LS-DYNA User-Defined Internal Ballistic Modeling

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2024 CAD/PAD Technical Exchange Workshop, August 13-15, 2024

Executive Summary

- LS-DYNA Explicit Finite Element Analysis software and CADPROG Internal Ballistic Analysis code are integrated as a single modeling tool to analyze pyro-mechanical devices.

- Coupling these two codes allows the ballistic calculations to be performed without modeling the propellant in an FEA mesh. At each LS-DYNA time step, CADPROG is run analytically using the kinematic data (stroke, velocity, chamber volume) fed back from the LS-DYNA simulation. The calculated pressure is then applied to a piston or any applicable surface mesh in LS-DYNA model interactively.

- All external loads such as friction, damping loads, assisting/resisting loads, locking/unlocking loads are modeled in LS-DYNA and coupled with pressure loads from CADPROG to create a fully defined equation of motion

- Both codes are written in Fortran 77. CADPROG is integrated in the LS-DYNA source code as a user-defined subroutine and recompiled to generate a custom executable.

LS-DYNA Overview

- Developed by Livermore Software Technology Corp (LSTC), LS-DYNA is a physics-based explicit FEA code that uses time integration to solve short duration transient and highly nonlinear dynamic problems
  - Extensive material model and Equation-of-State library, highly accurate contact algorithm and ability for Fluid-Structure Interaction (FSI) make LS-DYNA an excellent tool for evaluating complex mechanical and structural systems.

- Widely used for detonation problems using built-in JWL equation of state.

- While modeling the deflagration of a solid propellant with LS-DYNA is possible, it is very limited and mostly applicable to airbag systems that use gaseous nitrogen generated by burning of sodium azide.

- Allows users to define their own custom material models, equations of state and loading models through user-defined subroutines.

CADPROG Overview

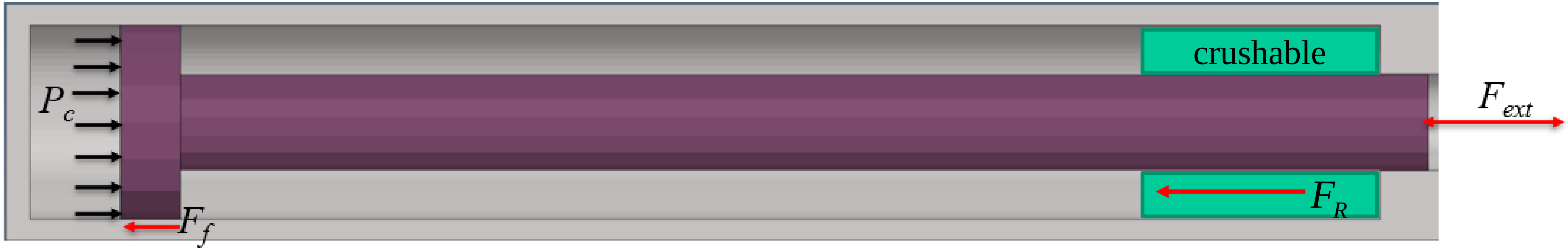
- CADPROG is a one-dimensional internal ballistic code developed by NSWC Indian Head Division and is widely used to analyze CAD/PAD devices and ejection seat catapults
  - Differential Equations of State and Energy are solved using 4th Order Runge-Kutta Method

- Capable of modeling solid propellants with many geometries, such as multi-perforated cylindrical grains, spherical ball powders, flakes, slabs.

- Single and Hi-Lo dual chamber CAD/PAD devices can be modeled with a mixture of up to three propellant types.

- NASA/JSC made various updates to the source code over the years to improve its capabilities:
  - *Improved heat-loss module for during and post-burnout heat loss*
  - *Added stroke-dependent external load capability*

Internal Ballistics - Governing Equations



- *Conservation of Energy*

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

- *Noble-Abel Equation of State*

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

- *Equation of Motion*

$$m \frac{d^2 x}{dt^2} = P_c A_P - F_f - F_R - F_{ext}$$

- *Conservation of Mass*

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

- *Propellant Burn Rate*

$$r = BP_c^n$$

With LS-DYNA/CADPROG feedback method, Acceleration is calculated by LS-DYNA using the CADPROG pressure and LS-DYNA Modeled Loads (friction, crush resistance, external aero, etc.)

Creating LS-DYNA User-Defined Executable

- Fortran source code that contains a collection of subroutines is required to create a custom LS-DYNA executable.
  - The Fortran file dyn21.f can be obtained from LSTC.
  - dyn21.f is modified by the user to integrate the user-defined loading, in this case the entire CADPROG code.
  - dyn21.f must be compiled by using the latest version of Intel® Visual Fortran Compiler.
    - Running the *makefile* supplied by LSTC compiles the file and links with the object files that are also provided.
    - The new LSDYNA.EXE file should be selected as the solver when running LS-DYNA.
  - Subroutine receives TIME, TIMESTEP, elemental X and V input and initial conditions from the LS-DYNA run, and outputs calculated pressure curve, udL(i), interactively for each element “i” on selected pressure surface.

User-Defined Loading Keyword Commands

- User-defined loading is invoked in LS-DYNA keyword file (input deck) with following keyword commands:

***USER_LOADING_SET**

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

ELEMENT SET id → SID

Load Type "PRESSS" → LTYPE

***USER_LOADING**

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

PARMi : CADPROG input parameters

User-Defined Mods to dyna21.f

```
      subroutine loadsetud(time,lft,llt,crv,iduls,parm,nod,nnml)
# 803

c
c**********************************************************************
c|  Livermore Software Technology Corporation  (LSTC)                |
c|  ------------------------------------------------------------     |
c|  Copyright 1987-2008 Livermore Software Tech. Corp                |
c|  All rights reserved                                             |
c**********************************************************************
c
c     Input (not modifiable)
c       time : analysis time
c       x    : coordinate of node or element center
c       d    : displacement of node or lement center
c       v    : velocity of node or lement center
c       temp : temperature of node or element center
c       crv  : value of LCURV at time=time
c       iduls: id of user_loading_set
c       parm : parameters from user_loading
c       nod  : internal node numbers
c       nnml : offset for node block
c     Output (defined by user)
c       udl : user-defined load curve value
      include 'nlqparm'
      common/aux8loc/
     & x1(nlq),x2(nlq),x3(nlq),v1(nlq),
     & v2(nlq),v3(nlq),d1(nlq),d2(nlq),
     & d3(nlq),temp(nlq),udl(nlq),
     & xx11(nlq),xx21(nlq),xx31(nlq),
     & xx12(nlq),xx22(nlq),xx32(nlq),
     & xx13(nlq),xx23(nlq),xx33(nlq),
     & xx14(nlq),xx24(nlq),xx34(nlq),
     & xctr(nlq),yctr(nlq),zctr(nlq),
     & f(nlq), tr1(nlq), tr2(nlq), tr3(nlq)
c
c
C
C     S.OGUZ 5/17/2023
C

      dimension parm(*),nod(*)
      common/bk02/iburn,dt1,dt2,isdo
      COMMON /RUNDAT/ XX(8),OLDX(8),FF(8),X,P,T,C,V,ACCEL,
     +                PL,PLA,TH,TL,CH,CL,FC
       open(16, file='UD_load.out')
```

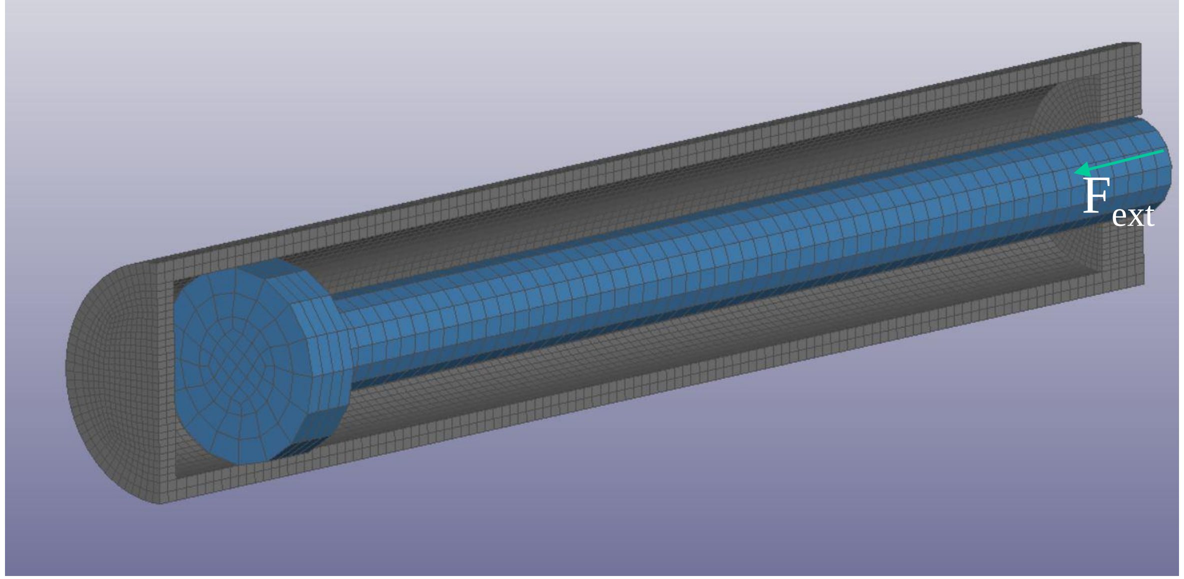
```
C
C        input to CADPROG:  DT1,TIME, D1(I),V1(I)
c        return from CADPROG:  PRESSURE
C%%%%%%%%%%%%    CADPROG PARAMETERS    %%%%%%%%%%%%%%%%
C  Fixed input parameters are read from CAGDROG subroutine
C%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
      call CADPROG(parm)
      x=d1(1)
      V=v1(1)
C
C         CALL SUBROUTINE RUN  TO 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)
      .
      .......enter cadprog fixed paramaters here
      .
      .
      end
      return

      subroutine RUN(DT,TIME, ddd, vvv)
      .
      ....enter Runge-Kutta and all other CADPROG subroutines here
      .
      .
      end
      return
```

Pressure on each element

Output for plotting

CADPROG Subroutines

Simplified Pyro Thruster Example



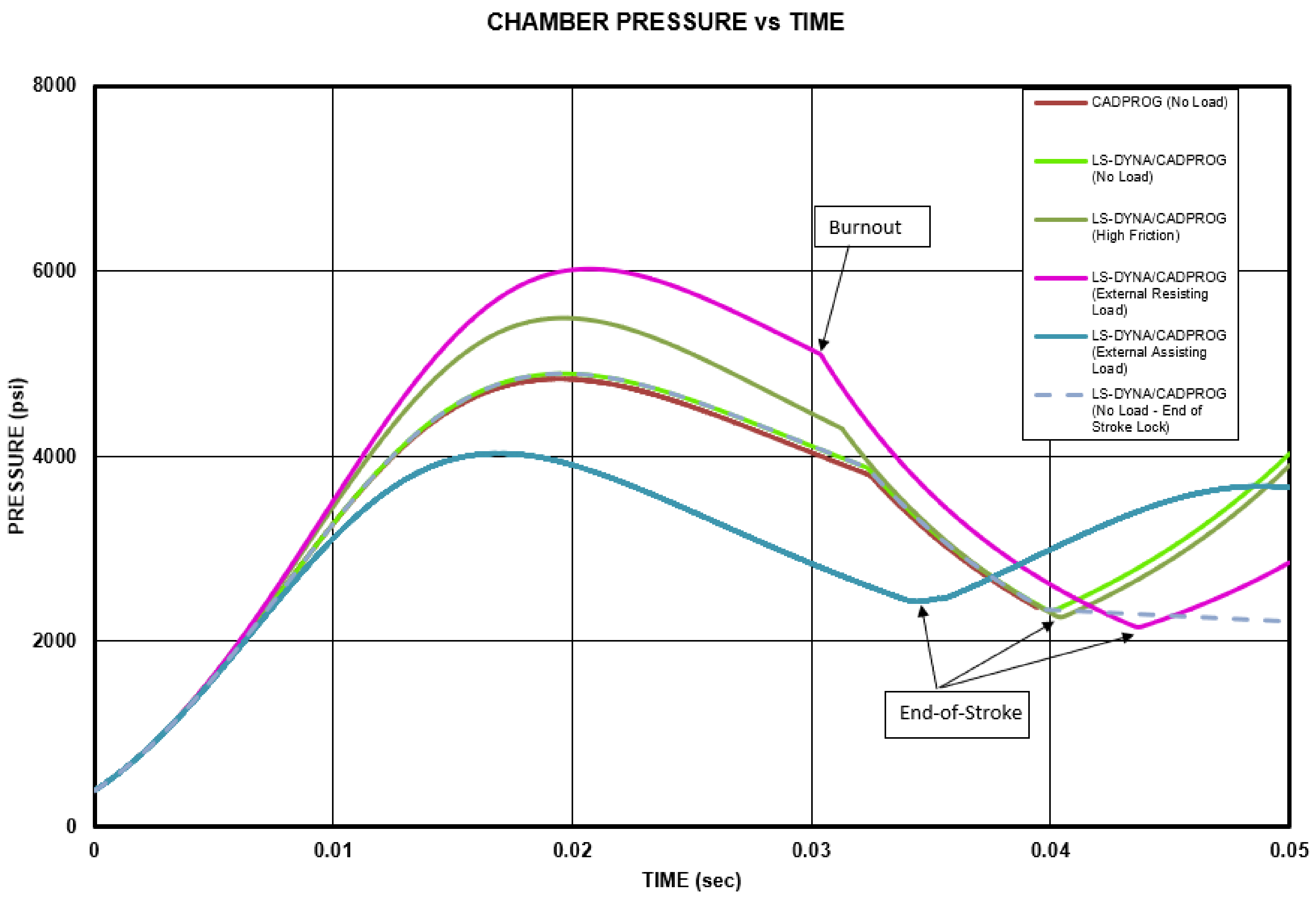
- Flexible Housing and Rigid Piston
- Piston pushes a 190 lbs mass
- FEA Model contains 26,256 solid elements
- Housing constrained at one end
- 10 inches of stroke

- *Propellant:* 7-perforated HES5808 grains
- *Igniter:* $BKNO_3$

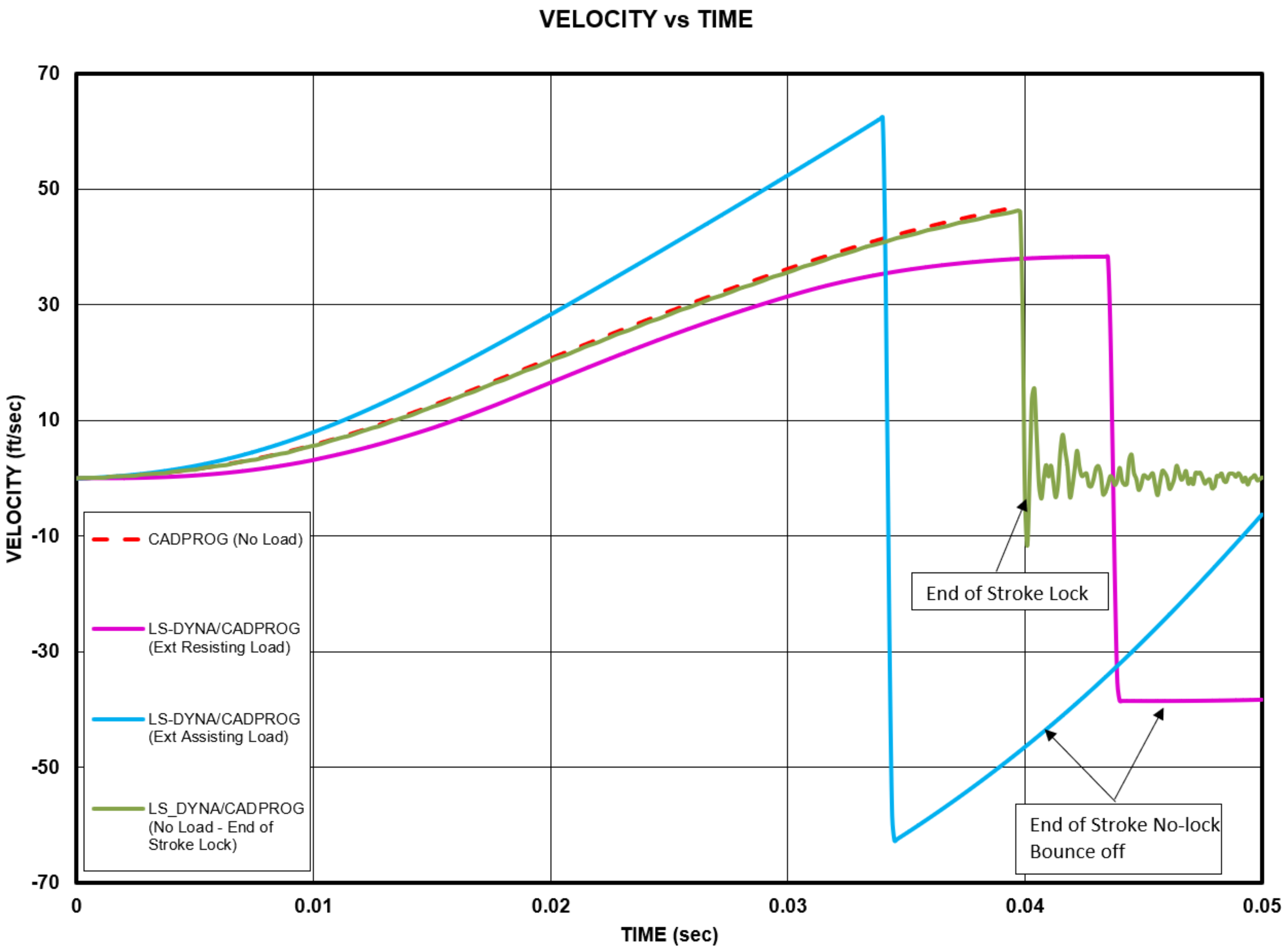
- Contact with static and dynamic friction coeff.
  *CONTACT_SURFACE_TO_SURFACE

- Various external assisting and resisting loads applied to piston end as nodal force.

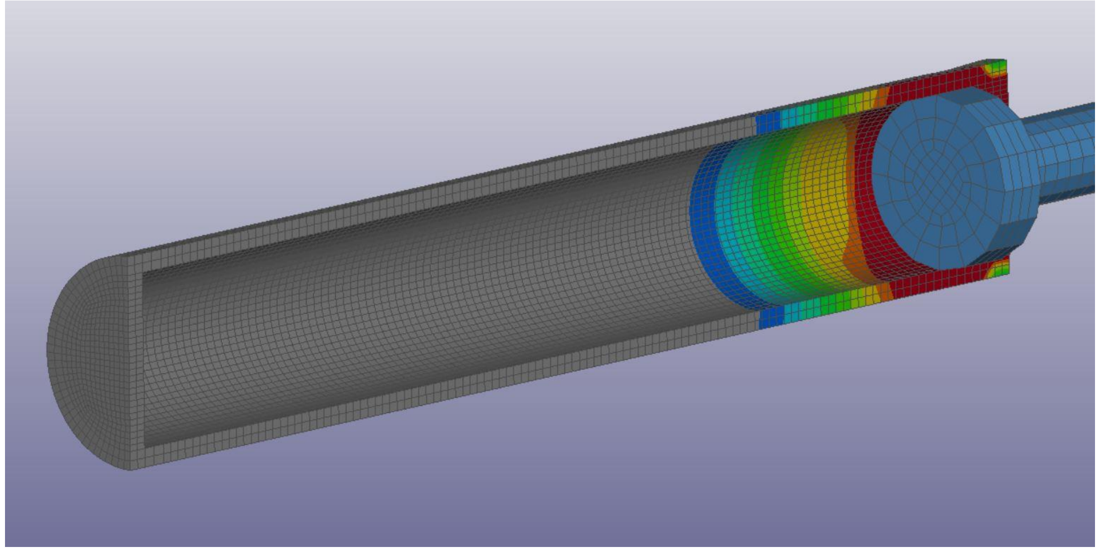
Pressure Results for various load conditions



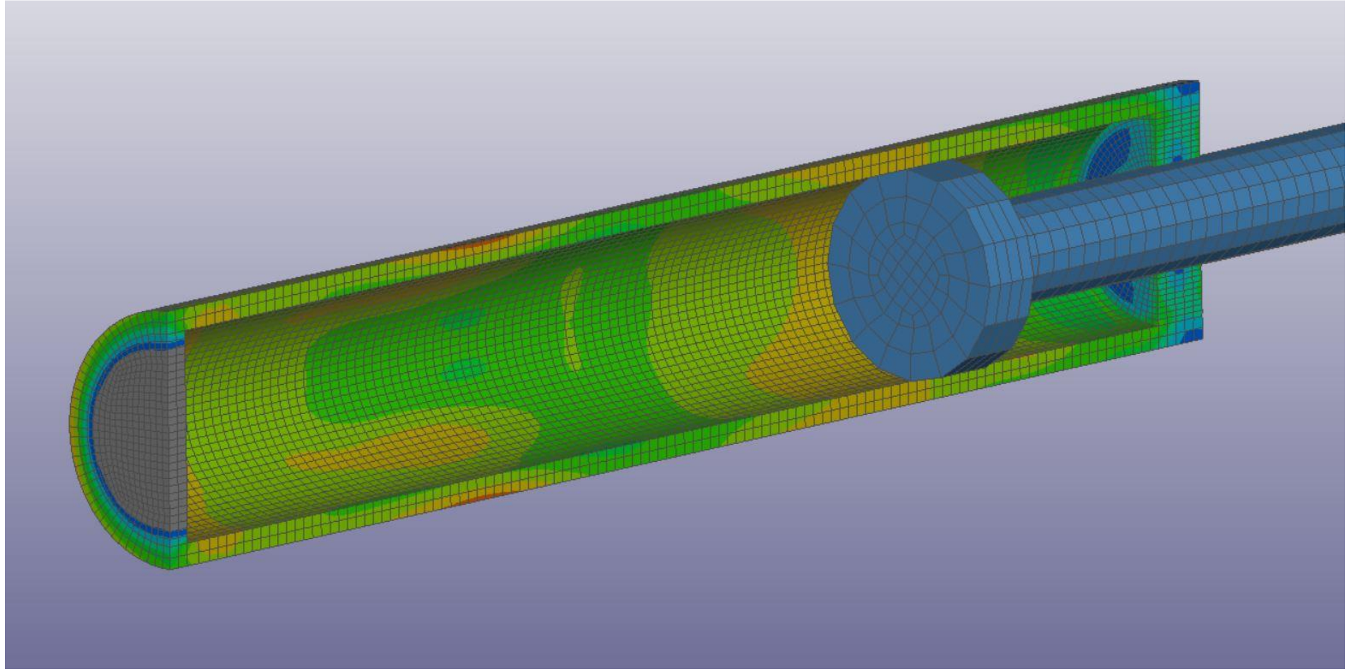
Piston Velocity



Post-Process Contours



End-of-Stroke Impact



Post impact bounce off

Future Work

- In our current model, pressure is applied only on pre-selected mesh surfaces such as the piston area and initial volume walls.

- Adding capability to update pressure application mesh surface (inner walls of gas chamber) as the volume expands will allow full structural analysis (stress, strain) in real time.
  - Euler mesh inside chamber volume with user-defined CADPROG EOS could be an option

- Hi-Lo chamber ballistic capability can be added to model the gas flow from high-pressure chamber to low-pressure chamber by using unique LS-DYNA solvers such as ICFD for incompressible and CESE for compressible flows.

Questions?

References

[1] Oguz, S and Salazar, F, “Orion Parachute Riser Cutter Development”, 47th AIAA Joint Propulsion Conference, San Diego, CA, August 1-3, 2011.

[2] LS-DYNA Keyword User’s Manual, Version R13, Livermore Software Technology Corporation.

[3] Holter, W.H., *Simplified Solutions to the Interior Ballistic Problems of Cartridge Actuated Devices*, U.S. Naval Weapons Laboratory, Report No. 1752, May 1962.

[4] Adoum, M., “Examples Manual for *USER_LOADING Option”, 4th European LS-DYNA Users Conference

Nomenclature

A_p=piston area
B= burn rate coefficient
C=propellant mass
c_v=specific heat at constant volume
E_{HL}=heat loss
F=impetus
F_{EXT}=external force
F_f =friction force
m=imparted 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
V=velocity
ρ=propellant mass density
η=co-volume

CAD/PAD = Cartridge/Propellant Actuated Device

JWL = Johns-Wilkins-Lee Equation of State