The Ping-Pong Cannon: A Closer Look

Richard W. Peterson, Benjamin N. Pulford, and Keith R. Stein

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The Ping-Pong Cannon: A Closer Look

Richard W. Peterson, Benjamin N. Pulford, and
Keith R. Stein, Bethel University, St. Paul, MN

This paper describes the use of laser pulse photography, optical timing, and pulsed Schlieren to look more closely at the dynamics of a popular lecture demonstration—the so-called "Ping-Pong cannon" or "vacuum bazooka."[1,2] These optical diagnostic techniques are applied to two types of cannons and lead to greater knowledge of the kinematics of the accelerating ball, along with some details of the exit mechanism and subsequent target interactions.

A 2.7-g, 39.7-mm Ping-Pong ball (nominal 40 mm) is placed at one end of either a PVC or acrylic tube evacuated to a pressure less than 100 Pa (0.7 torr). Sealing tape diaphragms (Scotch brand #375, 3-in width) cover each end of the tube. When the diaphragm near the ball is rapidly punctured, the ball undergoes a large acceleration toward the other end of the evacuated tube. Given an atmospheric pressure of 10^5 N/m^2 over its circular cross section, the ball is initially subject to a force of about 125 N, thus resulting in an initial acceleration approaching 5000 g's. In practice, for an ambient air implosion, balls are observed to leave the tube at between 260 to 310 m/s—depending on the tube/ball parameters.

The physics of such a dynamic system is complex and difficult to model. Ball dynamics are expected to be affected by air resistance and wall friction, gas leakage around the proceeding ball, shock waves produced within the tube by the accelerating ball, velocities of entering gas molecules, and ball interaction with the exit diaphragm. However, the basic application of Newton's second law, fluid dynamics, acoustics, and conservation laws still make it a fascinating demonstration given to excellent classroom and laboratory dialogue and interactions—often resulting in subsequent student projects.

Optical Diagnostics

Speed Measurements

One cannon studied was made of low-cost transparent, extruded acrylic, thus allowing convenient He-Ne laser/detector speed measurements along its entire length. This tube is 3.6 m in length and has a diameter notably larger than the ball—about 41.5-mm i.d. The other tube used was similar to that described by Cockman[1] and is sold as 1.5-in (Schedule 40) PVC pipe, while its actual i.d. is standardized at about 1.59 in (40.4 mm). This 3.0-m long PVC tube thus provides a tighter fit to a 39.7-mm ball but requires that holes be drilled—with glass or transparent tape "windows" attached for He-Ne laser beam speed measurements at specific points along its length.

Figure 1 shows typical digital oscilloscope signals as the ball moves through He-Ne laser beams that strike 1-MHz bandwidth optical receivers[3] at two path locations along the PVC tube. The lower trace is made with a laser/detector about 6 cm from the exit, while for the upper trace the detector is about 60 cm before the exit. With a blocking time of 128 μs for a 39.7-mm ball, the speeds at both locations are close to 310 m/s. The drop in signal observed after ball passage is apparently due to water condensation and increases with ambient humidity. The "fog" behind

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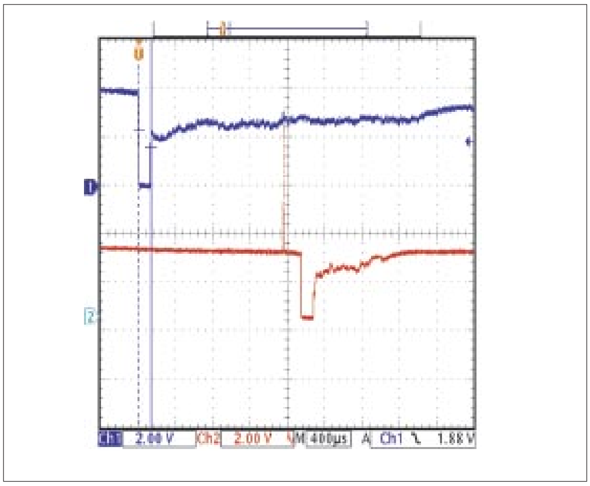

Fig. 1. Oscilloscope traces showing drop in detector signal as 39.7-mm ball passes through the laser beam. Upper trace is with detector 60 cm before the exit of the PVC tube, while for the lower trace it is within 6 cm of the exit. Beam is blocked for about 128 μs at each location.

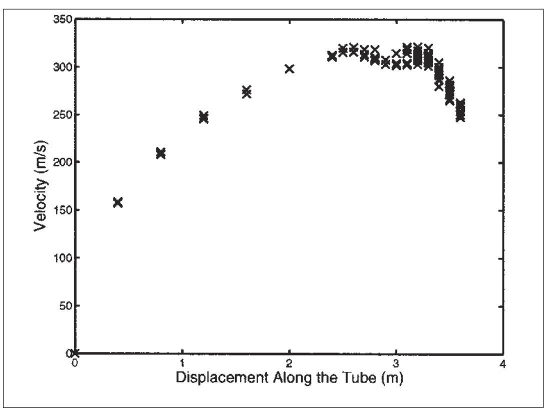

Fig. 2. Velocity measurements are plotted as a function of distance along the 3.6-m acrylic tube. Data obtained beyond 2.5 m show much greater variation from shot to shot.

the ball is often visually apparent at the tube exit for seconds after a shot, and condensation on the tube wall may also be seen in some cases. This change in the "behind the ball" signal is reduced with dryer air and is eliminated for the case of a helium gas implosion from a large plastic bag container at the input. For such helium gas implosion with the PVC tube, speeds within the tube have been measured as high as 370 m/s—with exit speeds of about 345 m/s.

Figure 2 summarizes speed measurements obtained for the longer acrylic tube. Up to about 2.5 m along its path, these measurements are reproducible to almost three significant figures, while after that point these data show the scatter displayed on the graph. For this loose-fitting 3.6-m tube, the graph indicates a strong negative acceleration during the last 1/2 m of path. The deceleration near the exit is not observed with the tighter fitting and somewhat shorter PVC tube, and for that case speeds during the last 1/2 m consistently remain at about 310 m/s. Thus for both tubes, peak speeds approximating 300 m/s are reached after 2.5 m of path.

Ball speeds measured by laser/detector systems immediately after exit are not measurably slower than those inside the tube just prior to exit. Indeed the PVC tube typically produces a speed after exit of about 310 m/s, while the acrylic tube has an exit speed (following deceleration) between 250 and 260 m/s. It becomes clear that any interaction of the ball with the exit tape does not significantly slow the ball while the tape is being removed. As shown with the high-speed photos that follow, the ball never contacts the tape while exiting, and the tape is apparently removed by a very rapid, piston-like pressure buildup or by reflecting shock waves prior to ball arrival.

Laser Pulse Photography

A flashlamp pumped dye laser (with Rhodamine 6G dye) provides convenient illumination for photography of these rapid events. Such a laser can be used to produce a bright 0.4-μs (FWHM) pulse of orange light at 590 nm. The laser is triggered off a He-Ne laser/detector system near the exit, and an adjustable pulse delay unit[4] allows pulse synchronization with exit cannon dynamics. The shutter of a digital camera[5] with bulb setting is momentarily held open during the cannon and laser flash, and the image appears on a nearby computer in seconds. To those who enjoy the romance of the darkroom, the process seems far too easy and fast.

In Fig. 3 the ball is caught exiting from the acrylic tube, and it follows behind the tape that was removed about 250 μs earlier. In this case the exit tape had been coated with a thin layer of spray talc, thus yielding some information about air currents at exit. The sequence of shots (with increasing delays of the laser pulse) shown on the cover of this issue image the ball from the PVC cannon during passage through two free-standing, nearly empty soda cans. It is interesting that a 2.7-g ball near 690 mph will almost always pass through two 14-g soda cans.

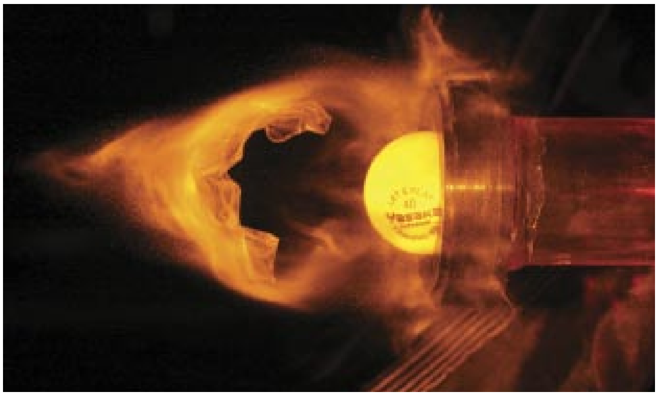

Fig. 3. Laser pulse of 0.4 μs images the ball following the tape upon exit from the 3.6-m acrylic tube.

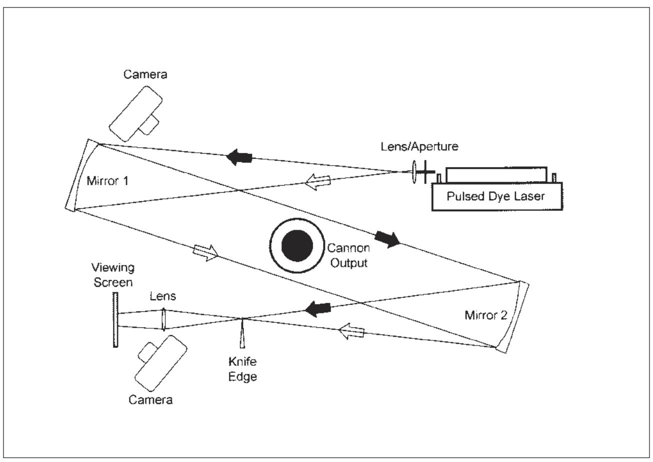

Fig. 4. Line drawing of the optical setup for simultaneous pulsed Schlieren and photographic imaging.

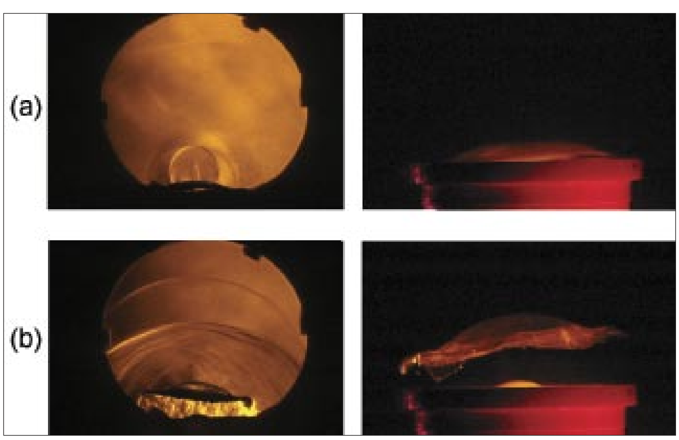

Fig. 5. Synchronized images for two different delays, with pulsed Schlieren (on left) and pulse photography of the emerging ball and tape (on right). Images of (a) are prior to tape being blown away from end of tube, while (b) is the delayed case with the tape removed and turbulent gas following. While the corresponding left and right images are synchronized, the camera angles and magnifications differ.

Schlieren Imaging

Figure 4 shows schematically a Schlieren system[6] that allows one to image air pressure wave fronts and gas proceeding from the tube exit. In Schlieren, refractive index changes in space may be imaged by their effect on where a beam of light will exactly focus. In this case, such spatial index gradients may be produced by gas puffing out behind the tape or by shock waves that come from the tube during tape removal and the ball exit. A knife edge or sharp tip is carefully placed at the focal point of the pulsed laser beam; however, refractive index gradients allow some light to pass the knife edge and thus be imaged on a screen. The large 6-in spherical mirrors[7] allow one to achieve an approximately collimated beam traveling through the tube exit test region, while the lens after the knife edge serves to sharply image this dynamic region on the viewing screen. In this setup, two digital cameras are used to record the desired images. One camera records the pulsed Schlieren image of refractive effects on the screen behind the knife edge, while the second simultaneously records the pulsed photo of the ball and tape.

The images of Fig. 5 show refractive effects at the exit as synchronized with photos of the ball and tape. Shock waves are clearly imaged, and the more spherically shaped of these wave fronts (a) appears to come from a rather localized source, while the other (b) appears to be a superposition of waves from across the accelerating tape surface as it pulls away. This Huygen's-type wave front seems analogous to an acoustic diffraction pattern from across the 40-mm exit aperture. Just behind the removed tape the almost "frothy" image of escaping turbulent gas can be seen.

Current Understanding and Ongoing Work

While we have gathered some helpful information regarding the ball's motion and exit dynamics, more experimental and theoretical work is needed to understand more fully the basic physics occurring during a shot. To that end we are developing a 1-D model for simulation of flow behavior ahead of and behind the accelerating ball based on the compressible fluid Euler equations. An accelerating ball within such a tube produces a pressure pulse that evolves into a shock wave[8-10] that reflects back and forth within the tube and is seen to play an important role as the ball approaches the exit diaphragm—with highly transient pressure and thermal conditions. In addition we are developing interferometric techniques to measure pressure and shock behavior within the tube on submicrosecond time scales.

Acknowledgments

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Dick Peterson *is professor of physics at Bethel University and enjoys optical measurements of transient phenomena and acoustical sources. He is a longtime participant in the work of the AAPT Apparatus Committee, has served six years as AAPT secretary, and is currently AAPT president.*

Ben Pulford *was a Bethel University physics major at the time of this work. He currently is enrolled in the University of New Mexico Optical Science and Engineering program and also works in an NSF-funded program for demonstrating optical science and engineering for K-12 students in New Mexico.*

Keith Stein *is associate professor of physics at Bethel University. He earned a B.A. in physics from Bethel College and an M.S. and Ph.D. from the University of Minnesota in aerospace engineering. His research interests are in computational fluid dynamics and fluid-structure interactions.*

Bethel University, Physics Department, 3900 Bethel Drive, St. Paul, MN 55112-6999; petric@bethel.edu