A low pressure, supersonic two-stage light gas gun

1. Introduction

High speed impact experiments are needed to better understand the behaviour of material under dynamic loading conditions. This is critical for many fields of research, including such as the testing of new materials for the aerospace vessels against space debris or to study the crater formation from hypervelocity impact. Impact experiments are used to isolate the impact phenomenon from other complex interactions that would normally occur with the impact event such as explosions. Light gas guns are often the primary choice to perform impact experiments on a laboratory scale.

Since the inception of light two-stage gas gun in 1948, it has been used as a standard tool to performance high velocity impact tests. It’s widely used for its….

In order to achieve the supersonic or hypersonic target velocity, highly pressurised gas (usually hydrogen) or reactive chemicals (gas powder, explosives, propellent) are often used in the compression stage of the gas gun. Although extreme velocities (above 20 km/s) can be achieved, this method requires large pistons, thick cylinder walls and long barrel lengths. This type of design is therefore associated with high design, production and operation cost, certification for high pressure vessels, stringiest safety operating protocols and therefore inaccessible to many. This types of development is often funded by large organisations, such as NASA and have long development cycles which is not feasible to smaller laboratories with limited funding.

This paper introduces a design for the two-stage light gas gun combined with a novel choice of sabot material. The gas gun realised X% of its theoretical limit during experimental tests and was capable of accelerating a 1.5g projectile to almost March 2. The gas gun was optimised for more general uses at university laboratories. So it was designed to be cost efficient and passively safe while still capable of supersonic experiments. The operations of the gas gun is simple by eliminating the need for evacuated barrel and target chamber.

The input pressure for the gas gun was limited to 10 bar (1MPa) as it is easily reached with most commercial compressors. This is lower than many espresso machines. The volume of the gas gun was limited to 5L so that it was not considered as a pressure vessel under SANS 347.

2. Gas gun design

2.1 Overview

A two-stage design was selected as a balance between higher driving efficiency and design complexity. A single stage gas gun would not achieve the desired velocity while a three-stage gas gun would too complex and expensive to construct, defeating the main goal of the development.

The final footprint of the gas gun was small and can easily fit into most laboratories. The length of the gas gun body was kept below 1 meter and the gas gun barrel was below 2.9 m.

A schematic of the two-stage gas gun design is shown in Figure 1. The first stage of the gas gun (contained in balloon 1) was used as the reservoir. The reservoir was filled to a maximum of 10 bars. The second stage (contained in balloon 2) labelled as the pump tube was where the compression occurs for the firing of the projectile.

The pump tube, where the highest pressure was expected, was mounted concentrically within the reservoir. This design choice reduced the size of the gas gun and increased its safety. In an event of unexpected failure of the pump tube, where higher pressure is expected, the failure shall be contained within the reservoir.

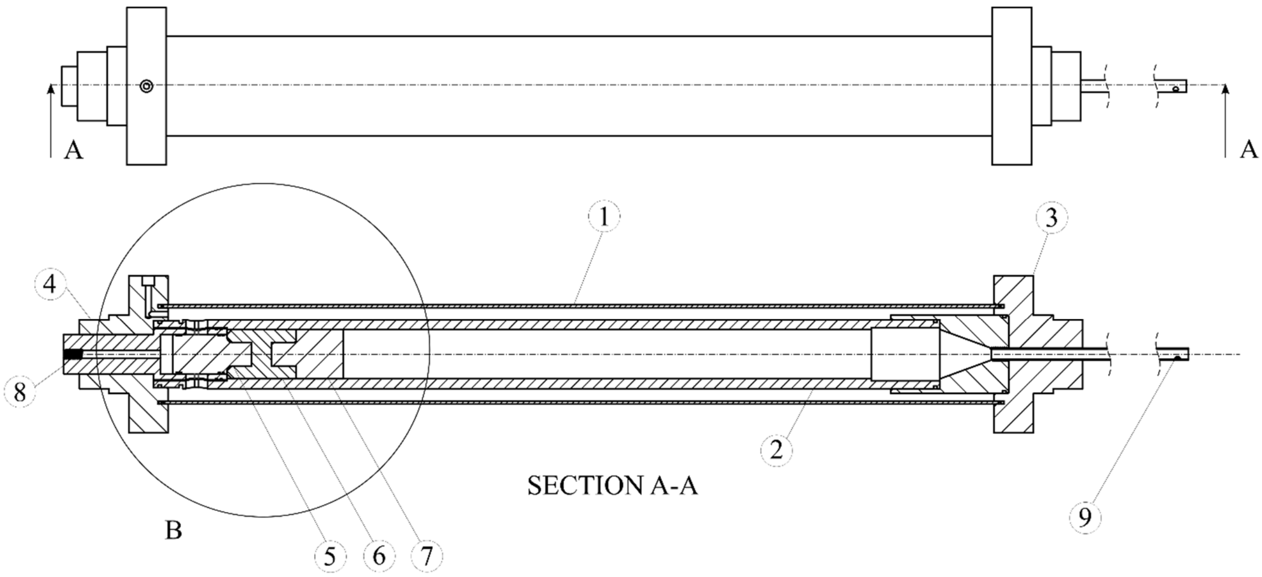


Figure 1 Side and sectional view of the two-stage gas gun body. Detail B is shown in Figure 2.

Table 1 Bill of material of the gas gun shown in Figure 1.

Part No.	1	2	3	4	5	6	7	8	9
Part Name	Reservoir	Pump tube	Front flange	Rear flange	Piston driver	Piston	Piston cap	Initiator	Barrel
Material	Aluminium	Mild Steel	Aluminium	Aluminium	HDPE	Al7075-T6	Polyethylene	Mild steel	Aluminium

2.2 Firing sequence

The detailed view of area B shown in Figure 1 is presented in Figure 2 where the firing sequence is demonstrated. In the first stage, air from a gas tank was used to fill the reservoir until the desired pressure was reached. The gas tank was disconnected before proceeding. Pressures up to 10 bars were used for this stage. Then, a very small amount of gas, leftover in the pneumatic piping, was used to move the piston assembly forward until the rear face of the piston driver is in front of the filling holes (stage 2 initiation). At this instant, gas from the reservoir flowed into the pump tube (stage 2) and drive the piston assembly forward. The piston assembly then compressed gas in front of it and fired the projectile.

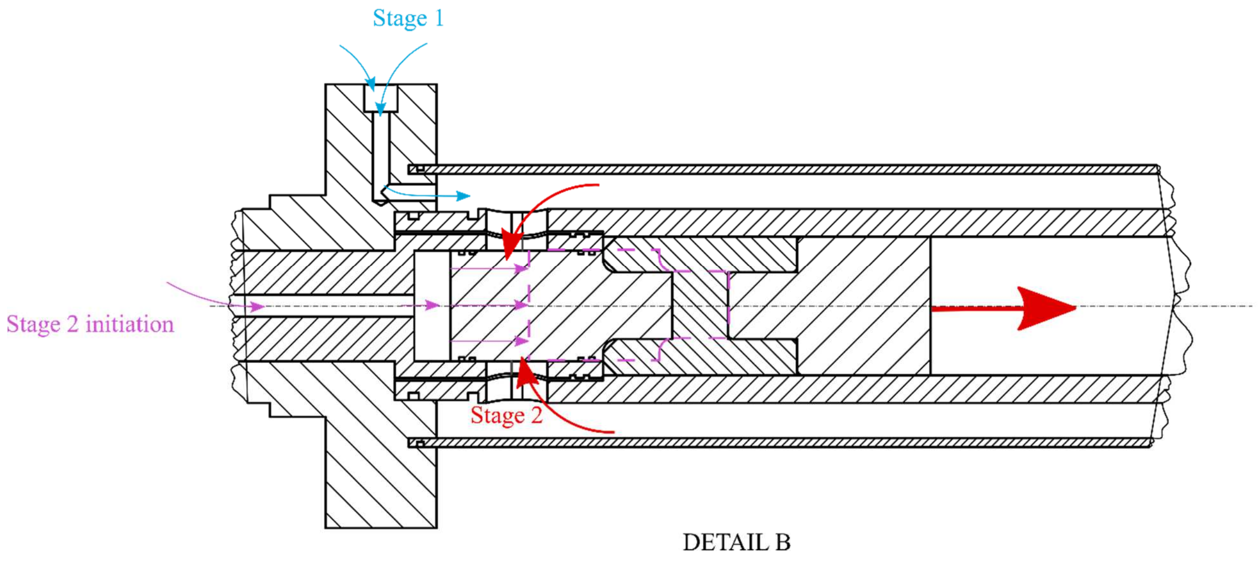


Figure 2 Detailed section view showing the firing sequence.

2.3 Sabot

Material choice and sabot production method

Sabots are often required to position the projectile in the centre barrel. In most designs, the sabot is a rigid device that travels with the projectile in the acceleration stage and separate from the projectile before impacting the target. The separation can be passive, such as through massive differences in air resistance between the projectile. Alternatively, an external device can be used to catch the sabot before the impact.

Sabot designs can critically impact the performance of the gas gun. The sabot should minimise any gas leaking during acceleration but also minimise wall friction against the barrel. Three types of sabots were tested during the development of the gas gun.

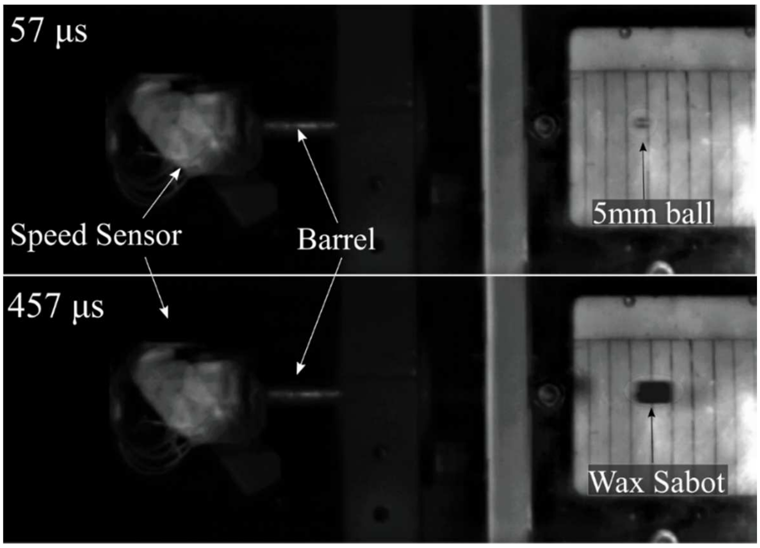
Initially, a 3D printed passive sabot was used. The sealing was achieved by 2 o-rings. The desired velocities were not achieved using this method. An aluminium hollow ogive projectile was also used to test the gas gun prototype. It was made to impact with a block of wax. Interestingly, it was noted that when the projectile was removed from the wax block and reused, the velocity would increase under the same input pressure.

This observation let to the use of a paraffin wax sabot. As shown in Figure, a custom brass mould was machined for the sabot. A 5 mm SS 420C ball bearing was used as the projectile. The concentricity was ensured by first placing the intended projectile in the slot at the base part of the mould. After which, small piece of solid wax was used to fill the mould. The mould was then heated with a heat gun until the wax was thoroughly melted. After the wax has cooled, the sabot as was taken out as shown in Figure. This method of sabot product is extremely versatile and allow any castable shape under the barrel diameter to be manufactured easily. By filling in the wax first and melting it after, the probability of the operator accidently spilling hot wax is greatly reduced.

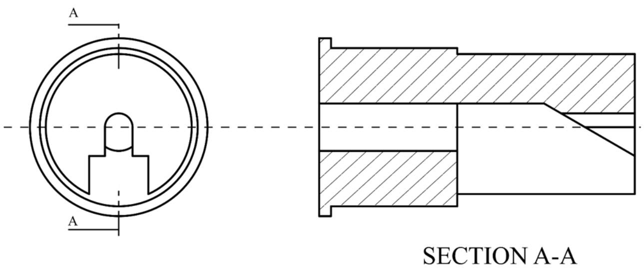
Wax is not only cheap and easy to obtain and to mould but is also reusable. After the experiments, wax can simply be recollected and reused.

Sabot, projectile separation and deflector

It was also observed that the wax sabot was able to self-detach from the ball bearing do to their differences in deceleration. High-speed footage of the bearing and sabot exiting the barrel at different times after detachment at 7 bar input pressure is shown in Figure. At higher input pressure the self-detachment was observed to be inconsistent. The self-detachment process was promoted by placing the wax mould in a freezer.



For higher input pressure (above 8 bars), a device was needed to prevent the sabot from impacting the witness plate. As shown in Figure, a steel sabot deflector was designed and fitted to the end of the barrel. The deflector allowed the ball bearing to pass through and deflected the sabot.



2.4 Piston assembly

Two-stage gas guns are fitted with a conical end section to stop the piston and to reduce the rebound of the piston which will cause back pressure. In this design, shown in Figure a deformable piston cap made from polyethylene was used. This allows the piston cap to travel slightly into the conical section will increase the final firing pressure of the projectile. The deformation of the piston cap was observed to increase with each use, i.e. the gas gun becomes more efficient with each firing. The material choice also makes it cheap to replace if broken.

A threaded hole was machined at the back of the non-deformable piston, this allows the operator to insert a matching rod to pull and reset the piston assembly to initial location.

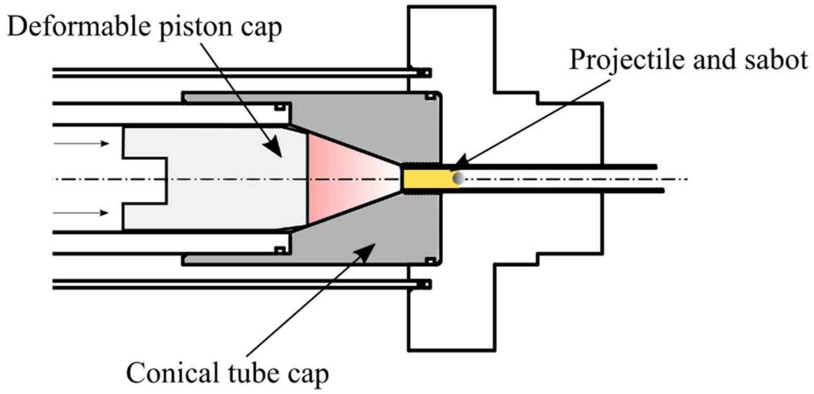
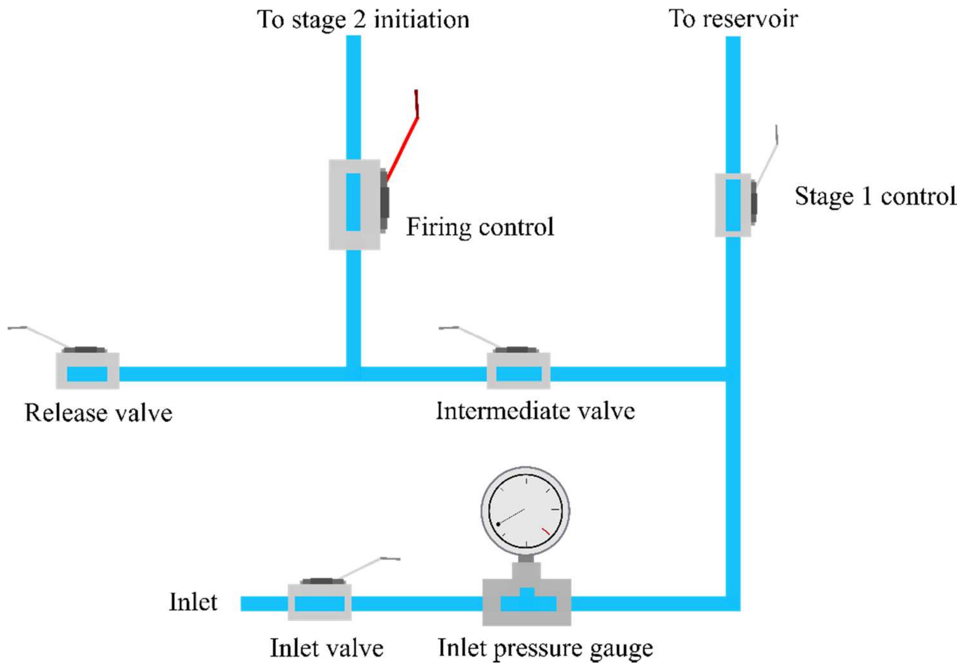


Figure 3 Schematic showing the final compression of gas before the firing of the projectile.

2.5 Operations



Simple pneumatic controls were used for the gas gun. All controls units and piping are rated for 10 bars. To use the gas gun, the intermediate is shut, the inlet valve and stage 1 control valve is opened until the desired inlet pressure is reached in the reservoir. Then, all valves are shut. The intermediate valve is now open. A siren is sound before the firing of the gun. Lastly, the firing control valve is opened, the residual pressure in the piping initiates stage 2 and causes the firing of the gun.

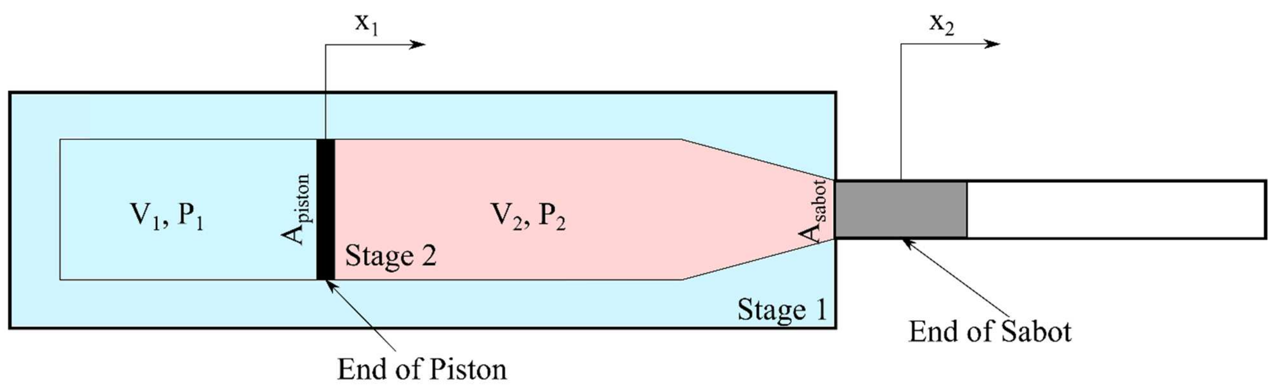
3. Numerical predictions

A two-degrees-of-freedom one dimensional model was used to predict the capabilities of the gas gun as shown in Figure. The description of the variables used in Figure is presented in Table, where P_{atm} is the atmospheric pressure in any given day and P_{in} is the input pressure decided by the operator. The maximum pressure in the second stage, $P_{2_{max}}$ is dependent on the movement of the projectile. Mathematically, the model can be expressed as:

$$\ddot{x}_1 m_{piston} = (P_1 - P_2)A_{piston}$$

$$\ddot{x}_2 m_{sabot} = (P_2 - P_{atm})A_{sabot}$$

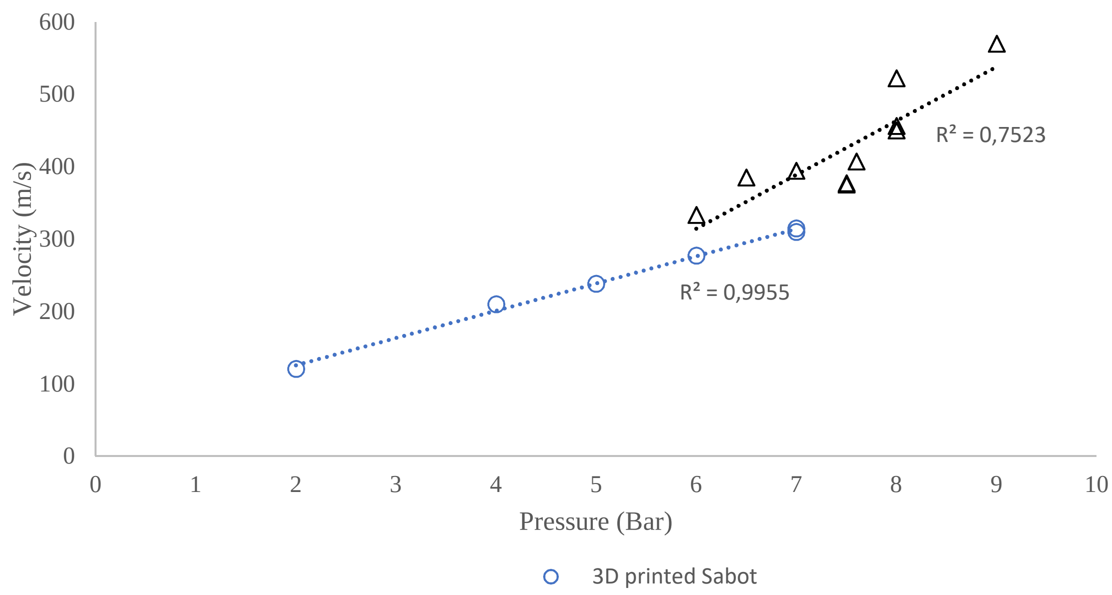
Where m_{piston} and m_{sabot} are the masses of the piston assembly and the mass of the sabot and projectile. Equations 1 and 2 were solved numerical using the central difference method.

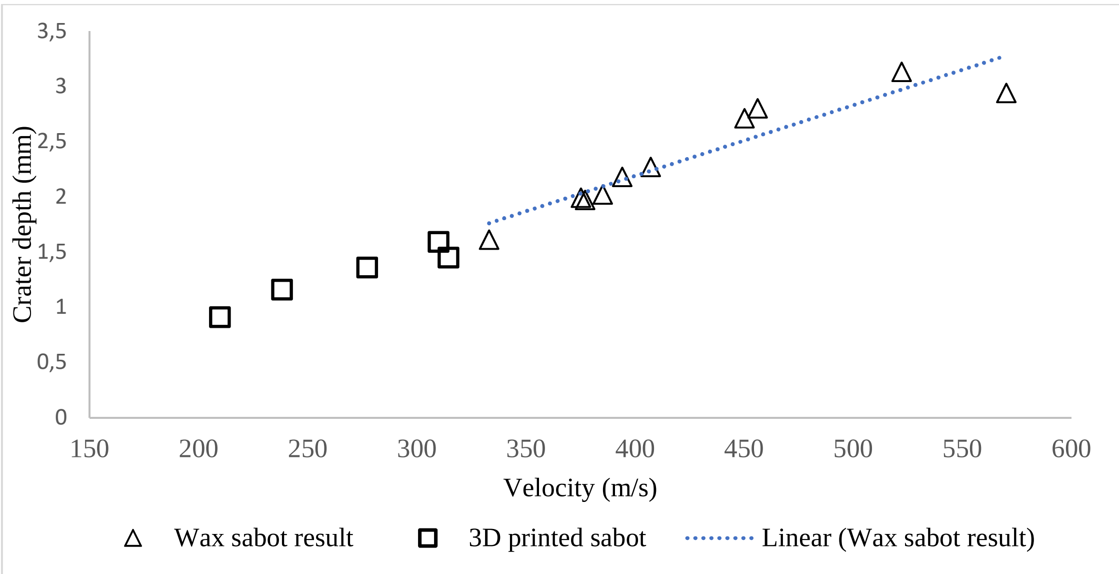


Variable	Description	Minimum	Maximum	Initial value	unit
x_1	Displacement of piston	0	0.625	0	m
x_2	Displacement of projectile and sabot	0	2.59	0	m
V_1	Stage 1 volume	2.649	3.857	2.649	$10^{-3}m^3$
V_2	Stage 2 volume	4.4×10^{-2}	$1.212+ A_b x_2$	1.212	m^3
P_1	Stage 1 pressure	P_{atm}	$10 + P_{atm}$	P_{in}	bar
P_2	Stage 2 pressure	P_{atm}	$P_{2_{max}}$	P_{atm}	bar
A_{piston}	Area of the piston			1.963	$10^{-3}m^2$
A_{sabot}	Area of the sabot			7.543	$10^{-5}m^2$

4. Experimentation and discussion of result

Impact experiments were performed by firing the SS 420C ball bearing projectiles at a witness plate made of Al 6082-T6. The graph of ball bearing exit velocity versus input pressure is shown in Figure, categorised by the type of sabot used. 3D printed sabot produced more consistent velocity with the change in input pressure than the wax sabot. This was





4.1 Comparison against results from literature

5. Conclusions

6. Planned capabilities