Development of a machine learning model to determine the forces on the piston in the pump-tube of a two-stage gas gun deforming due to a taper

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Abstract

Abstract here.

1 TODO

1. Get output parameters
2. Model automation
3. Mesh optimization

2 Introduction

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- We will use: ton, mm, s, N, MPa, N-mm

2.1 Gas gun design

2.1.1 title

3 Finite element model

3.1 Geometry

3.2 Interactions

3.3 Material models

The material models used for each component are presented here.

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MASS	LENGTH	TIME	FORCE	STRESS	ENERGY	Steel Density	Steel Modulus	G - Gravity Constant
kg	m	s	N	Pa	Joule	7.83E+03	2.07E+11	9.81
kg	mm	ms	kN	Gpa	kN-mm	7.83E-06	2.07E+02	9.81E-03
g	cm	s	dyne	dyne/cm^2	erg	7.83E+00	2.07E+12	9.81E+02
g	cm	us	1e7N	Mbar	1e7 N-cm	7.83E+00	2.07E+00	9.81E-10
g	mm	s	1e-6N	Pa	1e-9 J	7.83E-03	2.07E+11	9.81E+03
g	mm	ms	N	Mpa	N-mm	7.83E-03	2.07E+05	9.81E-03
ton	mm	s	N	Mpa	N-mm	7.83E-09	2.07E+05	9.81E+03
lbf-s^2/in	in	s	lbf	psi	lbf-in	7.33E-04	3.00E+07	3.86E+02
slug	ft	s	lbf	psi	lbf-ft	1.52E+01	4.32E+09	32.2

Figure 1: Consistent units for Abaqus . From https://www.researchgate.net/post/What-are-the-Abaqus-Units-in-Visualization units

3.3.1 High density polyethylene (HDPE)

High Density Polyethylene (HDPE) is modelled using the Ramberg-Osgood model as done so in the literature [2]. In 1D, the model is given by

$$E_c\varepsilon = \sigma + \alpha_c\sigma\left[\frac{|\sigma|}{\sigma_{yc}}\right]^{n-1}, \tag{1}$$

where E_c is the Young's modulus, α_c is the yield offset, σ_{yc} is the yield stress and n is the hardening exponent. In 3D, the model has the additional parameter of Poisson's ratio, denoted by ν_c. The material parameters are determined by fitting the model to data from [2] using a `Python` script which can be found at this link. Additionally, a 3D uniaxial Abaqus simulation utilizing the model is compared to the 1D model (equation (1)) to verify that the model behaves as expected in Abaqus . The results of the simulation, the behaviour of the model, and the data are displayed in Figure 2. The calibrated material parameters, as well as the other parameters required to define the model, are presented in Table 1.

Table 1: Material parameters for HDPE

Density ρ_c ton/mm3 [3, 2]	Young's modulus E_c MPa	Poisson's ratio ν_c [5]	Yield stress σ_{yc} MPa	Yield offset α_c	Hardening exponent n
0.95×10^{-9}	1.63×10^3	0.46	14.6	0.342	4.26

3.3.2 Mild steel

The mild steel components are expected to remain in the elastic region and so only linear elastic material behaviour is considered. The material parameters are given in Table 2.

Table 2: Material parameters for mild steel Ref later

Density ρ_t ton/mm3	Young's modulus E_t MPa	Poisson's ratio ν_t
8×10^{-9}	200×10^3	0.3

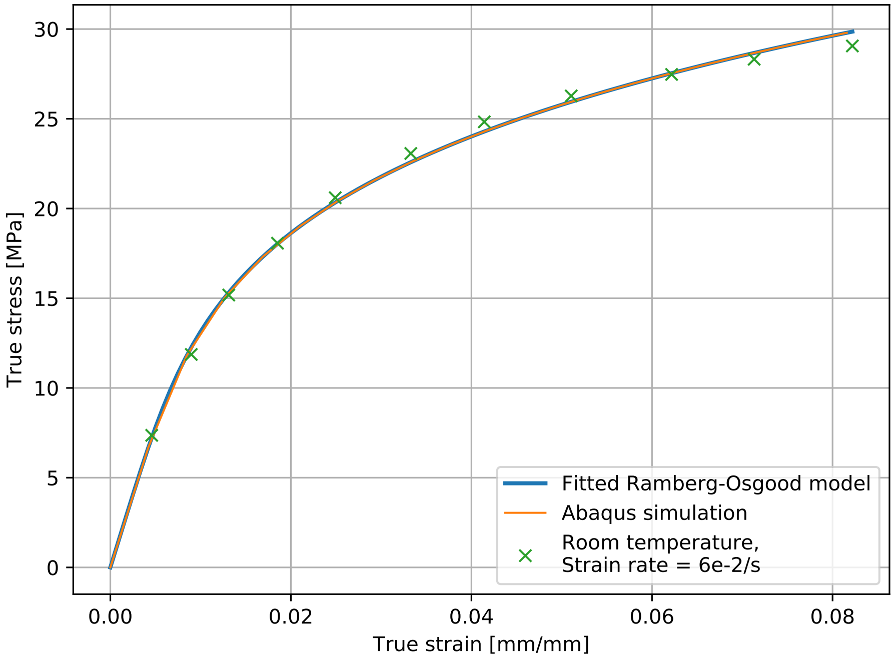

Figure 2: Stress-strain relation for HDPE modelled with the Ramberg-Osgood model. The model is calibrated to fit data from [2] (denoted by green 'x's). Additionally, the 1D model is compared to a uniaxial ABAQUS simulation using the calibrated material parameters. It is clear that the curves match each other and provide a good fit to the data.

3.3.3 Aluminium

The aluminium components are expected to remain in the elastic region and so only linear elastic material behaviour is considered. The material parameters are given in Table 3.

Table 3: Material parameters for aluminium taken from [1]

Density ρ_p ton/mm$_3$	Young's modulus E_p MPa	Poisson's ratio ν_p
2.69×10^{-9}	68.3×10^3	0.34

3.4 Initial and boundary conditions

3.5 Single test simulation

3.6 Mesh optimization

Parameters

1. ratio of element expansion for piston
2. ratio of element expansion for tube
3. n elements

Objective function

1. Min elements

Constraint

1. Force
2. Dissipation

4 Machine learning surrogate model

4.1 Feature engineering

Predictive features:

1. Coefficient of friction: μ
2. Taper angle: α
3. Velocity: v
4. Distance between piston front and taper start: x_{taper}
5. Pressure difference between piston front and back: Δp
6. Piston length: l_p
7. Piston density: ρ_p
8. Accumulative plastic strain in the piston: γ

Dependent variables:

1. Axial force on piston due to taper: F_z
2. Increment in accumulated plastic dissipation: $\Delta\gamma$

4.1.1 Dimensional analysis

Table 4: Fundamental dimensional units

Mass $[M]$	Length $[L]$	Time $[T]$

$$\Pi = F_c^{k_1} \left\langle \dot{\Phi}_c \right\rangle^{k_2} \Delta P^{k_4} v^{k_5} \left\langle \Phi_c \right\rangle^{k_3} x_t^{k_6} \tag{2}$$

$$r = 3 \tag{3}$$

$$n = 24 \tag{4}$$

$$n_{\text{n-dim}} = n - r = 21 \tag{5}$$

Table 5: Variables on which the problem depends Check that units are correct

Component	Description	Symbol	Units
Cap	Axial contact force	F_c	$[MLT^{-2}]$
	Rate of volume average plastic dissipation	$\left\langle \dot{\Phi}_c \right\rangle$	$[ML^{-1}T^{-3}]$
	Volume average plastic dissipation	$\langle \Phi_c \rangle$	$[ML^{-1}T^{-2}]$
	Pressure difference	ΔP	$[ML^{-1}T^{-2}]$
	Velocity	v	$[LT^{-1}]$
	Distance of cap past taper	x_t	$[L]$
	Length past piston	l_c	$[L]$
	Diameter	d_c	$[L]$
	Density	ρ_c	$[ML^{-3}]$
	Young's modulus	E_c	$[ML^{-1}T^{-2}]$
	Poisson's ratio	ν_c	$[\bullet]$
	Yield stress	σ_{yc}	$[ML^{-1}T^{-2}]$
Piston	Length	l_p	$[L]$
	Diameter	d_p	$[L]$
	Density	ρ_p	$[ML^{-3}]$
	Young's modulus	E_p	$[ML^{-1}T^{-2}]$
	Poisson's ratio	ν_p	$[\bullet]$
Transition piece	Length	l_t	$[L]$
	Diameter change	Δd_t	$[L]$
	Density	ρ_t	$[ML^{-3}]$
	Young's modulus	E_t	$[ML^{-1}T^{-2}]$
	Poisson's ratio	ν_t	$[\bullet]$
Friction	Cap-on-steel CoF	μ_{cs}	$[\bullet]$
	Steel-on-steel CoF	μ_{ss}	$[\bullet]$
	Aluminium-on-steel CoF	μ_{as}	$[\bullet]$

$$\begin{array}{c c} & \begin{array}{cccccc} F_c & \left\langle \dot{\Phi}_c \right\rangle & \Delta P & v & \langle \Phi_c \rangle & x_t \end{array} \\ \begin{array}{c} M \\ L \\ T \end{array} & \begin{bmatrix} 1 & 1 & 1 & 0 & 1 & 0 \\ 1 & -1 & -1 & 1 & -1 & 1 \\ -2 & -3 & -2 & -1 & -2 & 0 \end{bmatrix} \end{array} \begin{bmatrix} k_1 \\ k_2 \\ k_3 \\ k_4 \\ k_5 \\ k_6 \end{bmatrix} = \mathbf{0}\,. \tag{6}$$

1. Enter units as symbols in sympy
2. Construct dimensional matrix
3. Find solutions k_i^j to dimensional matrix by $n - r$ values in k to 0 (except for 1 which on sets to 1).
4. Automatically print out resulting dimensionless products table.

Based on [4]:

Notes:

Table 6: Non-dimensional parameters

F_c	$\left\langle \dot{\Phi}_c \right\rangle$	$\langle \Phi_c \rangle$	ΔP	v	x_t
k_1	k_2	k_3	k_4	k_5	k_6

1.

Direct quote from [4]

> "Dimensional analysis is a method with the aid of which one may for instance test a formula for dimensional correctness. It leads to a first understanding of the solution of a physical problem and yields a precise information about the number of variables that are necessary to describe it, a fact that is particularly important when experiments are being performed. Very often dimensional analysis reduces the number of variables upon which a physical problem was initially surmised to depend. If for instance the quantity y depends upon $x_1, x_2, ..., x_n$, where all quantities have a certain physical dimension, then dimensional analysis shows that y can only depend upon certain products of powers of $x_1, x_2, ..., x_n$, a fact that corresponds regularly to a considerable reduction of the number of variables. Naturally then, experiments may more simply or more economically be performed than without knowledge of this fact."

> "The first step in a dimensional analysis consists in the listing of the parameters, which influence a physical problem. This step is very decisive. If too many variables are listed that may describe a physical problem, then the final equations will contain superfluous variables, if too few variables are introduced, incomplete equations may emerge, which results in incomplete equations or "more often" false inferences or the result can not be expressed in terms of dimensionally homogeneous functions."

4.2 Experimental input parameters

In order of importance:

1. Initial velocity: v_0
2. Pressure path: p_{path}
3. Piston length: l_p
4. Coefficient of friction: μ

4.3 Experimental results

4.4 Model

5 Packaging of model for use in 1D code

5.1 PIP

5.2 Usage example

References

[1] *Aluminium: Specifications, Properties, Classifications and Classes*. URL: `https://www.azom.com/article.aspx?ArticleID=2863`.

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[5] K.-h. Nitta and M. Yamana. *Poisson’s ratio and mechanical nonlinearity under tensile deformation in crystalline polymers*. InTech Rijeka, 2012.