Journal of Physics: Conference Series **500** (2014) 142019 doi:10.1088/1742-6596/500/14/142019

Development of an accelerating piston implosion-driven launcher

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Abstract. The ability to soft-launch projectiles to velocities exceeding 10 km/s is of interest for a number of scientific fields, including orbital debris impact testing and equation of state research. Current soft-launch technologies have reached a performance plateau below this operating range. In the implosion-driven launcher (ILD) concept, explosives are used to dynamically compress a light driver gas to significantly higher pressures and temperatures than the propellant of conventional light-gas guns. The propellant of the IDL is compressed through the linear implosion of a pressurized tube. The imploding tube behaves like a piston which travels into the light gas at the explosive detonation velocity, thus forming an increasingly long column of shock-compressed gas which can be used to propel a projectile. The McGill designed IDL has demonstrated the ability to launch a 0.1-g projectile to 9.1 km/s. This work will focus on the implementation of a novel launch cycle in which the explosively driven piston is accelerated in order to gradually increase driver gas compression, thus maintaining a relatively constant projectile driving pressure. The theoretical potential of the concept as well as the experimental development of an accelerating piston driver will be examined.

1. Introduction

Launchers capable of accelerating relatively large (>0.1 g) well characterized projectiles to hypervelocity (>5 km/s) are widely used to study a variety of impact phenomenon. In particular, hypervelocity launchers are used extensively for high pressure equation of state research, orbital debris impact testing, and the study of planetary impacts. The study of these phenomena requires the ability to generate impact velocities as great as 15 km/s in a laboratory setting, a capacity that is beyond the performance envelope of current launcher technologies.

State of the art hypervelocity impact testing is primarily performed using two-stage light-gas guns (2SLGG). These launchers use a gas driven piston to adiabatically compress a hydrogen or helium propellant. The performance of the 2SLGG is ultimately limited by the need to keep the propellant temperature and pressure sufficiently low such that the launcher does not wear prematurely. As a result of this limitation, decades of development have not allowed the 2SLGG to exceed a practical performance limit of 8 km/s [1].

In the implosion-driven launcher (IDL) concept, a light gas contained within a thin walled steel tube is compressed using explosives to sequentially implode the pressurized tube. The progressive implosion of the tube forms an explosively driven piston which travels into the driver gas (typically helium) at the explosive detonation velocity. This drives a strong shock wave into the light gas and forms an increasingly long column of compressed gas travelling near the explosive detonation velocity. As the shock wave reflects off the projectile, the column of

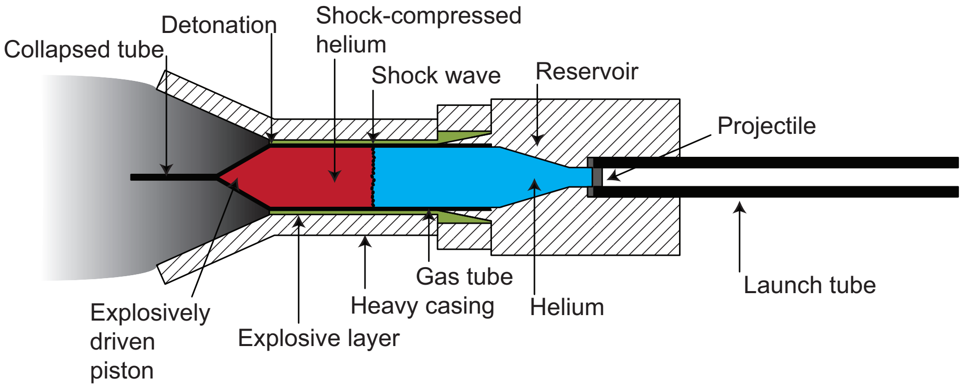

Figure 1. Schematic of the launch cycle of a typical single stage implosion-driven launcher.

driver gas is stagnated, reaching an estimated peak pressure and temperature of 5 GPa and 25 000 K respectively. The subsequent expansion of the high enthalpy driver gas propels the projectile. This launch scheme, which is illustrated in figure 1, has recently demonstrated the ability to launch a 0.1 g projectile to 9.1 km/s [2, 3]. Extensive launcher damage is caused by the use of explosives in the driver gas compression, as well as the flow of high temperature and pressure gas through the reservoir and launch tube. Despite the single use nature of the device, the IDL has a compact design which can be manufactured using low tolerance and low cost materials, resulting in a comparable per-shot cost to a 2SLGG. More importantly, the ability to generate propellant temperatures and pressures well beyond what can be accommodated in a reusable launcher offers the potential to significantly outperform the 2SLGG.

The IDL was first developed by Physics International (PI) in the late 1960's. They were able to demonstrate projectile velocities of 10.6 km/s using the basic device presented above [4]. PI also recognized the unique ability for explosives, which have very high specific energy and power, to continue to compress the driver gas during the launch cycle in order to maintain a high driving pressure on the projectile. In their concept, a second explosive stage was used to implode the launch tube behind the projectile. The resulting explosively driven piston was programmed to follow the projectile, thus re-compressing the expanding driver gas and maintaining a nearly constant base pressure on the projectile. The device demonstrated the ability to launch a 2-g projectile to 12.2 km/s, but had a number of limitations related to significant driving pressure loss in the first stage, as well as difficulties in collapsing the launch tube without significant driver gas loss [4]. The limitations of the launch tube implosion technique may be overcome if explosives can be used to deliver additional compression during the initial stages of projectile acceleration.

2. Accelerating piston launcher concept

In a gasdynamic launcher, the projectile driving pressure decays exponentially due to the unsteady expansion of the driver gas, unless additional energy is delivered to the gas [5]. The launch cycle of the single-stage IDL provides no additional compression to the driver gas once the projectile has been set in motion. As a result, the driving pressure decays quickly and the gains from increasing the maximum pressure or temperature of the propellant are limited. However, it is possible to maintain a nearly constant driving pressure in a gasdynamic launcher by gradually increasing the reservoir pressure [5]. In the accelerating piston launcher concept, the explosively driven piston is gradually accelerated, which provides additional compression to the driver gas ahead of the piston. The resulting compression waves travel into the reservoir, thus offsetting

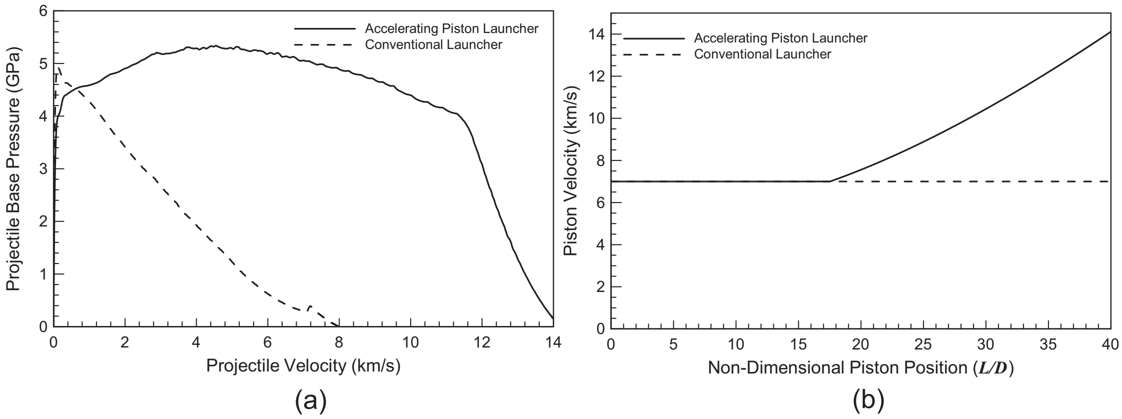

Figure 2. Computational simulation comparing the performance of an accelerating piston launcher with a single-stage implosion-driven launcher showing (a) the evolution in projectile driving pressure as a function of velocity, and (b) the corresponding piston velocity profile.

the pressure decay from the expanding gas. The acceleration profile of the explosively driven piston can be tuned to maintain a nearly constant base pressure on the projectile.

The theoretical advantage of the accelerating piston launch cycle is demonstrated in figure 2, which compares the predicted evolution in projectile driving pressure as a function of velocity for a basic single-stage launcher and an accelerating piston launcher. These pressure profiles were obtained using a quasi-one-dimensional internal ballistics model developed specifically for the implosion launcher [6]. The simulations include a model for the reservoir expansion caused by the high driver gas pressure, a key non-ideal effect in the performance of the IDL. As can be seen, the initial driving pressure is sustained up to nearly 12 km/s, resulting in a predicted velocity improvement of 6 km/s over the single-stage device. The programmed piston velocity profile used in the simulation is also shown in figure 2. It is important to note that the accelerating explosively driven piston has been modelled as an impermeable planar piston travelling into a perfectly rigid tube. In a real system, driver gas will inevitably leak through the explosive pinch, the thin walled tube will yield under the driver gas pressure, and the explosively driven pinch will get longer as its propagation velocity increases along the explosive tube [7]. For these reasons, the ability of the accelerating piston driver to deliver the additional compression required to implement the constant base pressure launcher will need to be demonstrated experimentally.

3. Experimental approach

In order to replicate the piston velocity profile shown in figure 2, the propagation velocity of the detonation wave along the driver will need to be gradually increased. This can be accomplished with an explosive lens, which uses the combination of two explosives with different detonation velocities to form an increasingly tilted detonation wave [8]. As can be seen in figure 3, the phase velocity (propagation velocity of the wave along an observation plane) of a wave increases as the angle (θ) between the wave normal and the observation plane increases. In a two-component explosive lens, the detonation in the fast explosive (located at the top of the lens) drags an oblique wave into the slow explosive. In order to produce an accelerating detonation wave at the base of the lens, the phase velocity of the oblique detonation wave travelling in the slow component explosive is increased by gradually increasing the angle between the tangent to the fast component explosive profile and the observation plane. This is shown schematically in figure 4.

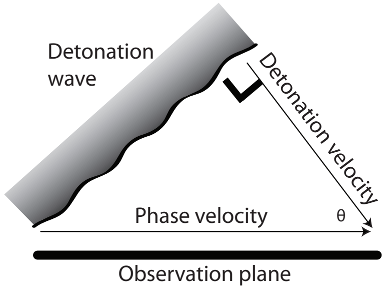

Figure 3. Phase velocity of an oblique detonation wave.

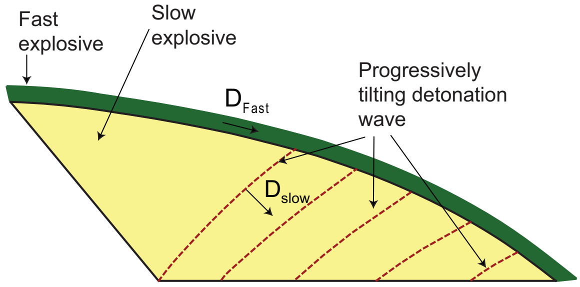

Figure 4. Two-component explosive lens.

The phased detonation wave produced by the two-component explosive lens must then be coupled to the explosive driver in order to accelerate the linear implosion of the pressurized tube. A method in which the phased detonation wave is introduced through a slit milled into the driver tamper (steel casing) has previously demonstrated the ability to compress the driver gas (i.e., drive a precursor shock wave) at phase velocities beyond 2.5 times the base explosive detonation velocity [9, 10]. It should be noted that these experiments were performed at constant phase velocities. In order to develop the accelerating piston implosion launcher, it is necessary to demonstrate the ability of an accelerating piston driver to provide increasing driver gas compression up to phase velocities of 16 km/s. Furthermore, it will be necessary to demonstrate the ability to couple a constant velocity section with an accelerating piston section, in order to replicate the piston velocity profile in figure 2 and ensure that the additional driver gas compression in the real device approaches that of the constant base pressure simulation.

4. Charge Details

A schematic of the charge design used to develop the accelerating piston driver can be seen in figure 5. The pressurized steel tube has a 19 mm OD with a 0.9 mm wall thickness and is filled with 22 atm of helium. It is surrounded by a 3 mm layer of Primasheet explosive (7.1 km/s detonation velocity), and a steel tamper having a wall thickness of 9.5 mm. The two component lens uses Primasheet as the fast explosive and a mixture of nitromethane diluted with diethylenetriamine (30% by mass), which has a detonation velocity of 5.5 km/s for a thickness of 6 mm in plastic confinement, as the slow explosive. The phased detonation wave in the lens is transmitted through a 3 mm slit in the tamper which places the nitromethane mixture in contact with the datasheet surrounding the pressurized tube. As can be seen in figure 5, the charge has two initiation points, which need to be carefully synchronized in order to provide the desired explosively driven piston velocity profile. A set of Primasheet strips having different lengths were used to program the delay between the initiation of the two-component lens and that of the constant velocity section with a single detonator.

Self-shorting wires were used at the beginning of the driver to track the position of the detonation wave in the constant velocity driver section. The phased detonation wave in the two component lens was monitored using an MREL 1-05-10 variable resistance gauge placed at the base of the lens. The gauge, which has a calibrated resistance as a function of un-collapsed length, allows for continuous monitoring of the detonation position. In order to monitor driver gas compression, the precursor shock wave in the helium was tracked using a series of Dynasen CA-1136 shock pins placed against the pressurized tube. The shock pins enable monitoring of the shock wave velocity in the helium gas, as well as its position relative to the explosively driven piston. Precise machining of the shock pin locations (within 0.1 mm), combined with the rapid

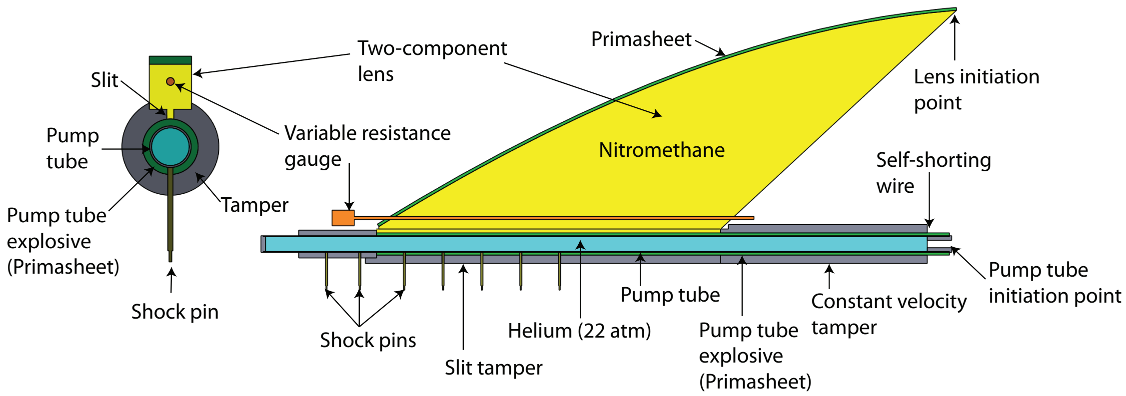

Figure 5. Schematic of the accelerating piston driver experiments.

rise time of the piezoelectric sensors (typically 400 V/µs in this configuration [7]) and rapid oscilloscope sampling rates allow for precise measurement of the shock wave velocity (within 50 m/s) and arrival time (within 0.01 µs). As a result, it is possible to monitor the variation in shock strength as additional compression is applied, as well as the loss of driver gas through the explosively driven piston.

5. Results

The first experimental configuration consisted of a driver in which the piston velocity was accelerated from 7.5 km/s to 16 km/s over a length of 38 cm with no constant velocity section. This simpler configuration can be directly compared to an ideal computational gasdynamics simulation. The results from the experiment along with the ideal shock wave trajectory are shown in figure 6. As can be seen, the precursor shock wave initially falls behind the ideal profile, but eventually stabilizes in the second half of the driver. An acceleration from 12.3 km/s to 14.1 km/s is observed, thus demonstrating a significant increase in driver gas compression.

An experiment was then performed using a the complete accelerating piston driver

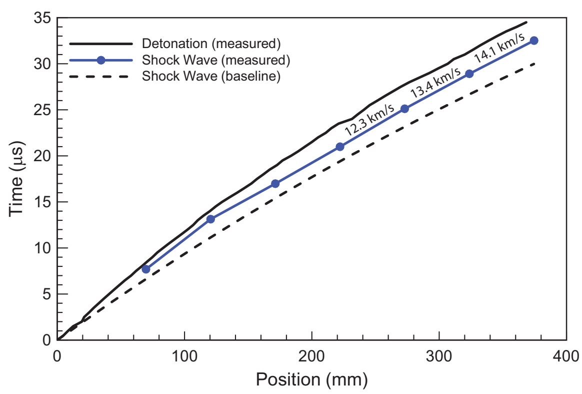

Figure 6. Position-time graph from a driver experiment with a piston velocity accelerating from 7.5 km/s to 16 km/s.

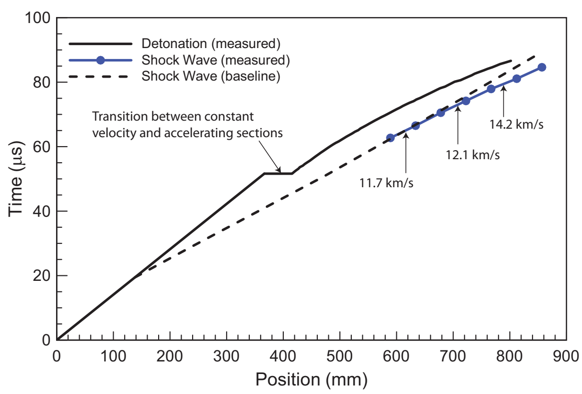

Figure 7. Position-time graph from a driver experiment with a 7.1 km/s constant velocity section coupled to an accelerating piston section (7.5 km/s to 16 km/s).

configuration shown in figure 5. A 41 cm constant velocity section (7.1 km/s) was coupled to a 38 cm section accelerating from 7.5 to 16 km/s. The measured detonation and shock wave trajectories from the experiment are shown in figure 7. A baseline shock wave profile for a constant velocity driver based on previously reported data [7] is also presented. As can be seen, the precursor shock wave is accelerated well ahead of the baseline trajectory. At its peak, the shock wave velocity was 14.2 km/s, 4.4 km/s faster than the baseline trajectory.

6. Conclusion

Computational simulations have demonstrated that the accelerating piston launch cycle has the potential to maintain an elevated driving pressure on the projectile, resulting in a significant increase in the terminal velocity of the projectile. A phased detonation wave introduced through a slit in the driver tamper has been used to accelerate the explosively driven piston and experimentally demonstrate an increase driver gas compression. Therefore, it appears possible that the driver design presented above could be used to implement the accelerating piston launch cycle.

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