LS-DYNA User-Defined Internal Ballistic Modeling

Sirri Oğuz

NASA Johnson Space Center, Houston, TX

Abstract

One of the challenges in modeling deflagration of solid propellants with LS-DYNA is its limited capability, which is mostly applicable to airbag systems that use gaseous nitrogen generated by burning sodium azide. To overcome this limitation and enable the modeling of custom propellant grains with specific geometries, perforations, surface inhibitors, impetus, burn rates, and co-volumes, a user-defined burn model must be defined. In this study, a custom internal ballistic analysis code is integrated into LS-DYNA to simulate kinematic systems driven by pyro-mechanical devices such as pyro pushers, cutters, thrusters, separations bolts, ejection seat catapults, etc. Step-by-step guidance is provided on implementing a user-defined loading subroutine and the requirements for compiling a custom LS-DYNA executable along with a simple pyro thruster example.

1 Introduction

Internal ballistic analysis is described as the study of processes occurring inside a pyrotechnically actuated mechanical device from the moment the pyrotechnic material, typically a solid propellant or mixture of propellants, is ignited until the projectile completes its stroke or exits the barrel of the device. In aerospace and defense applications these pyro-mechanical devices are commonly referred to as Cartridge and Propellant Actuated Devices (CAD/PAD). CAD/PADs are frequently used in spacecraft applications for stage separation, booster jettison, service module jettison, parachute deployment, fairing separation and propulsion system fluid and gas flow control valves (pyrovalve). In defense and military applications, CAD/PADs are used in systems such as fighter jet crew egress systems, ejection seats, pylon jettison, and ballistic missile wing deployment systems, where rapid actuation is crucial.

CAD/PADs are powered by high pressure generated through rapid exothermic chemical reactions resulting from deflagration of propellants. In a constant volume vessel, the pressure primarily depends on the chemical and mechanical properties of the propellant such as grain geometry, which dictates the burning surface area progression, burn rate, isochoric flame temperature, molecular weight, particle size, and propellant mass. For stroking devices, the mechanical and structural aspects of the design govern the internal ballistics during combustion as the chamber volume expands. Key factors, including piston diameter, propelled mass, resisting and assisting external forces, friction, hydraulic and pneumatic dampers, and initial chamber volume, are critical components of CAD/PAD design and significantly influence the gas pressure profile throughout the stroke.

LS-DYNA built-in equation of state *EOS_PROPELLANT_DEFLAGRATION is used by many analysts to model the burning of a solid propellant in an expanding volume using Arbitrary Lagrangian-Eulerian (ALE) meshing and Fluid-Structure Interaction (FSI). However, for a mixture of custom-shaped propellants this approach is impractical and may require extremely demanding computational resources, especially considering that many pyro-mechanical devices operate over durations of a few hundred milliseconds, rather than microseconds. Another recently developed keyword command for modeling pyrotechnic devices is *LOAD_PYRO_ACTUATOR. This load command requires a pre-determined mass flow curve as a function of time and does not constitute a true internal ballistics burn model.

Modeling and analysis of a CAD/PAD involves simultaneously solving the governing equations of combustion and the kinematic equations of motion. While most custom ballistic analysis codes use traditional one-dimensional numerical solution methods to solve these equations with high accuracy, more complex mechanical designs with features such as non-linear external loads, linkages, locking mechanisms, shock absorbers, lubricants, and springs require Finite Element Analysis (FEA) or rigid body modeling tools to achieve accurate kinematic and structural solutions.

In this study, CADPROG internal ballistic analysis code, originally developed by Naval Surface Warfare Center (NSWC) Indian Head Division, is integrated into LS-DYNA as a user-defined loading subroutine to generate hot gas pressure through the combustion process inside a CAD/PAD while utilizing the kinematic and structural aspects of LS-DYNA. This integration enables ballistic calculations to be performed without explicitly modeling the propellant with an FEA mesh, thereby simplifying the simulation process and improving the computational efficiency.

2 CADPROG Overview

CADPROG is a one-dimensional internal ballistic code that utilizes time-dependent nonlinear equations of gas dynamics. Originally written in Fortran by NSWC Indian Head Division and recently updated with a MATLAB version by Argent Technology LLC, CADPROG has been extensively used by NASA JSC in development of various pyrotechnic devices, including parachute riser cutters, pyro pushers, pyrovalves, jettison thrusters and pin pullers, all with a high degree of accuracy and success. NASA continues to use the Fortran version, regularly updating the code to meet the specific demands of space applications.

CADPROG is capable of analyzing the deflagration of solid propellants in a range of geometries, such as multi-perforated cylindrical grains, spherical ball powders, flakes, slabs, and other custom shapes. The code can model single or dual-chamber pyrotechnic devices, accommodating a mixture of up to three different propellant types.

Figure 1 illustrates a simplified CAD/PAD thruster with a pyro gas generator (GG), a piston, internal shock absorber and external forces including friction. In order to calculate the internal gas pressure generated by the burning of solid propellant, a set of governing equations must be solved. These equations encompass the classical conservation of equations of mass, energy and momentum, along with an equation of state and the propellant burn rate equation.

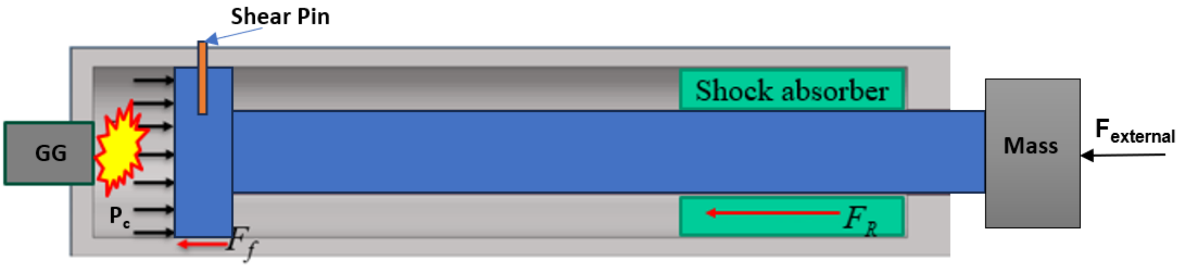


Figure 1: Simplified Pyro Thruster

CADPROG utilizes fourth-order Runge-Kutta method to solve the first-order governing ordinary differential equations of gas dynamics.

The conservation of energy for a propellant actuated stroking pyrotechnic device is represented by the following equation:

$$c_v \frac{d(m_p T)}{dt} = c_v T_0 \frac{dm_p}{dt} - A_P P_C \frac{dx}{dt} - \frac{d(E_{HL})}{dt} \tag{1}$$

The conservation of mass in the context of internal ballistics is defined as a function of the propellant burn rate and the burning surface area:

$$\frac{dm_p}{dt} = \rho.S.r \tag{2}$$

Propellant burn rate, *r,* is a function of the space-average pressure and is typically derived from the experimental data using the following equation:

$$r = BP_c^n \tag{3}$$

where *B* and *n* are empirical constants derived from the experimental data.

The Noble-Abel non-ideal gas equation of state (EOS) is employed to model the behavior of high-density propellant gases at elevated temperatures. This EOS establishes the relationship between chamber pressure, volume, and temperature, incorporating a non-ideal gas correction factor known as the co-volume, η. This factor accounts for the finite volume occupied by gas molecules, which becomes significant under the conditions present in the chamber.

$$P_c[V_c + A_P x - \frac{C - m_p}{\rho} - \eta m_p] = m_p F \frac{T}{T_0} \tag{4}$$

The chamber pressure, as derived from the equation of state, is then utilized to calculate the acceleration of the stroking piston by applying Newton's second law:

$$m\frac{d^2x}{dt^2} = P_c A_P - \Sigma F_{ext} \tag{5}$$

where F_{ext} is the total external loading, which includes friction, damping and any external resisting or assisting forces acting on the moving body.

3 CADPROG Integration into LS-DYNA

For relatively simple devices with well-defined external load conditions, the CADPROG equation of motion is generally adequate. However, in many applications, the loads can be highly non-linear, necessitating a more sophisticated modeling tool for accurate solutions. An accurate modeling of these loads is critical, as they directly influence the chamber pressure profile and the resulting acceleration, as described by Eq.4. For instance, a slower moving mass due to friction or other resisting forces will result in a higher chamber pressure because of the reduced rate of volume expansion.

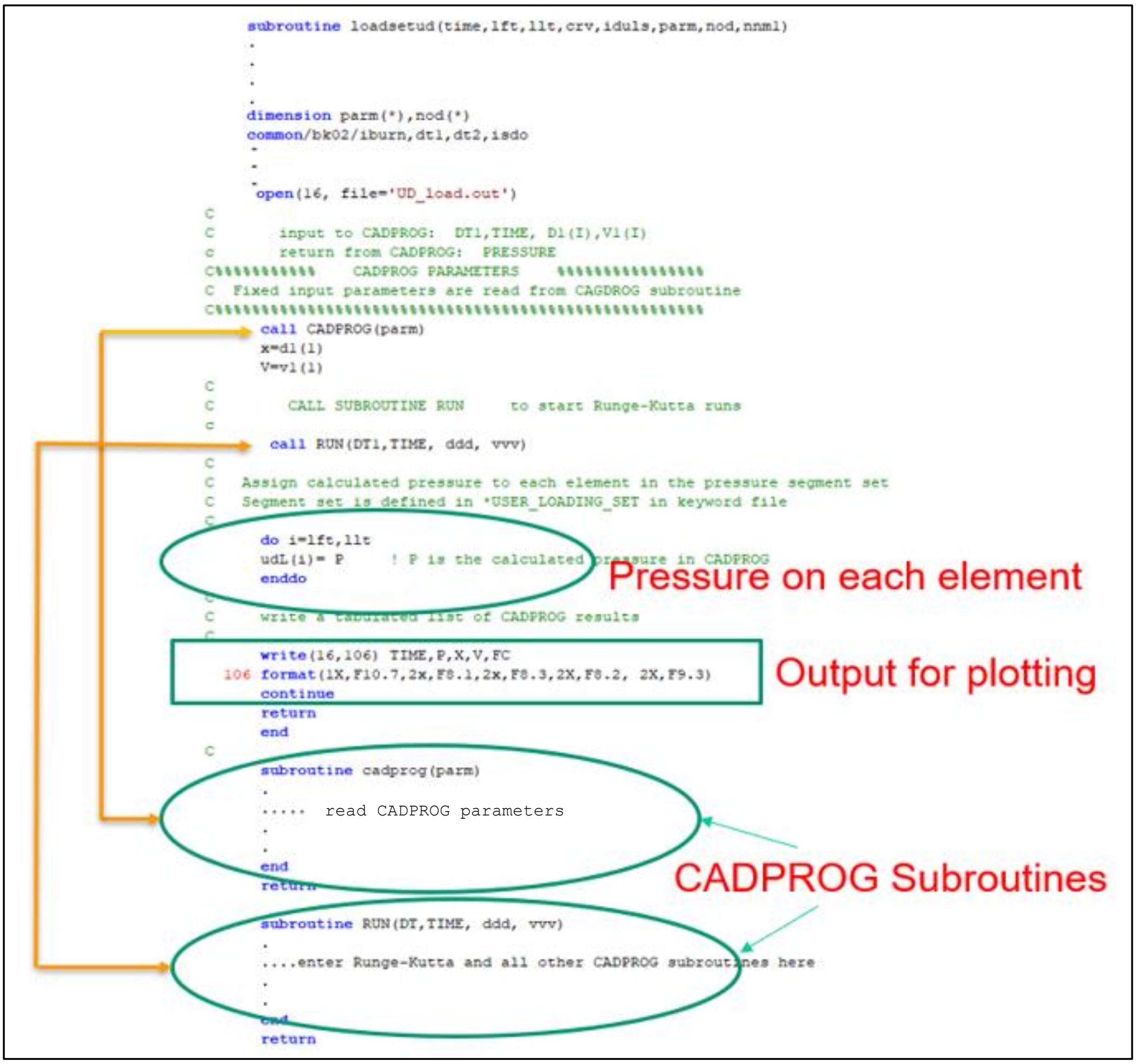
With the integration of CADPROG into LS-DYNA as a user-defined subroutine, CADPROG solves the equations of internal ballistics during each LS-DYNA time-step to determine the gas pressure, gas temperature and the fraction of propellant burned. These calculated pressure values are then passed to the LS-DYNA main routine, where they are applied to selected mesh surfaces. The resulting piston displacement is fed back to CADPROG, which initiates a new Runge-Kutta calculation using the updated chamber volume.

3.1 Creating LS-DYNA User-Defined Executable

Implementing a user-defined load model in LS-DYNA requires a Fortran subroutine source file to generate a custom LS-DYNA executable. The Fortran file *dyn21.f* can be obtained from Ansys, along with the necessary object files and a *makefile*. These resources allow the user to compile the modified *dyn21.f* file and ultimately create a new *lsdyna.exe* solver file. It is important to note that the *dyn21.f* must be compiled using the latest version of the Intel® Visual Fortran Compiler to ensure compatibility with the main code.

The dyn21.f file contains a set of subroutines that users can modify to create their custom-defined material models, loadings, constraints and element interfaces. For user-defined loading, the subroutine 'loadsetud' must be modified to integrate a custom code such as CADPROG. The subroutine 'loadsetud' receives inputs such as TIME, TIMESTEP, nodal displacements and velocities, element set for pressure application and the CADPROG input parameters which are defined in the input keyword file from the LS-DYNA run. The subroutine then returns the calculated pressure curve, *udL(i)*, interactively for each element "*i*" on selected pressure surfaces.

A shortened version of the modified 'loadsetud' subroutine is shown in Figure 2.



```
      subroutine loadsetud(time,lft,llt,crv,iduls,parm,nod,nnml)
      .
      .
      .
      .
      dimension parm(*),nod(*)
      common/bk02/iburn,dt1,dt2,isdo
      .
      .
      .
       open(16, file='UD_load.out')
C
C         input to CADPROG:   DT1,TIME, D1(I),V1(I)
c         return from CADPROG:   PRESSURE
C%%%%%%%%%%%%     CADPROG PARAMETERS     %%%%%%%%%%%%%%%%%
C  Fixed input parameters are read from CAGDROG subroutine
C%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
        call CADPROG(parm)
        x=d1(1)
        V=v1(1)
C
C          CALL SUBROUTINE RUN      to start Runge-Kutta runs
c
         call RUN(DT1,TIME, ddd, vvv)
C
C    Assign calculated pressure to each element in the pressure segment set
C    Segment set is defined in *USER_LOADING_SET in keyword file
C
        do i=lft,llt
        udL(i)= P      ! P is the calculated pressure in CADPROG
        enddo
C
C       write a tabulated list of CADPROG results
C
        write(16,106) TIME,P,X,V,FC
  106   format(1X,F10.7,2x,F8.1,2x,F8.3,2X,F8.2, 2X,F9.3)
        continue
        return
        end
C
        subroutine cadprog(parm)
        .
        .....  read CADPROG parameters
        .
        .
        end
        return
        subroutine RUN(DT,TIME, ddd, vvv)
        .
        ....enter Runge-Kutta and all other CADPROG subroutines here
        .
        .
        end
        return
```

Figure 2: Subroutine loadsetud modifications

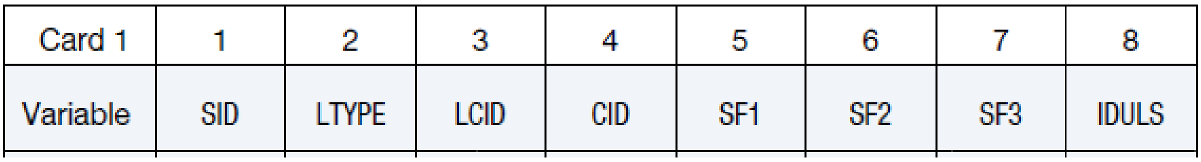
3.2 LS-DYNA Input Deck

Use-defined loading is invoked in LS-DYNA keyword input file (input deck) using two keyword commands:

*USER_LOADING_SET and USER_LOADING

*USER_LOADING_SET is used to define the type of loading and specify the element segment or nodal sets where the loading will be applied. The types of loading can be pressure, force, nodal body forces or nodal temperatures. For internal ballistics modeling, an element segment set and pressure loading type must be defined.

*USER_LOADING_SET



Card 1	1	2	3	4	5	6	7	8
Variable	SID	LTYPE	LCID	CID	SF1	SF2	SF3	IDULS

where,

- SID is the segment set ID of the pressure application surface. such as a piston head.
- LTYPE is the loading type “PRESSS”, which identifies it as pressure loading.

The original CADPROG code comprises 80 input parameters divided into three categories:

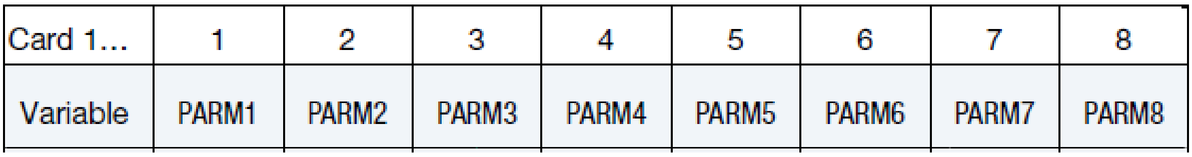
1. Chamber parameters such as chamber volume, initial ambient pressure and temperature, and heat loss parameters.

2. Propellant and ignitor parameters such as charge weight, density, co-volume, molecular weight, ignitor impetus, heat capacity, isochoric flame temperature, burn rate coefficients, and coefficients defining propellant geometry and surface area form functions.

3. Kinematic parameters such a piston area, total stroke, friction and other external loads, and accelerated mass.

In the integrated LS-DYNA model, all kinematic parameters are defined directly with the LS-DYNA FEA model, while the CADPROG parameters are provided using the *USER_LOADING command.

*USER_LOADING



Card 1…	1	2	3	4	5	6	7	8
Variable	PARM1	PARM2	PARM3	PARM4	PARM5	PARM6	PARM7	PARM8

where,

PARM1, PARM2….define the CADPROG input parameters for the propellant and the chamber.

4 Simple Pyro Thruster Example

A simple pyro thruster, as illustrated in Figure 3, with a 10-inch stroke and a 190 lbs mass (distributed in piston weight for simplicity) with various external load conditions is considered to demonstrate how these loading conditions directly affect the pressure profile while utilizing the same pyro gas generator across all cases.

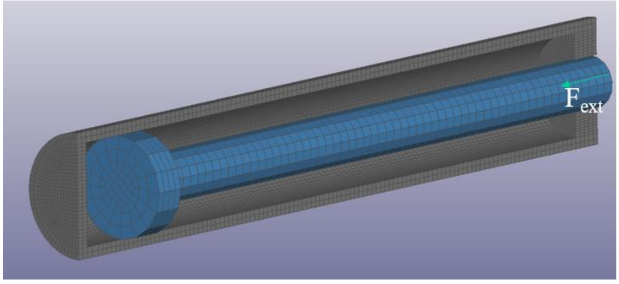
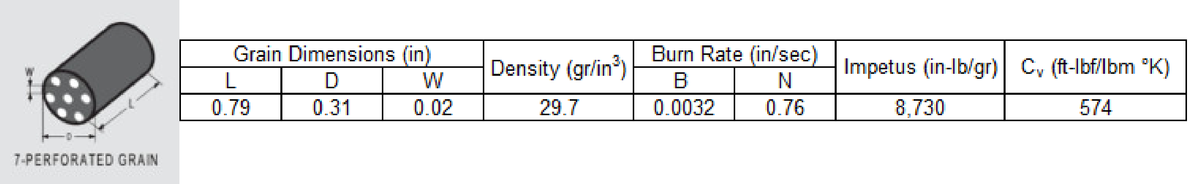


Figure 3: Simple Thruster FEA Model

The thruster housing is modeled using flexible steel material while the piston is made of rigid steel material. For this example, a 7-perforated HES5808 propellant is selected due to its well-characterized properties along with $BKNO_3$ ignitor, which is commonly used for these types of thruster designs. HES5808, manufactured by BAE Systems, is an Ammonium Perchlorate (AP) based composite propellant with relatively stable burn characteristics and frequently used in various defense and aerospace CAD/PAD applications. The HES5808 propellant properties used in this example are shown in Figure 4.



Grain Dimensions (in)			Density (gr/in^3)	Burn Rate (in/sec)		Impetus (in-lb/gr)	C_v (ft-lbf/lbm °K)
L	D	W		B	N		
0.79	0.31	0.02	29.7	0.0032	0.76	8,730	574

Figure 4: HES5808 propellant properties

Three load cases have been examined. As a baseline, a load case with zero external load was run to verify that the user-defined propellant burn subroutine is correctly implemented and yields the same pressure output as the original CADPROG code.

Figure 5 shows the pressure and velocity results obtained using CADPROG and the user-defined LS-DYNA model. Note that the LS-DYNA pressure curve in Figure 5 is interactively generated from the udL(i) output. The identical results confirm that the CADPROG subroutine correctly receives the kinematic output from LS-DYNA and returns the chamber gas pressure as expected. It is important to note that in this LS-DYNA model, an end-of-stroke final piston lock is used to fully stop the piston to prevent bouncing back, whereas in CADPROG, this is achieved by inputting a maximum allowable stroke.

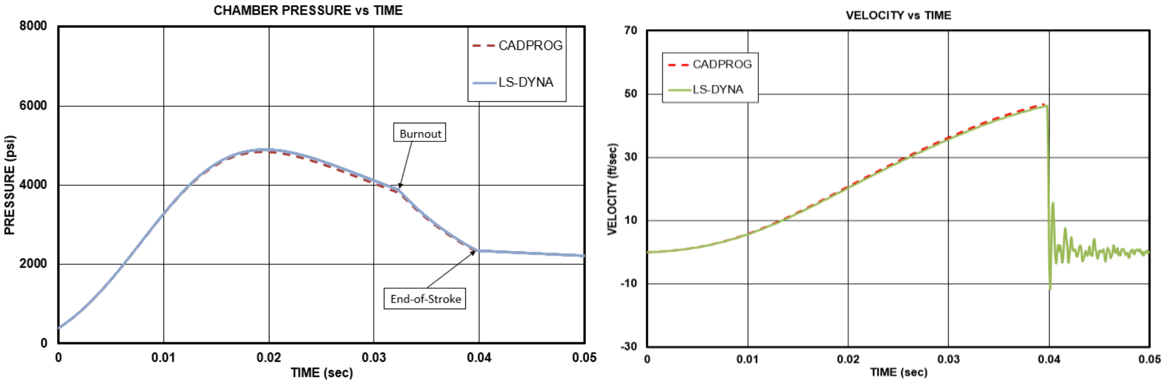


Figure 5: Pressure and Velocity Profile with LS-DYNA and CADPROG

Next, two cases with assisting and resisting external forces were analyzed. External loads were introduced by applying contact friction and positive or negative nodal forces to the piston end. As expected, the resisting forces slow down the piston, causing the propellant to burn in a slower-expanding chamber, which leads to an increase in peak pressure. In contrast, the assisting external forces, where a pull force is applied to the piston, increase the piston velocity. The increased velocity allows the propellant to burn in a faster-expanding chamber, resulting in a significant reduction in peak pressure. In fact, for the assisting load case where the pressure is the lowest, the pressure curve as shown in Figure 6 indicates that the propellant grains do not fully burn out before the end of the stroke whereas the high pressure case clearly shows complete burnout before the piston finishes its stroke. This highlights the significance of maintaining an optimal pressure profile for complete combustion, which is directly affected by the external loading conditions.

It is also important to note that the cases shown in Figure 6 do not include an end-of-stroke locking mechanism, allowing the piston to bounce back against the residual gas pressure. As the piston moves back, the residual pressure increases. If the model is run for an extended period of time, the CADPROG heat-loss module would eventually cause the pressures in all three cases to stabilize at a steady-state level within the final chamber volume.

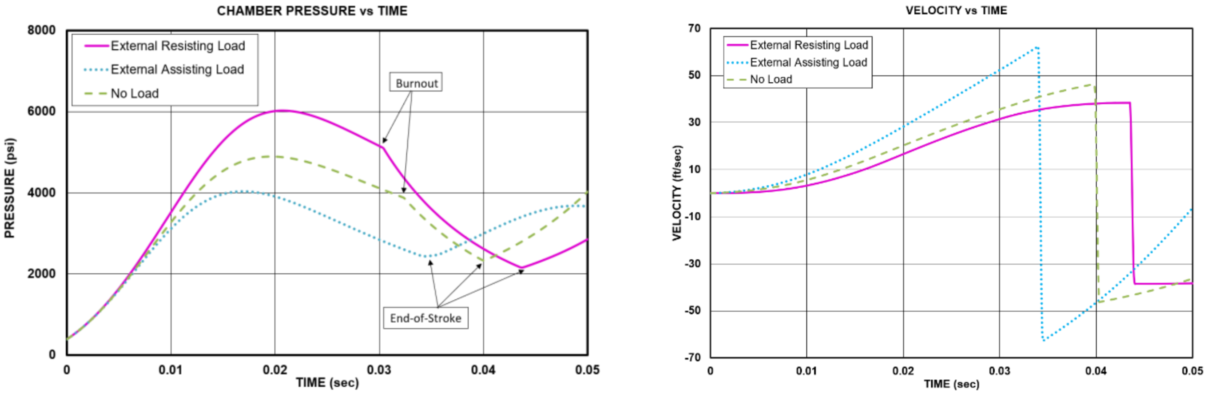


Figure 6: Pressure and Velocity for various load cases

5 Conclusion

The simple thruster example illustrates that designing a CAD/PAD pyrotechnic device requires an accurate gas generator charge sizing and interior mechanical/structural design to meet the specification envelope across all load cases and environmental conditions. The traditional development approach, relying on rough charge sizing and extensive testing, often leads to prohibitively expensive and time-consuming test programs while still failing to cover the full design domain. For instance, achieving a minimum muzzle velocity at the end of the stroke while keeping the peak pressure below a structural minimum across a wide range of temperatures and external load conditions can be extremely challenging. Test-based design-of-experiment (DoE) techniques are commonly used for an optimized design, but they often fall short as design complexity increases. A proven physics-based FEA model like LS-DYNA, combined with high-fidelity internal ballistics burn model, can significantly reduce the development timeline while accurately assessing untested design extremes.

A feed-back propellant burn model is introduced using the user-defined loading features and subroutine to analyze pyro-mechanical devices commonly known as CAD/PAD. The necessary modifications to the user-defined Fortran subroutine source file are summarized to integrate the custom internal ballistic code CADPROG. Users can easily follow the method outlined here to integrate their own load and burn models in a similar manner.

NASA JSC is currently working on further enhancements to the integrated code to incorporate additional features needed for more complex systems. In the current model, pressure is applied only to pre-selected meshed surfaces, such as the piston area and the initial chamber volume walls. Enhancing the model to update the pressure application mesh surface (e.g., inner walls of the gas chamber) as the piston strokes and the volume expands would enable real-time full structural analysis.

It is important to note that this model does not account for turbulent gas flow, where pressure fluctuations and unsteady flow effects play a significant role. Integrating CADPROG as a user-defined pressure generator with LS-DYNA Conversion Element/Solution Element (CESE) solver could be a promising area for further research. Implementing a user-defined equation of state with CADPROG within the CESE framework may address limitations of current EOS options, such as CESE_EOS_IDEAL_GAS or CESE_EOS_INFLATOR, which fall short in defining the ballistic parameters of solid propellants.

6 Nomenclature

A_p = piston diameter
B = burn rate coefficient
C = propellant mass
C_v = specific heat at constant volume
E_{HL} = heat loss energy
F = propellant impetus
F_{EXT} = external force
m = piston mass
m_p = mass of propellant gas produced
n = burn rate exponent
P_C = chamber pressure
r = propellant burn rate
S = propellant surface area
T = gas temperature
T_o = isochoric flame temperature
V_C = initial chamber volume
x = stroke
ρ = propellant mass density
η = propellant co-volume

7 References

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