Aluminum-Extrusion, Square-Bore, Aero-Ballistic Range for Launching Three-Dimensional Projectiles

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Abstract

The flexibility of a ballistic range can be improved by using launch tubes manufactured by aluminum extrusion; with a reasonable cost the bore configuration can be tailored to a specific purpose. In this paper, a ballistic range with a 25 mm × 25 mm square bore was developed for aerodynamic free flight of three-dimensional objects. Combining the in-tube sabot separation technique, three-dimensional projectiles could be launched at speeds of up to Mach 2 without rolling.

NOMENCLATURE

P = pressure measured on launch tube wall
P_d = initial pressure in driver chamber
P_t = initial pressure in test chamber

1. INTRODUCTION

The ballistic range is a classical, yet still uniquely functional, laboratory tool: in aerodynamics one may realize disturbance-free laboratory simulation of free flight; in impact physics one may inexpensively obtain ideal one-dimensional impact data. The aero-ballistic range, which hereafter will be referred to as a 'gas gun,' is widely used as a fundamental tool because of its advantages in simplicity, low cost, availability, safety, etc. over other types such as the rail gun and the electro-thermal gun. However, in free flight aerodynamics experiments, attitude control of a free flight model (projectile) is not an easy task. Usually, since the shape of a projectile does not fit to the bore, the projectile is launched with sabot(s). However, with a conventional circular-bore gun, the rolling motion of the projectile cannot be actively controlled. Therefore, launching a projectile with a three-dimensional shape poses a challenging problem in implementing gun operation.

In a rail gun, in which the barrel contains opposing electrodes, Marshall concludes that a square bore is preferable to a circular one as a research launcher [1]. However, almost all gas guns have a circular bore. Hutchings, et al. developed a rectangular-bore gas gun in order to avoid rolling [2]. The barrel, composed of two opposing member plates, had a 16 mm × 1.5 mm rectangular bore milled into one of the plates. The members were bolted together. An 8 mm × 8 mm square steel plate with a thickness of 1.5 mm was launched as a test specimen with a full-bore sabot, mechanically stopped at the muzzle. This square-bore gun offered significant advantages over the circular-bore type in some impact experiments.

Sasoh and Oshiba[3] developed an 'impactless' in-tube sabot separation technique. The sabot holding the projectile is separated before the muzzle by utilizing its larger deceleration compared to the projectile, generated by aerodynamic confinement in a launch tube. However, their gas gun had a circular bore, so only axi-symmetric projectiles were available.

Recently, a technique for aluminum extrusion has been developed and applied in manufacturing various structural elements. This technique can also be applied to manufacture gun barrels for moderate pressure operation. The bore shape can be easily tailored to desired specifications for reasonable

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expense. In the present study, a square-bore gas gun with impactless, in-tube sabot separation has been developed using the aluminum extrusion technique. The operational characteristics and critical technical issues will be presented and discussed.

2. APPARATUS

Figure 1 shows a schematic illustration of the entire gas gun developed in this study. The original facility is the one which is documented in Sasoh and Oshiba [3]. The circular tubes of the original were replaced with new launch tubes with a 25.0 mm × 25.0 mm square bore. The launch tubes are made of A6065 aluminum alloy, manufactured with the aforementioned aluminum extrusion technique.

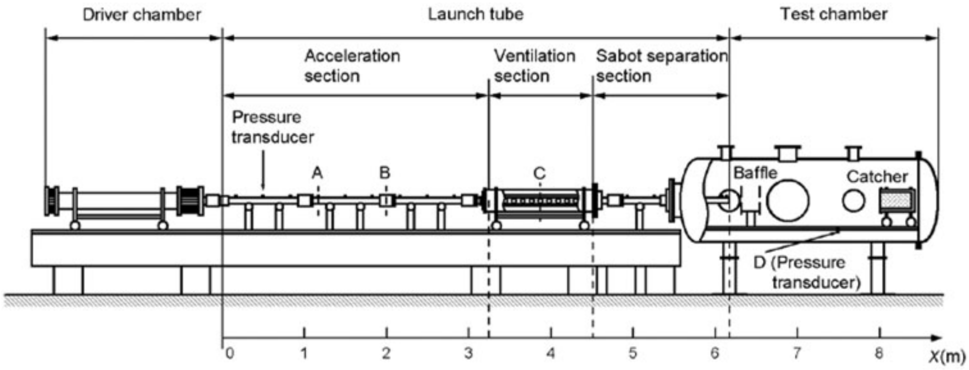


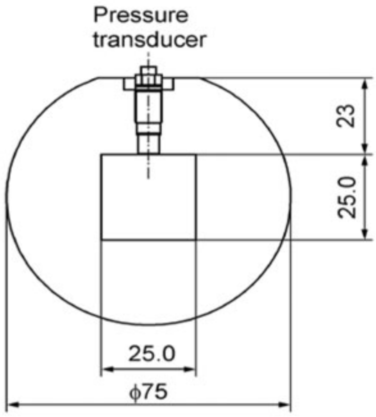
Figure 1. Schematic illustration of gas gun.

The gas gun is composed of a driver chamber with a quick-opening valve (so-called 'Oguchi piston' [4]), launch tubes and a test chamber. The driver chamber has an inner diameter of 100 mm and a length of 1.48 m. In the quick-opening valve (characterized by a 40-mm-dia. breech), a high-molecular-mass polypropylene piston is driven by the pressure differential between the driver chamber and the room behind the piston. It realizes reliable and reproducible operations with a reasonably short turnaround.

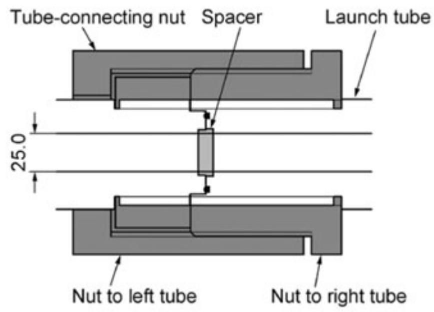
Figure 2 illustrates the cross-sectional views of the launch tubes. In order to utilize the existing supports, the outer diameters of the launch tubes were set equal to the original, at 75 mm. A 27 mm-wide, upper flat surface is made so that the tube orientation is readily seen. The manufacturer-guaranteed allowance is 0.05 mm of a specified dimension. At thirteen positions (e.g., at position A in Fig. 1), piezoelectric pressure transducers (PCB Piezotronics, Inc.; HM112A21, rise time 2 µs, sensitivity 7.2 ± 1.5 mV/kPa or HM113A21, rise time 1 µs, sensitivity 3.6 mV/kPa) are flush mounted (Fig. 2(a)). As seen in Fig. 2(b), the launch tubes are connected using three nuts. The left and right tubes have screws of opposing rotations to each other so that the tube-connecting nut does not loose the connection. A square brass spacer ring is inserted between the launch tubes to align their orientations. In assembling the launch tubes, fine orientation was adjusted by inserting brass rods with 24.9 mm 24.9 mm square cross-section (length 50 mm) into tube connections.

As seen in Fig. 1, the launch tubes are divided into three parts; the acceleration, ventilation and sabot separation sections. In the acceleration section, three 1 m-long launch tubes are connected together. In the ventilation section, a 1.8 m-long launch tube is inserted into a 300 mm-dia., 1.5 m-long dump chamber [3]. The launch tube has one hundred 8 mm-dia. ventilation holes (see Fig. 2(c)). They are designed so that the overpressure of a precursory shock wave generated by sabot motion in the acceleration section is attenuated to an acceptably low level after passing over the holes. Also, the driver gas pressure behind the sabot is lowered by venting. In the sabot separation section, the sabot experiences a drag force due to a balance between the post-shock pressure ahead of it and reduced driver gas pressure behind it. However, the projectile experiences a negligible drag because it moves almost at the post-shock flow speed. Further details of the sabot separation scheme are described in [3].

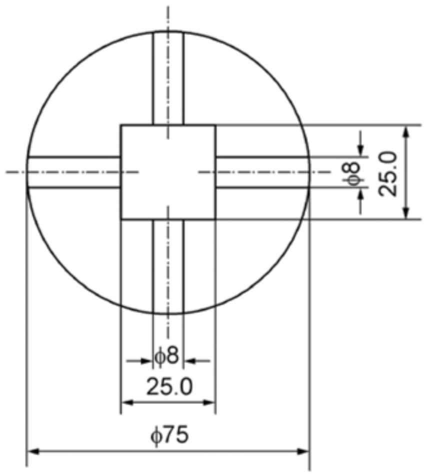
Along the launch tubes, thirteen piezoelectric pressure transducers are flush-mounted. In the test chamber, free flight speed is measured by the time-of-flight method, sensed with four pairs of sensing elements. A single pair is composed of a diode laser and a photodiode. The motion of free flights of projectiles and sabots, and associated aerodynamics, were captured through a Schlieren arrangement, recorded by a high-speed framing camera (Shimadzu Co., HV-1, 384 × 240 pixels) at a framing interval of 16 µs.



(a) Cross-sectional view at A in Fig. 1



(b) Cross-sectional view at B in Fig. 1, the left and right tubes have screws with opposite rotations to each other.



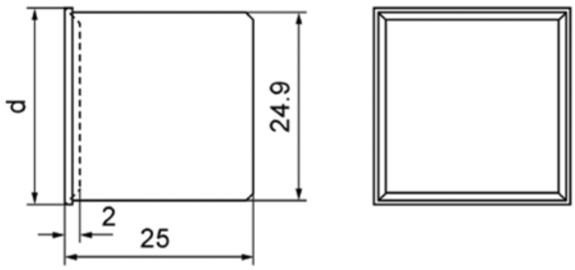
(c) Cross-sectional view at C in Fig. 1

Figure 2. Cross-sectional views of launch tube, length unit in [mm].

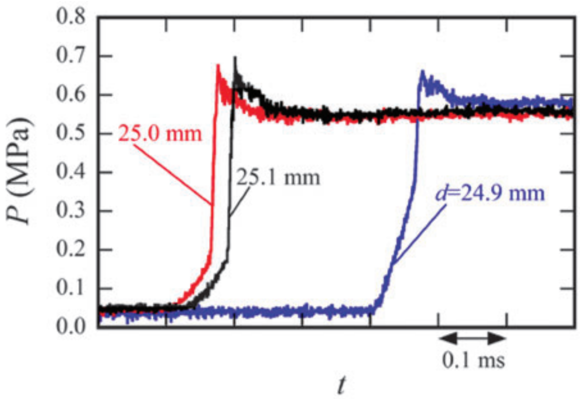
3. RESULTS AND DISCUSSION

3.1 Bridgman seal design

First series of launch experiments are conducted to examine the performance of a sabot for driver gas seal and the friction against the tube wall. Only a cube-shape sabot (see Fig. 3(a)) is launched. The sabot has a mass 13.0 g, and is made of polycarbonate. It has a 24.9 mm × 24.9 mm square cross-section, fits snugly into the launch tube. The rear side of the sabot is shaped as a ‘square’ Bridgman seal; the frame has a thin lip 1.0 mm (apex angle of 45°) so that during launch it expands and seals against the driver gas. The outer dimension of the lip was experimentally determined from the trade-off between lowering wall friction force and lowering gas leakage through the interface against the launch tube wall. We examined three different lip dimensions: d = 24.9, 25.0 and 25.1 mm. Figure 3(b) shows typical in-tube pressure histories measured in the acceleration section at x = 2.82 m with operating conditions other than d held constant. The time origin is arbitrary. In each pressure history, the pressure starts to rise gradually due to compression waves driven by the sabot motion. Some compression waves coalesce, forming a normal shock wave. In Fig. 3(b), a shock wave is recognized by an abrupt pressure jump. After the pressure jump, P overshoots and in the time frame of Fig. 3(b), settles to an almost constant value of around 0.55 MPa, then gradually increases. This pressure profile is a typical one in a gas gun launch tube in which the driver gas experiences unsteady expansion coupled with the sabot motion.



(a) Schematic design of sabot (polypropylene, 13.0 g).



(b) In-tube pressure histories at x = 2.82 m in acceleration section (Fig. 1)

Figure 3. Bridgman seal examination

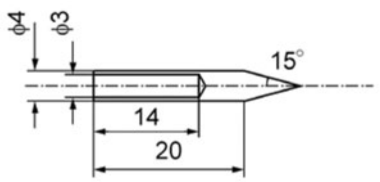
If the driver gas significantly leaks through the clearance between the sabot and the launch tube wall, the compression waves are enhanced; the arrival time relative to the shock wave becomes earlier and the pressure level in the 'precursory' part increased. This enhancement is observed only with d = 24.9 mm, where the pressure increment through the compression waves becomes largest; the driver gas leakage significantly affects the pressure waves generated ahead of the sabot. The increments with d = 25.0 mm and 25.1 mm are comparable; further increase in d does not lead to better sealing. Since the larger d, the larger the wall friction force, in the following experiments d = 25.0 mm is adopted as a nominal Bridgman seal dimension.

3.2 Acceleration and Sabot Separation Performance

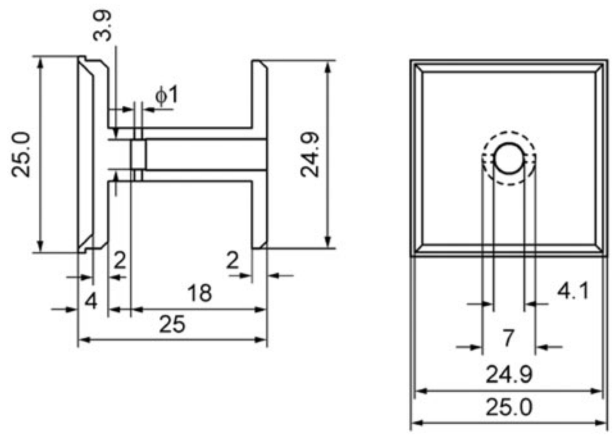
Projectile launch performance is examined using the combination of a conically-nosed, cylindrical projectile and sabot as shown in Fig. 4. The projectile is made of aluminum alloy (A2024), has an outer diameter of 4.0 mm, hollowed from the base, with a mass of 0.47 g. The sabot (mass 3.7 g) is mechanically manufactured from a block of polycarbonate. It fits snugly into the launch tube cross-section with two parallel, 24.9 mm × 24.9 mm square 'plates.' The plates are connected by a central cylindrical container which holds the projectile. In the rear surface of the container (inner diameter 4.1 mm), a cavity (inner diameter 3.9 mm) is machined. The cavity is perforated by four holes so that the projectile is not sucked out of the holder when the launch tube is evacuated before a shot.

As is described in Sasoh and Oshiba [3], in this facility the sabot is separated in the sabot separation section before the muzzle. Figure 5 shows examples of in-tube pressure histories in the sabot separation section. At each location, the pressure first jumps due to a precursory shock wave (PS) that is driven by the sabot in the acceleration section. This PS is vastly weakened through the ventilation section. The overpressure of the first PS equals 150 to 200 kPa in the sabot separation section, whereas (as shown in Fig. 3(b)) it is about 600 kPa in the acceleration section. The second pressure jump corresponds to another PS which is caused by the sabot motion after entering the sabot separation section. After the sabot passed at x = 5.3 m and x = 6.1 m, the pressure decreased by 320 kPa and 280 kPa, respectively. These values correspond to sabot deceleration of about 5.4×10^4 m/s^2 and 4.7×10^4 m/s^2, respectively.

Once the projectile detaches from the sabot, it is surrounded by the post shock gas flow of an almost-equal particle velocity. Therefore, the projectile experiences a much smaller drag than the sabot does. In this case, using the length of the sabot separation section, 1.7 m, and the entry speed of 700 m/s, as shown in Fig. 6, the sabot speed decrement and the separation distance of the projectile from the sabot are roughly evaluated to be 120 m/s and 0.15 m, respectively.



(a) Schematic design of conically-nosed, cylindrical projectile



(b) Schematic design of sabot

Figure 4. Projectile and sabot used in launch process examination.

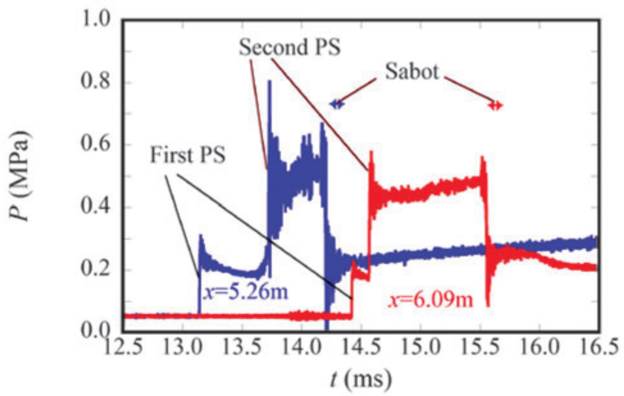
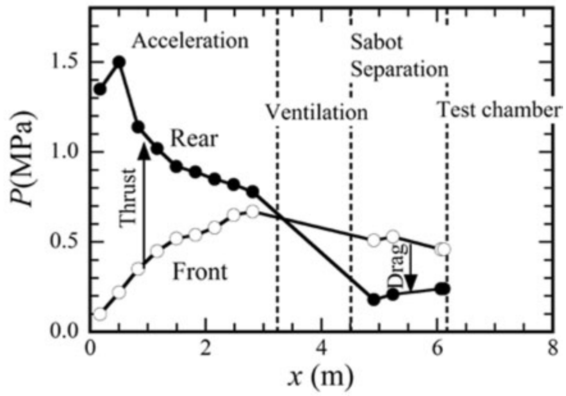
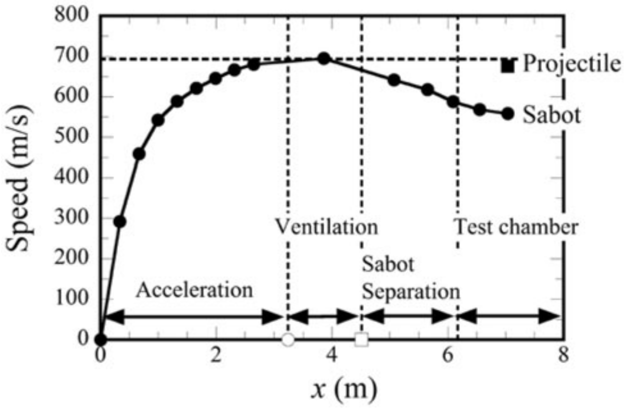


Figure 5. In-tube pressure histories in sabot separation section, projectile and sabot as shown in Fig. 4.

Figure 6 shows the spatial variation with respect to the travel distance of the pressures on the sabot front and rear, and the speeds of the projectile and sabot. In the acceleration section, the net force exerted on the projectile and sabot combination corresponds to a maximum pressure balance of 1.3 MPa. However, near the exit of the acceleration section, the positive pressure balance is decreased to 0.1 MPa. At the exit of the acceleration section, the sabot and projectile attain a transition speed of 700 m/s. At the muzzle, the speed of the sabot is decreased by 130 m/s, which is consistent to the first-order estimation in the previous paragraph. The speed of the projectile was reduced by only 20 m/s.



(a) Pressures on sabot



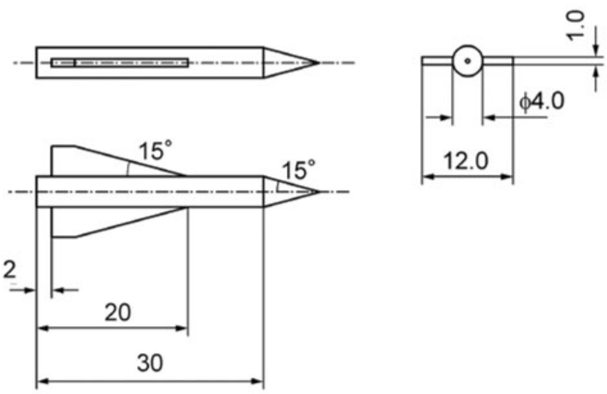
(b) Speeds of projectile and sabot

Figure 6. Variations in launch processes, driver gas; He, P_d=2.1 MPa, P_t=50 kPa, projectile and sabot as shown in Fig. 4.

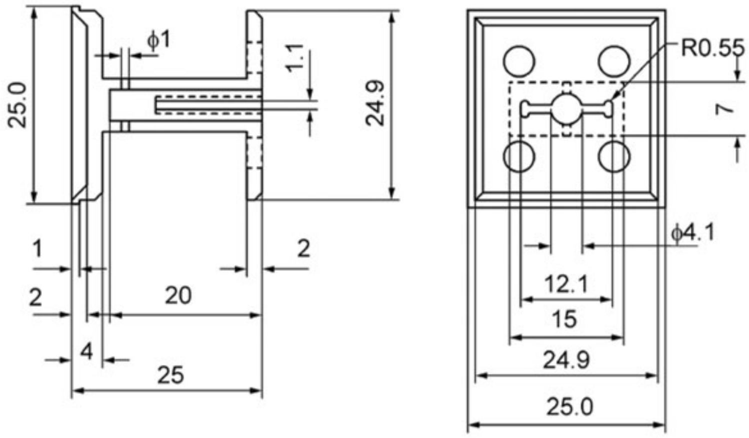
3.3 Free flight experiments

Figures 7(a) and (b) show the design of a three-dimensional projectile and its sabot. The projectile is made of A2017 aluminum alloy and comprises a cylinder rod with an outer diameter of 4 mm and delta wings with an apex angle of 15 degrees. The cylinder rod has a conical nose (SUS304) with an apex angle of 30 degrees. The mass of the projectile equals 1.57 g. The polycarbonate sabot (mass 4.84 g) has a similar structure to the one in Fig. 4. However, in this case the central holder has a rectangular cross-section, fit to the winged body. Figure 7(c) shows an example of a Schlieren image (from one hundred total frames) taken using the high-speed camera. Three conical shocks can be seen: one from the nose, one due to flow attachment on the side of the cylinder and one from the base. The shock waves from the wings are not seen with the sensitivity of the Schlieren system used. This picture demonstrates that the projectile can be launched without noticeable attitude failure.

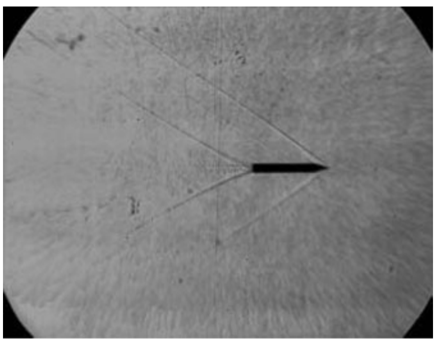
Figure 8 shows a group flight experiment of two circular, hollow cylinder projectiles. Each cylinder is made of aluminum alloy (A2024) with outer diameter 4.0 mm, length 27.5 mm, conical nose with 30-degree apex angle, and mass 0.40 g. The polycarbonate sabot (mass 4.44 g) has a 7 mm × 13 mm rectangular central holder to hold two projectiles with horizontal and vertical separation distances of 4.0 mm and 6.0 mm, respectively. In order to improve the mechanical stability during the sabot separation, the frontal plate was perforated with four 4-mm-dia. holes. Figure 8(c) shows Schlieren images captured in a launch shot. The first three frames capture group flight of the projectiles; the last frame captures the sabot and its detached shock wave. In the first frame, the upper projectile has an angle of attack of 9 degrees whereas that of the lower one is not resolved. With increasing flight distance, the angle of attack increases to 15 degrees in the third frame. So far, in the case of group flights, the angle of attack of each projectile varied depending on subtle asymmetry generated during the launch process; moreover, aerodynamic pitching moment enhances the asymmetry in the formation. As seen above, it is demonstrated that this facility is useful for inexpensive, in-laboratory, free flight experiments for various purposes and configurations.



(a) Schematic design of projectile

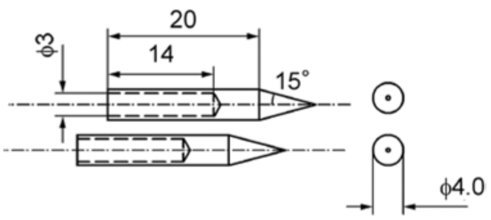


(b) Schematic design of sabot

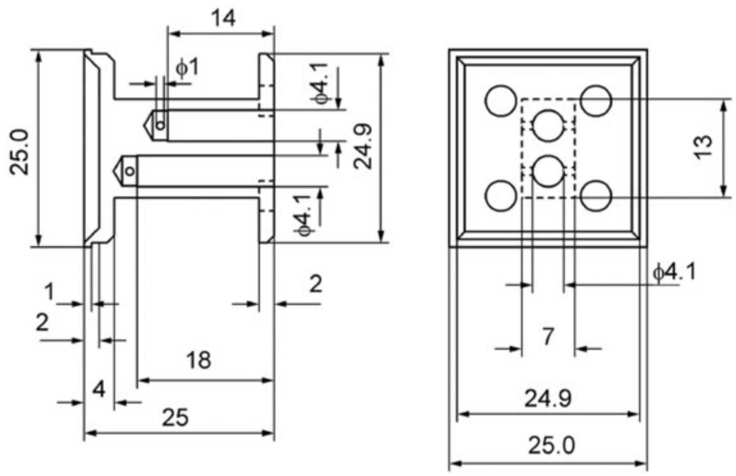


(c) Schlieren image of free flight at a Mach number of 1.75.

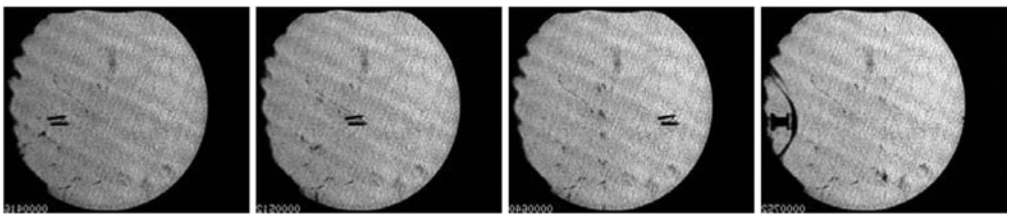
Figure 7. Data of cylindrical projectile with delta wings



(a) Schematic design of projectiles set at initial relative locations



(b) Schematic design of sabot



(c) Schlieren images; framing interval 16 μs, exposure time 2 μs, flight Mach number 1.97.

Figure 8. Data of group flight of two circular cylinders.

4. CONCLUSION

In this paper, a square-bore ballistic range useful for inexpensive, in-laboratory free flight experiments with three-dimensional configurations has been developed. The Bridgman seal sabot was optimized based on the trade-off between the friction force and driver gas leakage over the tube inner wall. A winged circular cylinder can be successfully launched with controlled attitude; a group flight shot was also demonstrated. This facility can launch almost any three-dimensional body with a sabot designed to fit to its shape. Moreover, the aluminum extrusion technique has even higher design flexibility and cost-effectiveness; a gun bore can be manufactured to virtually any specified shape

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