Modelling internal gas flows in a single stage gas gun using Eulerian/Lagrangian coupling in LS-DYNA

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Abstract

Most research on gas guns for impact testing investigates the velocity reached by the projectile or sabot when it hits the target. In this research attention is paid to the effect of initial loading conditions on the velocity reached by the projectile upon exit from the barrel. The work is focussed on the single stage nitrogen gas gun at the Department of Applied Mechanics in the School of Engineering at Cranfield University of this research. This gas gun was used to generate test data for a range of initial pressures in the pressure vessel. An LS-DYNA model of the gas gun which uses the Eulerian/Lagrangian coupling feature is described. The LS-DYNA model results, as well as results from an analytical model, are compared to the test results. The results indicate that, while the analytical model over predicts the projectile velocity, the LS-DYNA model is capable of accurately predicting the projectile velocity as a function of the initial pressure in the pressure vessel. The results also indicate that the opening time of the valve affects the projectile velocity at higher initial pressures.

Keywords: Eulerian/Lagrangian coupling, ALE, Fluid Structure interaction, gas gun

1 Introduction

Most research on gas guns for impact testing investigates the velocity reached by the projectile or sabot when it hits the target. Impact testing using gas guns is an important tool which helps to gain an understanding of the behaviour of materials and structures when subjected to impacts or impulsive loading. Different types of projectiles are fired, representing different impact conditions, e.g. debris impact, bird strike, ice impact, Hopkinson bar testing [3]. These different impact conditions require different materials but also different impact velocities.

The main question addressed in this paper is the dependency between the initial conditions of test setup and projectile exit-velocity. Different initial settings such as pressure and compressibility of gas affect the velocity of the projectile. The theory shows that there is a nonlinear relationship between initial pressure and velocity upon exit from the barrel. It has also been shown that the velocity is affected by the opening speed of the valve [2], therefore the effect of the valve opening time is also investigated in this paper.

The paper begins with a description of the gas gun used to generate experimental data and a summary of this data. The data is then compared to an analytical model. The second part of the paper discusses the numerical model itself. The modelling choices to gain accurate results and the treatment of contact between expanding gas and projected and valve in LS-DYNA ALE. Finally results are shown for different chamber pressures and different valve opening-times and compared to the test results and results of the analytical model.

2 Experiments

The single stage nitrogen gas gun (SSNGG) available at the Crashworthiness, Impact and Structural Mechanics Group in the School of Engineering at Cranfield University is shown in Fig. 1. This gas gun can launch projectiles at velocities of up to 280m/s with an initial pressure in the pressure chamber of 50 bar. The impact velocity range covers low speed impact velocities required for dynamic material testing using a split Hopkinson pressure bar [3], up to bird strike or debris impact testing.

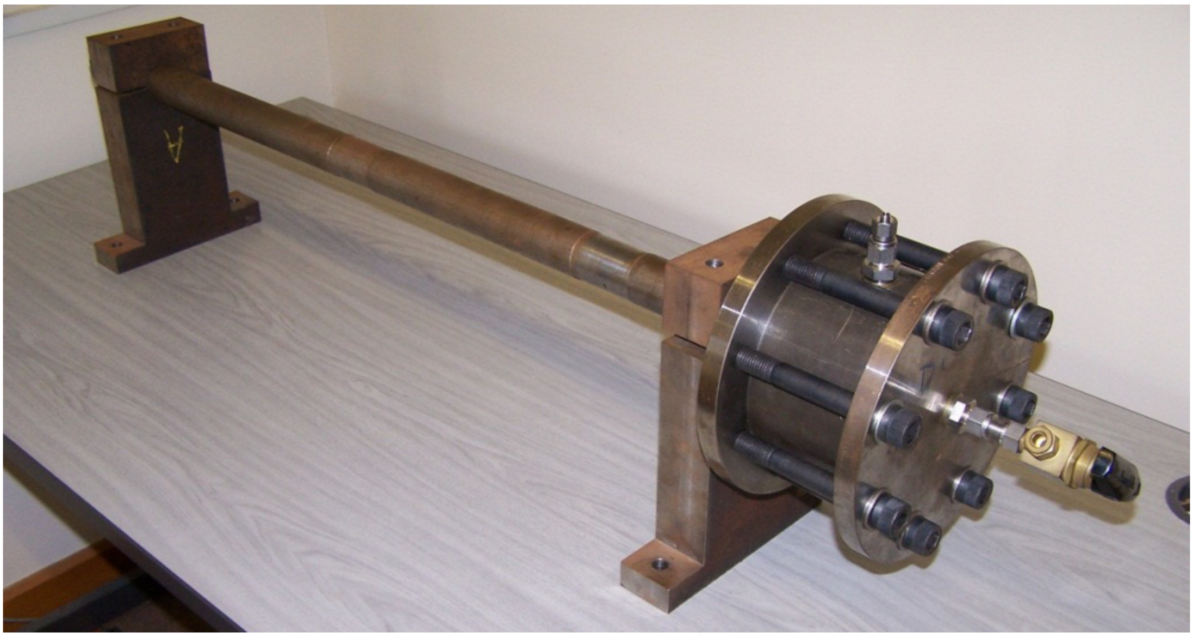

Fig. 1: Picture of SSNGG with closed chamber

A diagram schematically representing the operation of the gas gun is shown in Fig. 2. The valve initially isolates the pressure chamber from the barrel in which the projectile is placed. When the valve opens the compressed nitrogen expands and accelerates the projectile along the barrel.

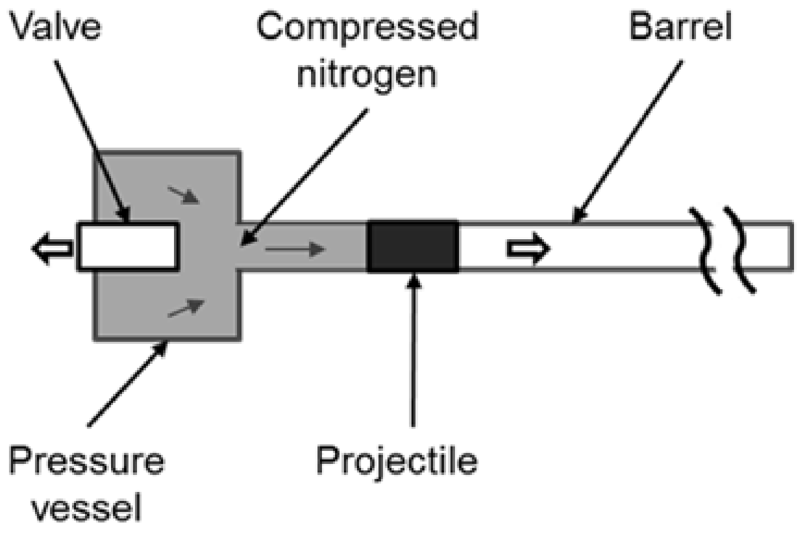

Fig. 2: Schematic diagram of SSNGG at firing

The gun can be used with a range of barrels of different lengths and diameters. Experiments conducted for this paper used a barrel of 1m length and a diameter of 31mm. The exit-velocity of the projectiles was measured with an optical velocity measurement system fitted to the end of the barrel. The velocity is measured with an error of about 0.1%. A 40g acetal projectile was used for all experiments. A number of experiments was conducted at Cranfield University in which the gun's chamber was filled at different pressures and the exit velocity of the projectile was measured. The results of the tests are summarised in Table 1 and shown in Fig. 3. As expected the relationship between projectile velocity and initial pressure in the pressure chamber is nonlinear.

Table 1: Measured exit velocity of projectile for various chamber pressures

Pressure in bar	**Velocity of projectile upon barrel in m/s**		
	Experiment 1	**Experiment 2**	**Experiment 3**
2	41	11	56
5	80	96	92
20	171	178	-
30	200	189	-
40	221	215	-

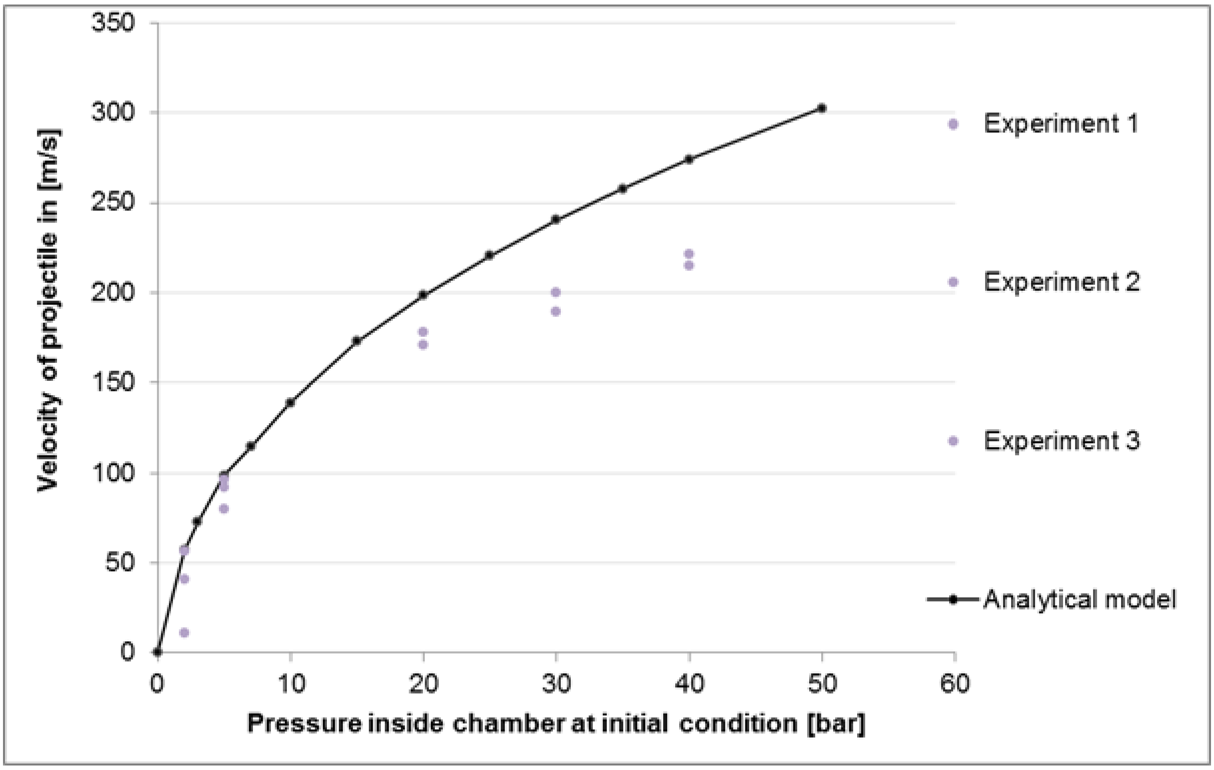

Fig. 3: Comparison of experimental measured exit velocity as a function of inital pressure and analytical model predictions

3 Analytical model

In order to provide a point of comparison for the accuracy of the LS-DYNA model an analytical model available at Cranfield University has been used to calculate projectile velocities. This analytical model assumes an adiabatic expansion (γ is adiabatic coefficient of 1.4 for nitrogen) of a diatomic gas from a chamber with specific volume.

$$\frac{V_2}{V_1} = \left(\frac{p_1}{p_2}\right)^{\frac{1}{\gamma}} \tag{1}$$

The gas expands from the pressure chamber (Volume V1 and pressure p1) inside the barrel (Volume V2 and pressure p2). By considering conservation of energy the velocity of the projectile can be calculated as a function of the pressure of the gas expanding from the pressure vessel.

The analytical calculations do not assume a fluid in the barrel. The input parameters for the model are the properties of the N_2 gas, the volume of the pressure chamber, initial pressure, barrel diameter and length.

The analytical model predicts the nonlinear relationship between initial pressure and exit velocity. However it is clear from Fig. 3 that at higher pressures the analytical model over predicts the projectile velocity.

4 LS-DYNA Model

Because of the discrepancies between the experimental data and the analytical model it was decided to investigate the ability of LS-DYNA to predict the test results to simulate the complex interaction between the gun mechanism, gas and projectile. The fully Eulerian description in LS-DYNA's ALE (Arbitrary Lagrangian Eulerian) option is used to simulate the internal gas flow. LS-DYNA has been used previously for designing a gas gun and showed good results [1].

Due to the symmetry of the problem it was decided use a quarter model with appropriate boundary conditions. The model is shown in *Fig. 4*. The pressure chamber, the barrel are represented through boundary conditions on the Eulerian grid. The valve and the projectile are represented in a Lagrangian description and are modelled as rigid materials. The nitrogen gas in the pressure chamber is defined using standard temperature pressure (STP) in *MAT_NULL. A similar approach was used by Gladman [4]. The volume described by barrel could be described as void, however it was decided to run the simulation with air in the barrel using the same standard temperature pressure (STP) in *MAT_NULL used for the nitrogen gas. Both fluids are defined with ELFORM 11.

At the barrel end an additional part represents infinite space after the barrel (see *Fig. 4*). It is an extension to the barrel which has the same mesh size as the barrel, and is defined as a fluid with *MAT_NULL. This is the third fluid in the simulation set up as an *ALE_MULTI_MATERIAL_GROUP, and uses ELFORM 7 in the *SECTION_SOLID card. This setting reapplies the defined initial values in the *EOS_LINEAR_POLYNOMINAL every time step. The fluid flow is transported using the 2nd order Van Leer advection scheme [9] and the time step scale factor is set to 0.7

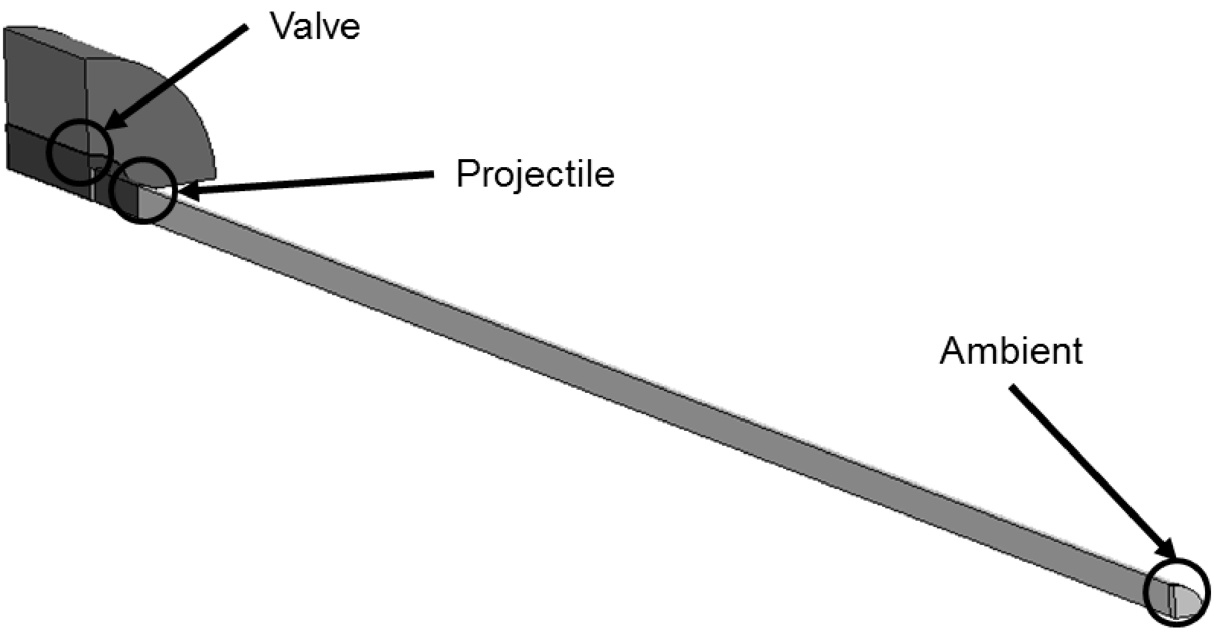

Fig. 4: 3D LS-DYNA model of the gas gun using two symmetry planes

The opening of the valve is modelled by the application of a constant velocity using *BOUNDARY_PRESCRIBED_MOTION. The Lagrangian mesh representing the valve is coupled with the fluid using the *LAGRANGE_IN_SOLID option [5]. A rectangular coupling grid of 3 coupling points for each edge is defined. The coupling direction acts only on compression [7]. The penalty factor PFAC is dependent on mesh size and was determined using a sensitivity study.

The algorithm shows a better coupling when the precompressed fluid (nitrogen gas) is not in direct contact with the Lagrangian segments [6]. Therefore, the valve is extended in all directions by one tenth of the element size (see *Fig. 5*). This design facilitates the coupling of fluid with the solid at the edges of intersection.

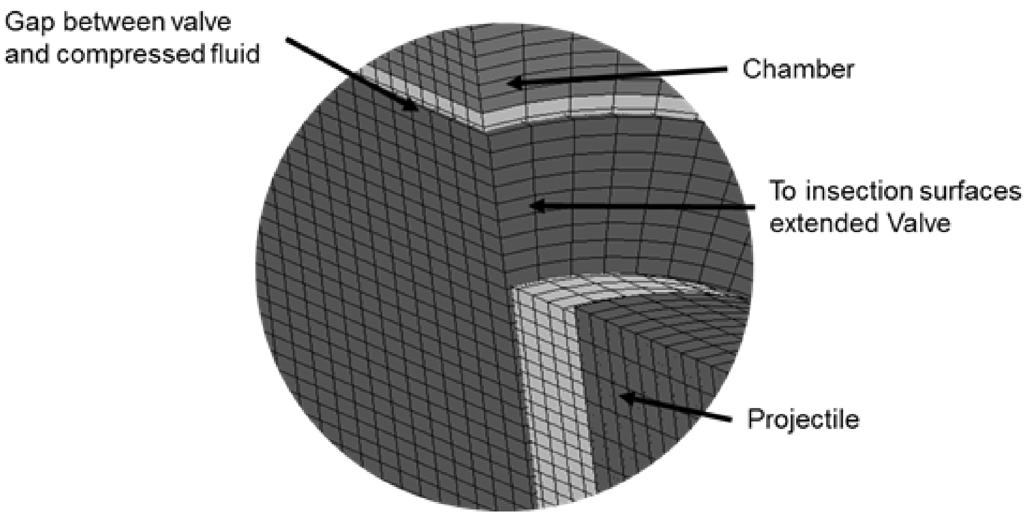

Fig. 5: Modified 3D model; valve is extended at the intersection surfaces for better performance of fluid

The projectile is also extended by one tenth of its elements size for the same purpose. This is the reason the projectile appears slightly larger than the barrel diameter in *Fig. 6*. Like the valve, the projectile modelled as a rigid body, defined with *MAT_NULL. The coupling with the nitrogen gas behind the projectile and the air in front of the projectile is achieved through the use of the *LAGRANGIAN_IN_SOLID card.

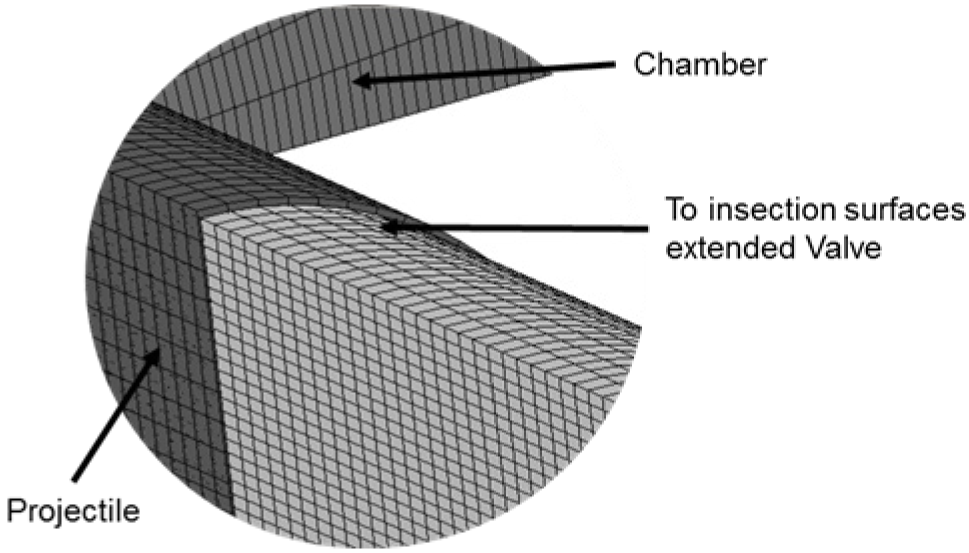

Fig. 6: Modified 3d model; projectile diameter is extended

5 Results and Discussion

The LS-DYNA model was ran with different initial pressure in the chamber. The results for pressures of 5bar, 10bar, 30 and 50 bar are summarised in Table 2 and are shown in Fig. 7. This allows the resultant velocity predicted by LS-DYNA to be compared to the experimental results and to the analytical model. At pressures above 10bar the analytical model predicts velocities about 20% higher than the experimental data (Fig. 7). In contrast the LS-DYNA results closely match the experimental results over the complete pressure range. One of the reasons for this could be that the LS-DYNA model takes into account the air in front of the projectile while the analytical model does not.

The evolution of projectile velocity and acceleration as a function of position in the barrel is shown in Fig. 8 and Fig. 9. These figures clearly show the lower levels of acceleration and velocities predicted by the LS-DYNA model in comparison to the analytical model. Although the velocity curves are in both cases smooth (none of the data has been filtered) the LS-DYNA model shows a noisier signal for the acceleration than the analytical model.

Table 2: LS-DYNA and analytical model predictions of exit velocities of projectile

Pressure in bar	Velocity in m/s			
	1	10	30	Analytical model (no opening time for valve)
5	81	83	85	98
10	123	123	123	141
30	196	204	203	240
50	230	247	247	302

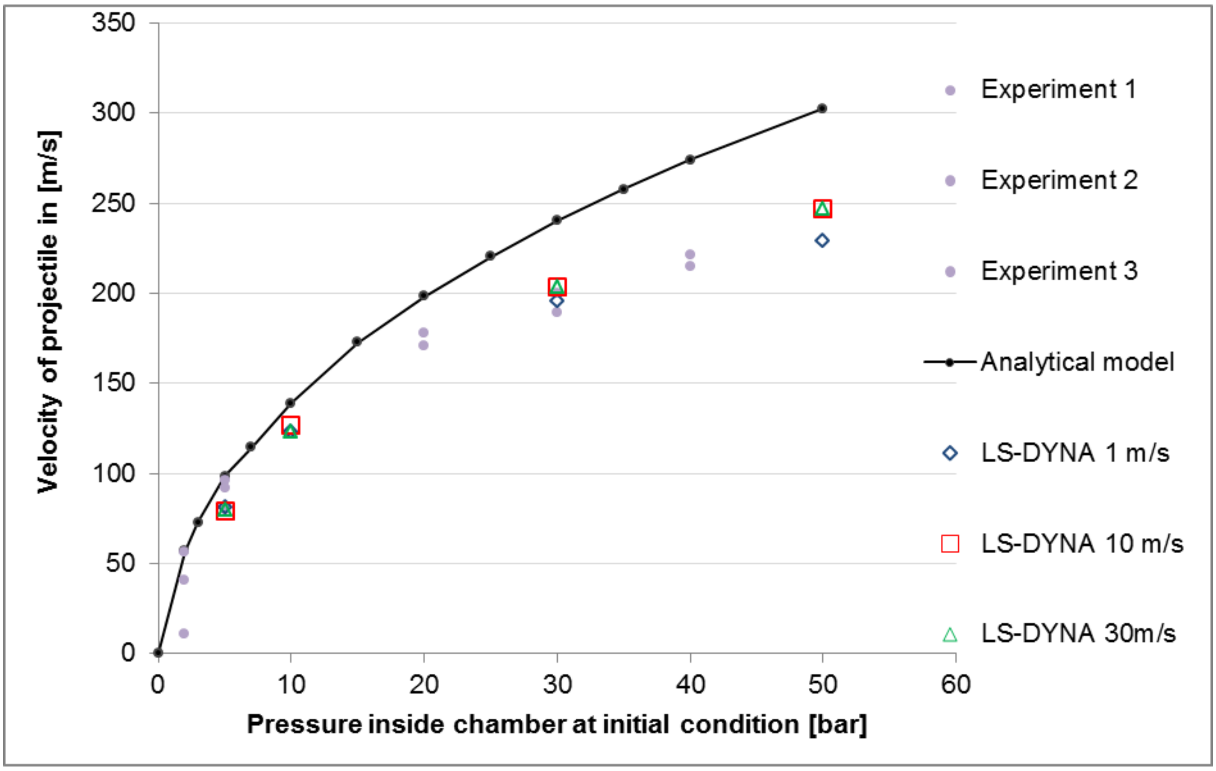

Fig. 7: Comparison of numerical model with experimental data and analytical model

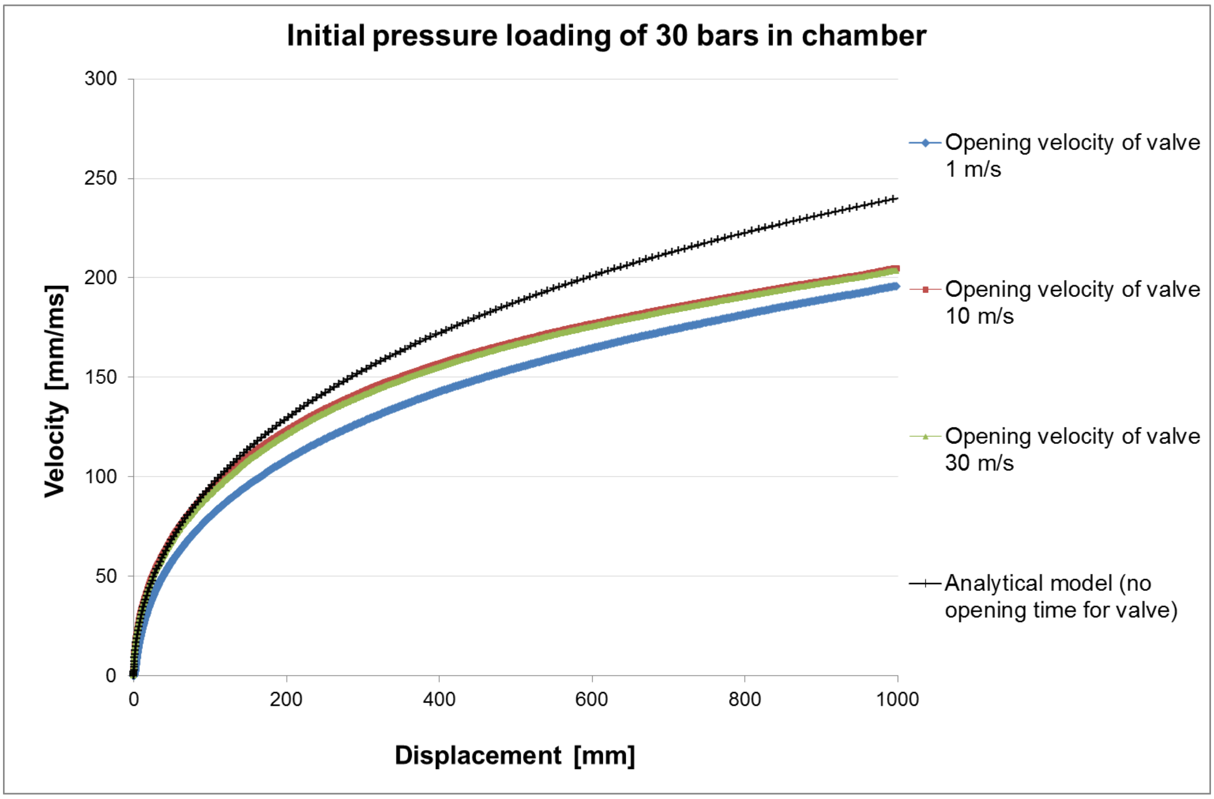

Fig. 8: Velocity of projectile at 30 bar with different valve opening-times

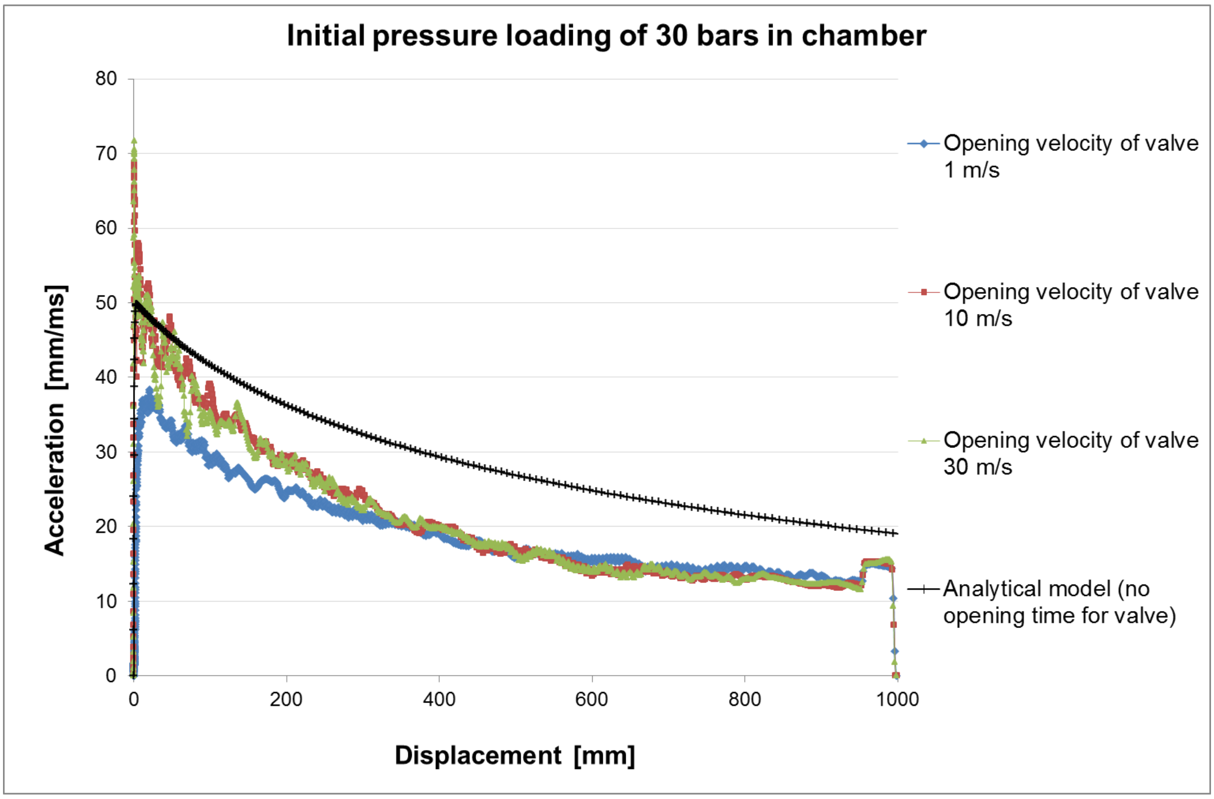

Fig. 9: Acceleration of projectile at 30bar with different valve opening-times

The potential effect of the valve opening time was investigated by changing the prescribed velocity of the valve. Three valve opening velocities of 0.1, 1, 10 and 30 m/s (Table 2) were investigated.

The results show that the projectile exit-velocity is more sensitive to valve opening-times higher initial pressure loadings. At 30 bar the numerical model shows an increase of 8 m/s between an increased opening speed of 1 m/s to 10 m/s (see Fig. 8). At 30 m/s opening time the end velocity does not increase further. The end velocity for an initial pressure of 50 bar (see Table 2) shows a difference of 15 m/s, between 1 m/s opening time and 30 m/s opening time.

At lower pressures the simulation predicts that the exit velocities are less sensitive to the valve opening speed.

6 Summary

An LS-DYNA model has been described which allows the internal gas flows in a single stage gas gun, and their interaction with the projectile and the retracting valve to be modelled.

The model predicts the exit velocity of a projectile for a range of initial pressures to a good degree of accuracy when compared to test data from the gas gun of the Crashworthiness, Impact and Structural Mechanics Group in the School of Engineering at Cranfield University.

For this test data the model has also been shown to be more accurate than an analytical model of the same gas gun.

The LS-DYNA model results suggest that at higher pressures the SSNGG is more sensitive to the valve opening time than at lower pressures.

7 References

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