TITLE:

High-Speed Optical Diagnostics of a Supersonic Ping-Pong Cannon

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SUMMARY:

We describe a method for the construction of a supersonic ping-pong cannon (SSPPC) along with optical diagnostic techniques for the measurement of ball velocities and the characterization of propagating shock waves during the firing of the cannon.

ABSTRACT:

The traditional ping-pong cannon (PPC) is an educational apparatus that launches a ping-pong ball down an evacuated pipe to nearly sonic speeds using atmospheric pressure alone. The SSPPC, an augmented version of the PPC, achieves supersonic speeds by accelerating the ball with greater than atmospheric pressure. We provide instructions for the construction and utilization of an optimized PPC and SSPPC.

Optical diagnostics are implemented for the purpose of investigating the cannon dynamics. A HeNe laser that is sent through two acrylic windows near the exit of the pipe is terminated on a photoreceiver sensor. A microprocessor measures the time that the beam is obstructed by the ping-pong ball to automatically calculate the ball's velocity. The results are immediately presented on an LCD display.

An optical knife-edge setup provides a highly sensitive means of detecting shock waves by cutting off a fraction of the HeNe beam at the sensor. Shock waves cause refraction-induced deflections of the beam, which are observed as small voltage spikes in the electrical signal from the photoreceiver.

The methods presented are highly reproducible and offer the opportunity for further investigation in a laboratory setting.

INTRODUCTION:

The PPC is a popular physics demonstration used to show the immense air pressure to which people are continually exposed[1–5]. The demonstration involves the placement of a ping-pong ball in a section of pipe that has an inner diameter that is approximately equal to the diameter of the ball. The pipe is sealed off on each end with tape and evacuated to an internal pressure of less than 2 Torr. The tape on one end of the pipe is punctured, which allows air to enter the cannon and causes the ball to experience peak accelerations of approximately 5,000 g's. The ball, which is accelerated by atmospheric pressure alone, exits the cannon at a speed of approximately 300 m/s after traveling 2 m.

Although the PPC is commonly operated as a simple demonstration of atmospheric pressure, it is also an apparatus that exhibits complex compressible flow physics, which has resulted in numerous open-ended student projects. The dynamics of the ball are influenced by secondary factors such as wall friction, the leakage of air around the ball, and the formation of shock waves by the accelerating ball. The substantial acceleration of the ball introduces a large-amplitude compression wave that travels down the tube in front of the ball. These compressions travel faster than the local sound speed, resulting in a steepening of the compression wave and the eventual formation of a shock wave[6]. Previous work has studied the rapid buildup of pressure at the exit of the tube due to the reflections of the shock wave between the ball and the taped exit of the tube and the resulting detachment of the tape prior to the exit of the ball[2]. High-speed video using a single-mirror schlieren imaging technique has revealed the response of the tape to the reflecting shock waves and the eventual detachment of the tape at the exit of the PPC[7,8] (**Video 1**). Thus, the PPC serves as both a simple demonstration of air pressure that intrigues audiences of all ages and as a device exhibiting complex fluid physics, which can be studied in great detail in a laboratory setting.

With the standard PPC, the ping-pong ball speeds are limited by the speed of sound. This basic version of the PPC is covered in the scope of this paper, along with a modified cannon used to boost the ball to supersonic speeds. In previous work by French et al., supersonic ping-pong ball speeds have been achieved by utilizing pressure-driven flow through a converging-diverging nozzle[9–11]. The SSPPC presented here utilizes a pressurized (driver) pipe to provide a larger pressure differential on the ping-pong ball than is provided by atmospheric pressure alone. A thin polyester diaphragm is utilized to separate the driver pipe from the evacuated (driven) pipe containing the ball. This diaphragm ruptures under sufficient gage pressure (generally 5–70 psi, depending on the diaphragm thickness), thus accelerating the ping-pong ball to speeds up to Mach 1.4. The supersonic ping-pong ball produces a standing shock wave, as can be seen using high-speed shadowgraph imaging techniques[7,12] (**Video 2**).

A low-power (class II) HeNe laser is used to carry out optical diagnostic studies on the performance of the cannon. The HeNe laser beam is split into two paths, with one path traversing through a set of acrylic windows near the exit of the cannon and the second path traversing just past the exit of the cannon. Each path terminates on a photoreceiver, and the signal is displayed on a dual-channel oscilloscope. The oscilloscope trace recorded during the firing of the cannon reveals information about both the speed of the accelerated ping-pong ball and the compressible flow and shock waves that precede the exit of the ball from the cannon. The speed of the 40 mm diameter ping-pong ball at each beam location is directly related to the time the ball blocks the beam. A sensitive "knife-edge" shock detection setup is achieved by covering half of the detector with a piece of black electrical tape and positioning the edge of the tape at the center of the beam[2]. With this setup, slight deflections of the He-Ne laser beam, produced by the compressible flow-induced index of refraction gradients, are clearly visible as voltage spikes on the oscilloscope trace. The shock waves traveling toward the cannon exit and the reflected shock waves deflect the beam in opposite directions and are, therefore, identified by either a positive or negative voltage spike.

Here, we provide instructions for the construction and utilization of an optimized PPC and SSPPC, as well as optical diagnostic techniques (**Figure 1**, **Figure 2**, and **Figure 3**). The optical diagnostic techniques and measurements have been developed through previous years of study[1–2].

PROTOCOL:

1. Building and assembly of the ping-pong cannon (PPC)

1.1. Assemble all the components of the PPC according to **Figure 1**.

1.2. Insert two high-clarity acrylic windows in the sides of the cannon to allow for optical probing across the interior of the cannon.

1.2.1. Drill two 1/2 in holes through opposite sides of the PVC near the cannon's exit.

1.2.2. Prepare two 1/8 in thick acrylic windows using a laser engraver. Download the three supplementary svg files.

NOTE: There are three files labeled "JoVE_AcrylicWindows_Step1_Engrave.svg" (**Supplementary File 1**), "JoVE_AcrylicWindows_Step2_Engrave.svg" (**Supplementary File 2**), and "JoVE_AcrylicWindows_Step3_Cut.svg" (**Supplementary File 3**). These three files should be used in the order provided by using the process described in the title (engrave/cut). The laser speed and power settings should be set according to the manufacturer's recommended settings for acrylic. Each engraving step should remove approximately 1/3 of the thickness of the material.

1.2.3. Add silicon sealant to the edge of the acrylic, being careful not to get any on the window. Then, place windows in the holes, ensuring they are perpendicular to one another. Leave ample time for the silicone to cure after this part of the process.

NOTE: If a laser cutter is not available, a piece of clear tape can be wrapped around the circumference of the pipe to seal the 1/2 in holes and act as a window through into the interior of the pipe. Further experimentation can be carried out by inserting additional windows in the cannon to measure the velocity and acceleration of the ping-pong ball along the length of the driven pipe.

1.3. Using a belt sander, sand off the face of the flange at the exit of the cannon. Finish sanding with fine-grit sandpaper so that the tape can adhere well to the flange.

1.4. Using a laser cutter, cut an acrylic cap following “JoVE_AcrylicCap_Cut.svg” (**Supplementary File 4**). Attach a full-faced rubber gasket to the acrylic cap. The acrylic cap is a component of the pressure seal used when firing the PPC.

1.5. Firmly secure the cannon for firing, and position a sturdy container to safely catch the ping-pong ball with ample padding to minimize the impact with the back wall of the container.

NOTE: There are many solutions for securing the ping-pong cannon and safely catching the ball. For the presented experiment, a custom clamping system was created to firmly secure the cannon with a horizontal orientation. These clamps can be constructed following “JoVE_CannonMountTemplate.png” (**Supplementary File 5**).

1.5.1. Use **Supplementary File 5** as a template to cut out 2 in x 6 in wood planks. Connect the upper and lower portions of the clamping system with a draw latch and hinge to secure the cannon.

1.5.2. Line the insides of the clamps with rubber gasket material to prevent the slipping of the cannon during the firing process. Attach the connected upper and lower portions of the clamping system to the base using four corner brackets.

1.5.3. Mount the completed clamping system to a tabletop using four C-clamps. Construct a 13 in x 13 in x 24 in plywood container, and back it with four 1 in plywood sheets to catch the ping-pong ball. Place a cushioning material in the container to prevent ball rebounds. Mount this container with C-clamps to a tabletop.

2. Building and assembly of the supersonic ping-pong cannon (SSPPC)

2.1. Assemble all the components of the driver pipe following **Figure 2**.

NOTE: The primary difference between the PPC and the SSPPC is that the SSPPC is augmented with a driving, pressurized section of schedule 80 PVC pipe that is connected to the entrance of the PPC. Therefore, if the PPC has already been constructed, all that remains to be assembled to construct the SSPPC is the driver pipe section.

2.2. Firmly secure the cannon for firing and position a sturdy container that can safely catch the ping-pong ball with ample padding to minimize the impact on the back wall of the container.

NOTE: The mounting and catching systems described in step 1.5 are the same systems used to secure the SSPPC.

3. Optical diagnostics

3.1. Set up the laser, beam splitter, mirror, and photoreceivers by mounting the components on an optical breadboard, according to **Figure 3**. Orient the laser perpendicularly to the cannon, with the first beam traversing the interior of the pipe through the acrylic windows and the second passing just outside of the cannon exit.

3.2. Power the photoreceivers and laser module by connecting them to a 15 V current limited power supply and laser power supply. Connect the photoreceivers to the two channels of the oscilloscope using BNC cables.

3.3. Place black electrical tape over half of the photoreceiver sensor. The tape serves as a “knife edge” to create a sensitive shock detection setup.

NOTE: The sensitivity of the knife-edge detection can be further enhanced using a converging lens to focus the beam on the knife edge. The sensitivity can also be enhanced by increasing the distance the beam travels to the photoreceiver, resulting in a greater refractive displacement of the beam.

3.4. Prior to setting the trigger level on the oscilloscope, pay special attention to avoid clipping, which can result from the sensitivity of the knife-edge setup. To avoid clipping, adjust the position of the beam on the knife edge so that the baseline voltage is approximately 50% of the maximum voltage. The maximum voltage is the voltage when the full beam is on the unobstructed detector.

3.4.1. Adjust the settings on the oscilloscope to collect 20 million data points. Set the data acquisition rate to 500 MHz by adjusting the horizontal scale knob. Turn the trigger knob to trip at a voltage slightly below the baseline voltage acquired from the photoreceiver.

NOTE: The velocity of the ping-pong ball can be found through simple mathematics using the photoreceiver modules. The velocity is the diameter of the ping-pong ball divided by the time the beam is obstructed by the ball. A microprocessor is utilized to process the signal received from the interior photoreceiver module to automatically measure the velocity of the ball at the end of the cannon.

4. Automatic velocity measurements

4.1. To utilize a microprocessor for automatic velocity measurements, convert the signal from the photoreceiver module to a 0–5 V pulse, as shown in **Figure 5**, using a comparator that triggers at approximately 10% of the baseline voltage. Connect the converted signal to port 7 of the microprocessor.

4.2. Download “JoVE_AutomaticVelocityDisplay.ino” (**Supplementary File 6**), and upload it to the microprocessor.

4.3. Connect the RA8875 display and driver board to the designated ports on the microprocessor.

5. Setup and firing of the ping-pong cannon

5.1. Put on ear and eye protection before firing the cannon.

5.2. Insert a ping-pong ball into the exit of the cannon. Blow lightly into the end of the cannon until the ball hits the vacuum fitting near the entrance of the pipe.

5.3. Secure a 3 in x 3 in square of tape onto the flange at the exiting end of the cannon and a second square onto the acrylic cap. Seal the tape such that it adheres to the surface of the flange and cap.

NOTE: If there are any wrinkles or large bubbles, the tape needs to be discarded. If the tape does not sufficiently adhere to the surface, the vacuum can be lost, and the cannon can fire prematurely. If at any point the vacuum is lost, the needle valve connected to the vacuum pump can be opened to bring the system to equilibrium.

5.4. Ensure the laser beam is centered on the knife edge, the trigger is properly set, and the catching container is secure.

5.5. Turn on the vacuum pump to evacuate the pipe to a reduced absolute pressure of less than 2 Torr. Once a sufficient vacuum has been reached, puncture the tape at the entrance with a sharp object such as a broadhead or razor tip.

5.6. After firing, turn off the vacuum pump. Remove the tape from the exit flange and the acrylic cap.

6. Setup and firing of the supersonic ping-pong cannon

6.1. For safety, wear hearing and eye protection throughout the firing process.

6.2. Cut sheets of 0.0005 in, 0.001 in, and 0.002 in polyester film that match the dimensions of the flange. These sheets can be cut by hand or, preferably, using a laser cutter. Use the supplementary file “JoVE_MylarDiaphram_Cut.svg” (**Supplementary File 7**) as an outline.

NOTE: For the purpose of this experiment, the cannon was fired with single sheets of 0.0005 in, 0.001 in, and 0.002 in polyester film, and the results are recorded in **Figure 7**. A template to laser-cut the polyester film can be found as an SVG file (**Supplementary File 7**).

6.3. Ensure the valve from the air compressor to the driver pipe is closed. Prefill the air compressor to allow for faster filling of the driver pipe when the cannon is ready to be fired.

6.4. Insert a ping-pong ball into the exit of the cannon. Blow lightly into the end of the cannon until the ball is stopped by the vacuum fitting near the entrance of the driven pipe.

6.5. Secure a 3 in x 3 in square of tape onto the exiting end of the cannon. Seal the tape such that it adheres to the surface of the flange.

NOTE: If there are any wrinkles or large bubbles, the tape needs to be discarded. If the tape does not sufficiently adhere to the surface, the vacuum can be lost, and the cannon can fire prematurely. If the vacuum leaks or other complications arise, use the pressure release valve on the driver pipe and the needle valve on the vacuum pump to bring the system to equilibrium.

6.6. Insert a precut thin polyester diaphragm between two rubber gaskets. Place the diaphragm and rubber gaskets between the driver and driven sections of the cannon. Tightly connect the two sections using 4 cam clamps.

6.7. Ensure the laser beam is centered on the knife edge, the trigger is properly set, and the catching container is secure.

6.8. Turn on the vacuum pump to evacuate the pipe to a reduced absolute pressure of less than 2 Torr. Release the pressure from the air compressor into the driver pipe. Allow the pressure to rise until the diaphragm bursts and the compressed air within the driver pipe rapidly fills the evacuated driven pipe.

6.9. After the cannon fires, turn off the air compressor and the vacuum pump. Remove the burst polyester diaphragm and tape from the cannon.

REPRESENTATIVE RESULTS:

Here, we provide instructions for the construction and utilization of a PPC and an SSPPC, along with the implementation of the optical diagnostics for shock characterization and velocity measurements. Representative experimental results are also provided. The completed systems of the PPC and SSPPC, along with necessary accessories, are shown in **Figure 1** and **Figure 2**. The SSPPC is an augmented version of the PPC, where a driving, pressurized section of pipe is connected to the driven pipe of the PPC. The optical diagnostics setup for the knife-edge detection of shock waves and ping-pong ball velocity measurements is shown in **Figure 3**. A sample oscilloscope trace demonstrating the effectiveness of the optical diagnostics for shock characterization and velocity measurements is shown in **Figure 4**, along with conceptual sketches showing the motion of the ball and the reflecting shock waves corresponding to the oscilloscope trace. The raw and processed signals received by the microprocessor, along with a depiction of the LCD-displayed velocity calculations, are presented in **Figure 5**. A representative dual-channel oscilloscope trace from a successful firing of the SSPPC is shown in **Figure 6**. The oscilloscope traces demonstrate the effectiveness of the knife-edge setup for the detection of shock waves inside and just past the exit of the cannon. The traces also display a clear cutoff in the signal as the ball passes, which is used for accurate ball velocity calculations. Tests were carried out for the firing of the SSPPC under different diaphragm rupture conditions. The correlation between the ping-pong ball velocities and SSPPC diaphragm rupture conditions is plotted in **Figure 7**.

FIGURE AND TABLE LEGENDS:

Figure 1: **Schematic of the standard ping-pong cannon.** This figure shows the setup and layout of the standard ping-pong cannon.

Figure 2: Schematic of the supersonic ping-pong cannon. This figure shows the setup and layout of the supersonic ping-pong cannon.

Figure 3: Schematic of the optical diagnostic hardware setup. This figure shows the setup and layout of the components for optical diagnostic measurement.

Figure 4: Representative oscilloscope trace with illustrated shock wave propagation. This figure depicts a propagating shock wave reflecting throughout the firing process of the cannon, which is represented by a change in voltage with respect to time. The five snapshots of the cannon portray the direction of the shock propagation in conjunction with the position of the ball in the cannon. The direction of the shock wave is determined by a positive or negative spike in the signal. The velocity can be measured through the width of the "square" pulse caused by the ball cutting off the beam.

Figure 5: Microprocessor signal conversion and display. Here, we show the trace of the internally sensing photoreceiver caused by a typical shot of the PPC. The pulse caused by the traveling ball is inverted by a comparator, extra noise is removed, and railed to 0 V and 5 V so that it can be easily read by the microprocessor. The width of the processed square pulse is read by the microprocessor and used to calculate the velocity, which is then displayed on the LCD.

Figure 6: Representative oscilloscope trace for the firing of the SSPPC. The dual-channel oscilloscope trace shows the knife-edge signal for the beams traversing the interior (red) and exterior (blue) regions near the exit of the cannon.

Figure 7: Dependence of the SSPPC ping-pong ball exit speeds on the diaphragm rupture conditions. The SSPPC was fired for a series of cases utilizing single sheets of 0.0005 in, 0.001 in, and 0.002 in polyester film. The membrane pressure differential upon rupture was plotted versus the Mach number for each case. The cannon was fired eight times for each diaphragm thickness, and the vertical and horizontal error bars represent the standard error in the differential pressure and Mach number, respectively.

Video 1: Schlieren imaging technique. The video reveals the response of the tape to the reflecting shock waves and the eventual detachment of the tape at the exit of the PPC.

Video 2: High-speed shadowgraph imaging technique. The supersonic ping-pong ball produces a standing shock wave.

Supplementary File 1: JoVE_AcrylicWindows_Step1_Engrave.svg

Supplementary File 2: JoVE_AcrylicWindows_Step2_Engrave.svg

Supplementary File 3: JoVE_AcrylicWindows_Step3_Cut.svg

Supplementary File 4: JoVE_AcrylicCap_Cut.svg

Supplementary File 5: JoVE_CannonMountTemplate.png

Supplementary File 6: JoVE_AutomaticVelocityDisplay.ino

Supplementary File 7: JoVE_MylarDiaphram_Cut.svg

DISCUSSION:

We have presented a method for the construction of a PPC and an SSPPC along with optical diagnostics for the measurement of ball velocities and for the characterization of shock propagation near the exit of the cannon. The standard PPC is constructed with a 2 m section of 1.5 in schedule 80 PVC pipe. The pipe is fitted with flanges at each end, quick-connect vacuum fittings, and acrylic windows near the exit for laser diagnostics. A detailed schematic of the PPC is shown in **Figure 1**. Prior to firing, a ping-pong ball is inserted into the cannon, and the ends are sealed. The exit end is sealed by securing tape directly onto the flange. At the other end of the pipe, tape is secured over an acrylic cap with a 1.5 in cutout, and the pipe is sealed using the acrylic cap with a rubber gasket. The PPC is firmly secured, and a sturdy container is positioned to safely catch the ping-pong ball. The cannon is fired by evacuating the pipe to a reduced absolute pressure of less than 2 Torr and puncturing the cannon with a sharp object. The SSPPC is an augmented construction of the PPC that produces increased accelerations and supersonic ping-pong ball velocities by securing a pressurized section of 4 in schedule 80 PVC pipe to the standard PPC. A detailed schematic of the SSPPC is shown in **Figure 2**. One end of the pressurized pipe is sealed with a cap, whereas the other end is connected to the PPC with a reducer coupling and flange. The pressurized pipe is fitted with a 1–100 psi pressure gauge, quick-connect fittings to an air compressor, and a safety pressure relief valve. Prior to firing, the ball is inserted into the cannon and the exit end is sealed by securing tape onto the flange. Then, the driver and driven sections are securely connected with a thin polyester diaphragm and rubber gasket in between them. The SSPPC is secured, and a sturdy container is positioned to safely catch the ping-pong ball. After reducing the pressure in the driven pipe to less than 2 Torr, the cannon is fired by releasing pressure from the air compressor into the driver pipe until the diaphragm bursts.

The knife-edge optical diagnostics are set up on an optical breadboard with a laser, beam splitter, mirror, and two photoreceivers, as shown in **Figure 3**. The laser is oriented perpendicular to the cannon, with one beam traversing the interior of the pipe through the acrylic windows and another beam (from the beam splitter) passing just beyond the exit of the cannon. The intensities of the beams are collected by two photoreceiver modules, and the signal is displayed on a two-channel digital oscilloscope. Black electrical tape is placed on the photoreceiver sensors to block approximately half of each beam. The tape serves as a knife edge and increases the sensitivity to detect small transverse deflections produced by shock waves or other density variations in the flow. Data from the photoreceivers are automatically recorded when the cannon is fired by triggering the oscilloscope when the ball traverses the first beam. Prior to setting the trigger level on the oscilloscope, special care must be taken to avoid clipping, which can result from the sensitivity of the knife edge system. Clipping can be avoided by adjusting the position of the beam on the knife edge such that the baseline voltage is approximately 50% of the maximum voltage. The ping-pong ball velocities are calculated using the traces from the photoreceiver modules. A simple and accurate calculation for the velocity is made by dividing the diameter of the ping-pong ball by the time the beam is obstructed by the ball. A microprocessor is utilized to process the signal received from the beam traversing the interior of the pipe to automatically calculate and display the velocity of the ball near the exit of the cannon.

The results of this method are highly reproducible and provide an immediate digital display of the ping-pong ball velocities, enhancing the value of the cannon as a demonstration device. The oscilloscope trace using the knife-edge setup contains a rich visual depiction of the compressible flow and shock waves associated with the cannon. This method focuses on an experiment that is influenced by many secondary factors that can be studied further in a laboratory setting, such as wall friction, the leakage of air around the ball, the formation of shock waves by the accelerating ball, the rapid buildup of pressure produced by the reflection of shock waves between the ball and the taped exit, and the subsequent detachment of the tape prior to the exit of the ball. A representative oscilloscope trace from the firing of the SSPPC is shown in **Figure 6**. The upper trace in the figure corresponds to the beam that traverses the interior of the cannon near the exit. The lower trace corresponds to the beam that traverses the ping-pong ball's path just after exiting the cannon. A clear cutoff in the signal is evident as the ball passes by and obstructs each beam. Voltage spikes prior to the ball passage, introduced by propagating shock waves, are enhanced by the knife-edge detection setup and can be seen on each trace. The successive voltage spikes in the upper trace invert due to the reflection of the shock waves inside the cannon between the ball and the tape. In contrast, each voltage spike on the lower trace is in the same direction because the shock waves outside the cannon do not reflect and pass through the exterior beam a second time.

In addition to the experiments that have been presented, follow-on student projects could be designed to provide additional control over the test conditions during the firing of the cannon. For example, the current SSPPC fires upon natural rupture of the diaphragm after a sufficient pressure differential builds up between the two sections of pipe. The development of a user-controlled rupture mechanism that is initiated by the user or automatically triggered at a desired driver pressure would allow for greater precision in controlling the test conditions. Other follow-on projects could be aimed at measuring the velocity of the ping-pong ball at multiple positions in a single firing of the cannon to provide a more complete description of the velocity and acceleration of the ball as it travels down the pipe. Velocity measurements in the PPC as a function of position have been previously studied, but with each velocity data point obtained from separate firings of the PPC[1].

The ping-pong cannon will continue to be a demonstration that generates intrigue and curiosity for audiences of all ages and types. The complex fluid physics exhibited by the cannon will continue to provide a seemingly limitless supply of follow-on studies that can be investigated in physics and engineering laboratory projects. In the classroom, it will continue to serve as a popular demonstration that stimulates excitement and intrigue about the magnitude of atmospheric pressure. We anticipate that the methods for the construction of the SSPPC and the optical diagnostics that we have presented will enhance the value of the cannon both as a demonstration device and as a useful apparatus for exciting laboratory experiments.

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The authors have nothing to disclose.

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