of pressure curves to the corresponding barrel locations and generate LS-DYNA® compatible keyword files for analysis. The approach yields better accuracy and eliminates tedious manual efforts. In short, the development greatly streamlines the modeling efforts and significantly increases the fidelity of in-bore pressure modeling.

Introduction

A mission program to investigate small caliber ammunition and weapon functions was performed by the U.S. Army Research laboratory (ARL). The objective of the program was to gain better understanding of the events that occur during the firing of a small caliber round as well as the dynamic chain of weapon events including round insertion, primer strike, ignition, shot start, engraving, extraction, ejection, and launch dynamics. Over the past few years, significant research efforts have been conducted under the Small Arms program and numerous technical reports have been published at the ARL [1-12]. One of the work units concerning ballistic technologies was to develop a complete simulation capability including in-bore modeling, experimental validation of the projectile-weapon interactions, and ballistic analysis. It was expected that the combined efforts should provide an in-depth understanding of small caliber ammunition. This paper addresses high fidelity in-bore pressure modeling that can facilitate the development of component and system models for small caliber weaponry. Specifically, space- and time-dependent in-bore pressures were directly computed with Lagrange formulation, a better approach compared with traditional linear interpolation. In addition, a computer program was implemented to enable the calculated pressures to be applied to the finite element model of a gun barrel programmatically for analysis.

When one dealt with gun tube pressurization, the time history of in-bore pressures was generally obtained for certain locations from interior ballistics codes, such as IBHVG2 (Interior Ballistics of High Velocity Guns, version 2)[13]. Subsequently, a linear interpolation of the derived pressure-time curves needed to be performed for a number of small increments along the gun tube in order to account for spatial variations. In general, the entire set of the pressures is imported to a preprocessor, such as HyperMesh, and then each pressure curve is applied to the elements associated with the inner surface of the gun tube at the corresponding location. That is one dedicated pressure-time curve needs to be associated with each ring to account for spatial variations. Lastly, a LS-DYNA keyword file that includes the spatially varying pressures can be written out by a utility function within HyperMesh. Note that the way to apply the pressures is a manual process since no explicit formulation can be specified for the space-time-dependent pressurization in the command keyword file of LS-DYNA. For instance, when 500 locations are selected along a gun barrel, i.e. 500 rings from geometric perspective, the whole process to manually apply 500 pressure-time curves on the respective rings is too cumbersome and sometimes infeasible. For clarification, an illustration of rings along down bore distance of a gun tube is given in figure 1. Because of the time-consuming and tedious steps, an initiative to automate the pressurization was launched to minimize the workload. In addition, there is no direct linkage between IBHVG2 and LS-DYNA such that the calculated in-bore pressures can be directly transferred to the finite element model of a gun system. Thus, a console application was developed to perform the following tasks at one fell swoop: (1) trigger IBHVG2 execution on the fly for pressure calculations; (2) create load curves at desired time steps; (3) parse LS-DYNA keyword file for extracting element information; (4) associate elements with a corresponding pressure curve; and (5) generate a final keyword file for explicit dynamic analysis.

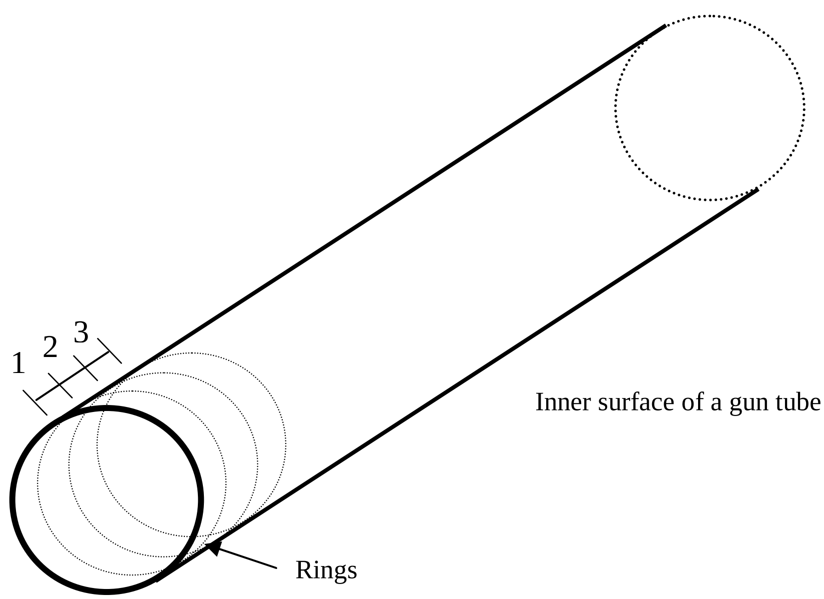

Figure 1 Illustration of rings in a gun tube

Software Implementation

A computer program named Pressurizer was developed to automate pressurization on a small caliber gun tube. The intent of the software system was driven by functional requirements. The baseline functionality necessary for the system is outlined below:

1. To increase the fidelity of the in-bore pressure gradient application, the spatially varying pressures should be calculated directly from IBHVG2 or from the Lagrange formulation instead of being linearly interpolated between base and chamber pressures.
2. A reasonable number of rings over the span of barrel length should be determined so that the spatial-time pressure variations can be better reflected.
3. The associated elements with each ring location should be programmatically selected over the finite element model of a gun barrel.
4. The pressure curve at each ring location should be automatically assigned to the prescribed element set.
5. The interaction with a preprocessor tool, such as Hypermesh, should be eliminated in the pressurization process and a complete LS-DYNA keyword file that contains the loading conditions should be created with Pressurizer.

Unified modeling language for writing software blueprints was employed to model the dynamics of the system with use case diagrams. A "use case" defines a goal-oriented set of interactions between external actors and the system under consideration. Actors are parties outside the system that interact with the system [14]. In this development, the actors are the end users and the use cases are the desired function requirements. The calculations of the pressure gradient require the space-time-dependent pressures derived from the Lagrange approximation. These must be explicitly defined in the computer codes. The formulation can be expressed by

$$P(x,t) = P_{breech} - \frac{w}{2}(P_{base} - P_{res} - P_{air})\left(\frac{x}{x_P}\right)^2 \tag{1}$$

in which P_{breech} = pressure at the breech

P_{base} = pressure at the base

P_{res} = bore resistance

P_{air} = air resistance

w = charge to projectile weight ratio

x_P = position of projectile base

The time history of breech pressure, base pressure, bore resistance, and air resistance can be obtained by issuing $TDIS commands from IBHVG2 execution [13]. Each $TDIS deck defines one variable, i.e., one of the trajectory-type output variables, to be printed out. They must be included in the input file. The ratio of charge to projectile weight is available in the IBHVG2 output file, which value can be parsed and directly used for the calculation. The weight ratio is a constant value, independent of time. The *x* variable refers to the axial direction of gun tube from ground reference system. The quadratic equation indicates that in-bore pressures from breech to base decay with the separation distance at the second order. To validate the equation used in IBHVG2, one can specify an array of gauge locations in $GUN deck that describes physical dimensions of the gun chamber and the tube. As a result, the pressure history at the corresponding locations can be retrieved. The gauge locations are based on the gun tube reference system, and are offset by the effective chamber length when compared with the results from equation (1).

When modeling the architecture of a software system, it is important to identify the "views" that are used to represent the architecture, including design view, implementation view, process view and deployment view. The implementation view that primarily concentrates on system assembly and configuration management, and the deployment view that mostly refers to distribution, delivery and installation, are less relevant to the objectives of this paper and therefore are not addressed here. The details for the design view and process view are outlined as follows.

The Pressurizer system is divided into four components that can be developed independently. The modular design is adopted for the purposes of scalability and maintainability. In addition, it provides simple interfaces that reduce the number of interactions when the intended functions are performed. The four function modules are described below:

Function Module 1		
Objective: Obtain time history of pressure components needed for pressure gradient calculations.		
Input	Process	Output
Preliminary IBHVG2 input decks (INP1)	1. Parse input decks 2. Revise input decks. 3. Trigger IBHVG2 on the fly 4. Execute revised input decks 5. Generate a result file	Output file from IBHVG2 execution (OUT1)

Function Module 2		
Objective: Compute Lagrange pressure gradient and create *DEFINE_CURVE cards		
Input	Process	Output
1. OUT1 file 2. *DEFINE_CURVE card options	1. Parse OUT1 file 2. Perform unit conversion 3. Retrieve ring locations 4. Calculate pressure gradient 5. Write files	1. LS-DYNA *Define_Curve cards (OUT2) 2. Optional pressure matrix 3. Optional ring file.

Function Module 3		
Objective: Determine loading element faces and create *LOAD_SEGMENT cards		
Input	Process	Output
1. Preliminary LS-DYNA keyword file (INP2) 2. OUT2 file 3. *LOAD_SEGMENT card options	1. Parse INP2 file 2. Collect nodal and element data. 3. Determine order of nodes on the loading face of elements. 4. Associate nodes with pressure curves 5. Write a file	LS-DYNA *Load_Segment cards (OUT3)

Function Module 4		
Objective: Combine *DEFINE_CURVE and *LOAD_SEGMENT cards with preliminary LS-DYNA keyword file.		
Input	Process	Output
1. INP2 file 2. OUT2 file 3. OUT3 file	Append OUT2 and OUT3 files into INP2	Enhanced LS-DYNA keyword file

Function module 4 is intended to append *DEFINE_CURVE and *LOAD_SEGMENT cards created from modules 2 and 3 to the end of the preliminary LS-DYNA keyword file. Any pre-existing *DEFINE_CURVE and *LOAD_SEGMENT cards are not to be removed and therefore remain valid in the keyword file [15].

A flowchart is a schematic representation of an algorithm or a process. It provides people with a common language or reference point when dealing with a project or process. In addition, it is an easy-to-understand diagram and therefore a useful tool for communicating how processes work, and for clearly documenting how a particular job is done. Figure 2 demonstrates a high-level flow chart of the Pressurizer, where detailed data and document processing are ignored. Generally speaking, the elapsed time for the whole process was less than three minutes on an Intel Pentium M processor.

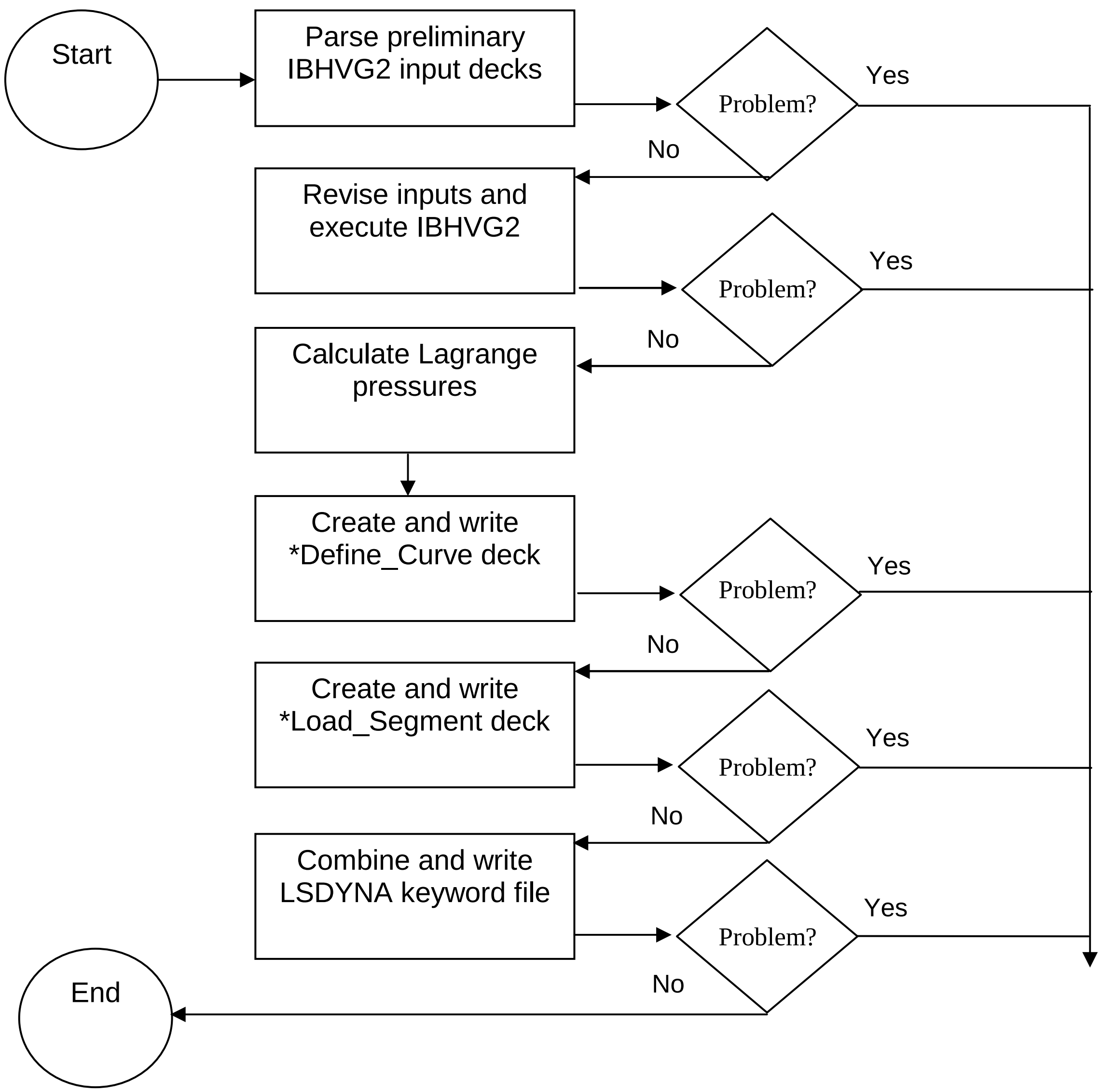

Figure 2 Flow chart of Pressurizer

The Pressurizer is a console application that can be executed in MicroSoft Disk Operating System (DOS) environment. It is a command driven program written in C# language, a new object oriented programming language for .NET environment developed by Microsoft. The DOS command to run the Pressurizer is "C:\> Pressurizer MyInputFile" in which MyInputFile is the input command file. The Pressurizer.exe and the input file can reside in different folders as long as the whole path of the input file is specified. In addition, since Pressurizer is designed to trigger IBHVG2 on the fly, both executable files must be in the same working directory. A log file named Pressurizer.log, which contains time stamps and any error message for the process, will be automatically created while the application is running. The log file and any associated output files will be generated in the working folder.

As prescribed, the Pressurizer consists of four different modules. Each module can be executed separately. Some cards are required and some are optional in a module. The cards required for each module are listed in the following:

Module 1: *RUN_IBHVG2
Module 2: *CREATE_LAGRANGE_PRESSURE_GRADIENT
Module 3: *CREATE_PRESSURE_LOAD; *SET_BORE_DIAMETER; *SET_PART_ID
Module 4: *CREATE_DYNA_FILE

The order of input cards can be random in an input file. The Pressurizer reads through the input file before starts processing any commands. Each input card consists of a number of fields separated by a comma. Detail specifications for each field are available in an ARL technical report [16]. The information include data type (text, integer or float), required (yes or no), I/O (input or output), description and default value.

Demonstration of Software Application

An M855 ball model of 5.56-mm round shown in figure 3 is used to demonstrate the results of the software application. The M855 cartridge is a 62-grain, gilded metal-jacketed, lead alloy core bullet with a steel penetrator. The firing weapon, an M4 carbine, a compact version of an M16A2 rifle, shown in figure 4 is also used in this study. A finite element model was created for the gun barrel model of the M4 carbine. Figure 5 displays the barrel model, which has a length of 12.82 inches. The total in-bore travel time for the M855 bullet was 0.98 ms. No preprocessor was found to provide contour displays of space-time-dependent pressures over the finite element model of the gun barrel. Therefore, the spatially varying pressures along down bore distance from rear face of the gun tube were calculated at selected times.

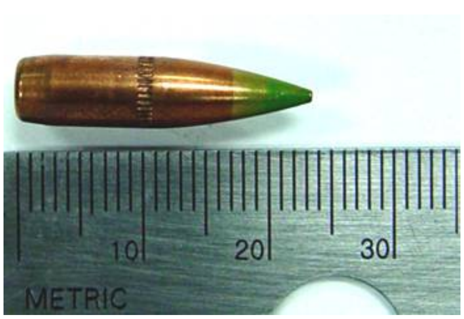

Figure 3 Display of M855 (5.56 mm) bullet

Figure 4 Display of M4 carbine

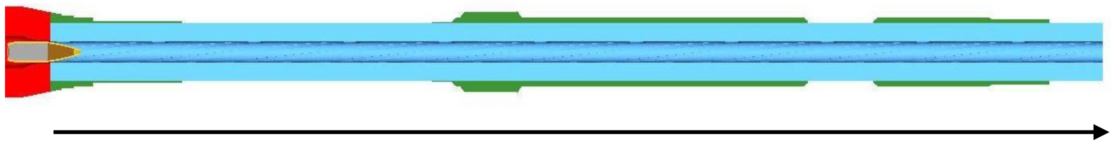

Figure 5 Gun barrel model of a M4 carbine

Figure 6 shows the plot of pressures vs. distance, which align with the barrel model for easy side-by-side comparison. Since the bullet had no movement until 0.18 ms from ignition, a start time of 0.2 ms was chosen. An increment of 0.1 ms was adopted thereafter until the bullet reached the muzzle. As a result, the chart includes nine different pressure-distance curves. Because of very small displacement, i.e., 1.236×10^{-4} inch, the curve at 0.2 ms is not visible. The pressure gradient along the distance appears to be high at peak pressure level and becomes more uniform as the bullet exits the barrel. On the other hand, figure 7 provides the relationships between pressure and time at selected in-bore bullet locations. Similarly, at certain down bore distance, no pressure should exist until the time when the bullet travels to the location. For instance, at x = 1.0 inch, the pressure initially stays at zero and suddenly rises to 46,000 psi at 0.51 ms. Note that when sufficient number of curves are provided, an envelope that traces the spikes of the curves is equivalent to the pressure applied to the base of the projectile. For comparison, the time history of the base and breech pressures is given in figure 8.

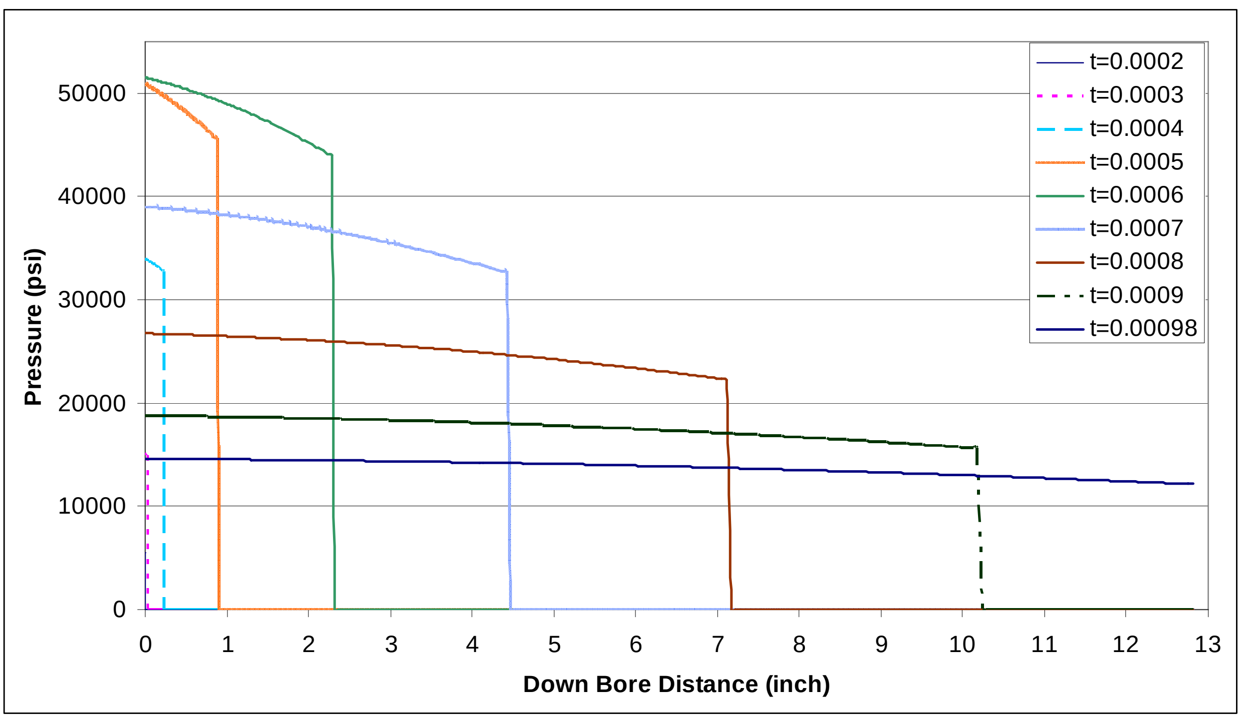

Figure 6 Plot of spatially varying pressure curves at selected time instant

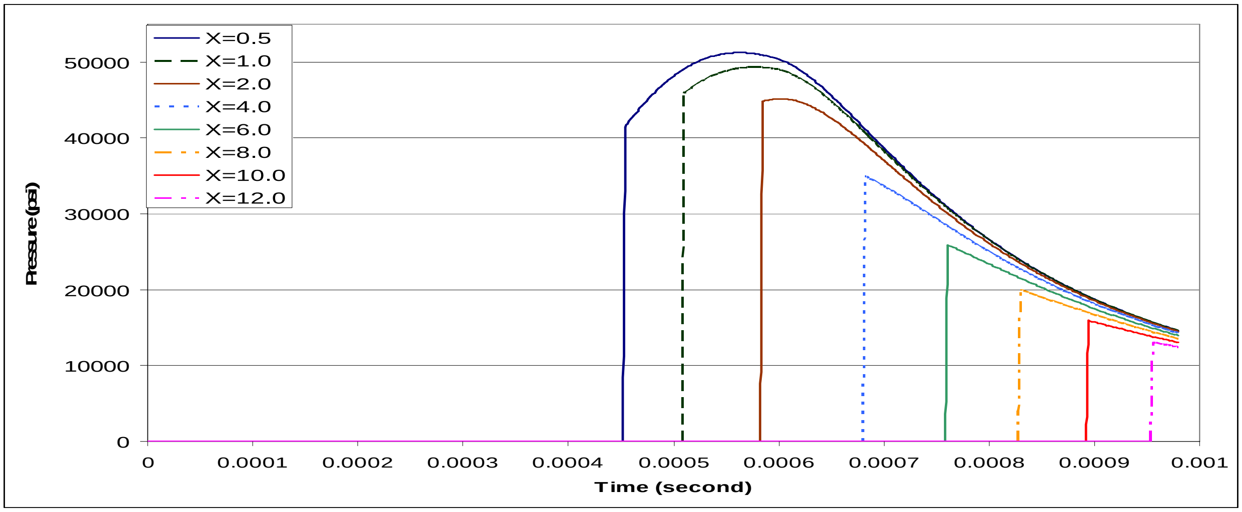

Figure 7 Plot of time-dependent pressure curves at selected locations (inch)

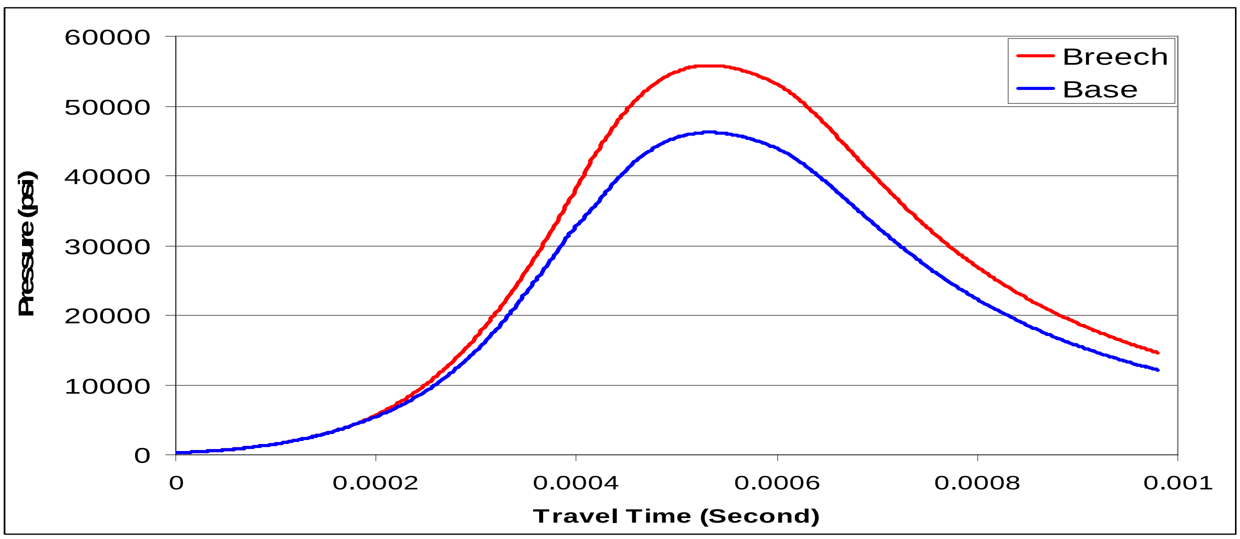

Figure 8 Computed breech and base pressure-time curves

Summary

A console application program was implemented to eliminate tremendous manual efforts in defining and applying space-time-varying pressures on finite element models of gun barrels. The computer program coupled with IBHVG2 interior ballistics code was designed to leverage some outputs from IBHVG2 and to calculate in-bore pressures at any given locations. Furthermore, the enhancement of LS-DYNA keyword files by incorporating Lagrange pressure gradient for explicit dynamic analysis was greatly streamlined through the application program. Many parsing techniques were developed to accomplish the prescribed efforts.

The circular diameter between two selected rings in the chamber area can be determined by linear interpolation. The value of the diameter is utilized to determine the elements on the chamber surface. Subsequently, the chamber pressure is applied on the elements. However, when the geometry of a curve shape exists in the chamber area, such as forcing cone, the technique of linear interpolation is not sufficient to adequately capture surface elements. In this case, mean gas pressure in the chamber, which is automatically populated and defined as ID#3, may be used and linked to the LOAD_SEGMENT keyword for the chamber area as a workaround.

An M4 carbine was utilized for demonstration. In fact, the tool is applicable to any size of gun barrels as far as the in-bore pressure variations are of concern. The software implementation is expected to improve the fidelity of modeling exact mechanisms that drive small caliber weaponry, and further allow for the development of weapons with increased performance and reliability.

Acknowledgement

A finite element model of M855 weapon system provided by Dr. Joseph South and utilized for the demonstration of the developed software application is appreciated.

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References

1. Horst A.W. and Conroy P.J., “Flamespreading Processes in a Small Caliber Gun,” Proceedings of the 54th JANNAF Propulsion Meeting, Denver CO, 14-17 May 2007.
2. South J.T., Kamdar D., Minnicino M., “Small Caliber Modeling from Design to Manufacture to Launch,” Proceedings of the 23rd International Symposium on Ballistics, Tarragona, Spain, PP. 557-564, 16-20 April, 2007.
3. Huang X., Conroy P. J. and Carter R., “5.56 mm Ceramic Gun Barrel Thermal Analyses with Cycled Ammunition", Proceedings of the 23rd International Symposium on Ballistics, April 2007.
4. Brant A. L., Williams A. W., Conroy P. J., and Colburn J. W., “Experimental Investigation of Inbore Trajectory Differences for Steel and Lead Core Projectiles,” Proceedings of the 41rst CS/ 29th APS / 23 PSHS Joint Meeting, San Diego California, 3-8 December 2006.
5. South J, Keppinger R., Minnicino M, “Evaluation of Finite Element In-Bore Predictions and Experimentally Soft Recovered 5.56mm Projectiles,” ARL-TR-3967, U.S. Army Research Laboratory, Aberdeen proving Ground, MD, October 2006.
6. Ehlers T., Guidos B. and Webb D., “Small-Caliber Projectile Target Impact Angle Determined from Close Proximity Radiographs”, ARL-TR-3943, U.S. Army Research Laboratory, Aberdeen proving Ground, MD, October 2006.
7. South J., Yiournas A. and Minnicino M., “The Effect of Slug Material on the Behavior of Small-Caliber Ammunition”, ARL-TR-3901, U.S. Army Research Laboratory, Aberdeen proving Ground, MD, September 2006.
8. Bujanda A. and South J., “Analysis of Candidate Green Ammunition Slug Materials,” ARL-TR-3927, U.S. Army Research Laboratory, Aberdeen proving Ground, MD, September 2006.
9. South J., Prichett J, Weerasooryia T., Moy P., Yiournas A., “Experiments and Numerical Predictions to Evaluate the Stress Strain Response of a 5.56MM Projectile Jacket,” ARL-TR-3949, September 2006.
10. Weinacht P., Newill J. and Conroy P., “Conceptual Design Approach for Small-Caliber Aeroballistics With Application to 5.56-mm Ammunition”, ARL-TR-3620, U.S. Army Research Laboratory, Aberdeen proving Ground, MD, September 2005.
11. South J., “Thermal Analysis of an M4 with Cycle Ammunition,” ARL-TR-3629, U.S. Army Research Laboratory, Aberdeen proving Ground, MD, November 2005.
12. South J., Newill J., Kamdar D., Middleton J., Hanzl F., DeRosa G., “Bridging the Gap Between the Art and Science of Materials for Small Caliber Ammunition,” AMPTIAC Quarterly, 8, (4), 2004 pp. 57-64.

13. Anderson R. and Fickie K, "IBHVG2 – A User's Guide", BRL-TR-2829, Ballistic Research Laboratory, Aberdeen proving Ground, MD, July, 1987.
14. Booch G, Rumbaugh J. and Jacobson I, "The Unified Modeling Language User Guide", Addison Wesley, 1999.
15. LS-DYNA Keyword User's Manual Version 970, Livermore Software Technology Corporation, Livermore, CA.
16. Chen M. and South J., "Software Development for Automation of Space-Time-Varying Pressurization on Small Caliber Gun Barrels", ARL-TR-4197, U.S. Army Research Laboratory, Aberdeen proving Ground, MD, August 2007.