This Instrument Keeps the Beat

AS part of their responsibilities for stewardship of the nation's nuclear stockpile, Livermore researchers study the behavior of materials detonated with high explosives or struck with projectiles at extreme velocities. In diagnosing these experiments, researchers must measure velocities as great as 3,000 meters per second over distances from less than 0.5 millimeter to more than 50 millimeters.

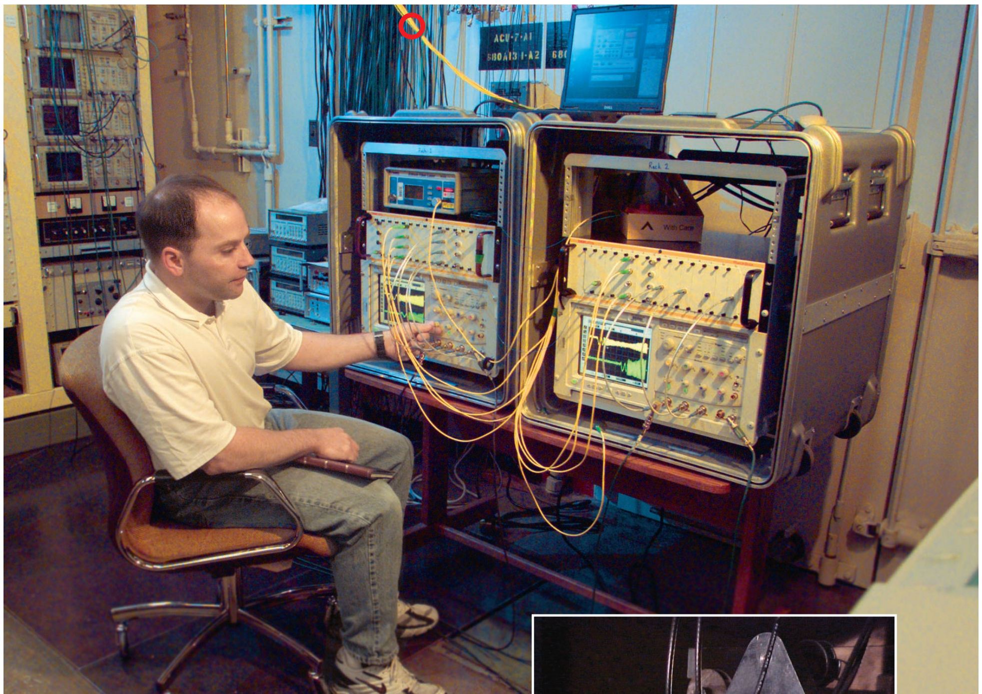
The ability to measure continually changing velocities is important. Within a few microseconds, shock waves cause objects, especially metal samples shocked by high explosives, to accelerate, decelerate, and then accelerate again. Precise velocity data gathered from experiments are used to refine the computer codes that model weapons physics. These data are especially important for improving the hydrodynamics codes used to simulate materials under the extreme pressures and temperatures generated by a high-explosives shock, when metals seem to flow as if they were liquid.

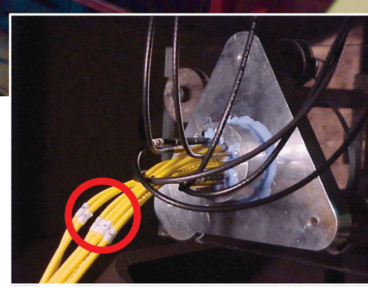
Livermore's Advanced Diagnostics Group, part of the Defense and Nuclear Technologies Directorate, is tasked with diagnosing hydrodynamics tests and other experiments that shock materials. To characterize these experiments, researchers use radiation detectors, imaging cameras, temperature probes, and velocimeters. They are continually in search of better diagnostic equipment to measure the extreme velocities. One recent Livermore development is a cost-effective and easy-to-operate technique called the photonic Doppler velocimeter (PDV). (See the figure at right.) Equipped with two new telecommunication devices, the PDV takes advantage of a basic phenomenon that's taught in high school physics—the beat frequency.

Making Use of Doppler Shift

One method to determine the velocity of a moving surface is to measure the Doppler-shifted frequency of light reflected off that surface. The Doppler shift is the difference between the frequency at which sound or light waves leave a source and the frequency seen by an observer. The difference is caused by the relative motion of the observer and the source. A well-known example of the Doppler shift from sound waves is the falling pitch of a train as it moves away from a stationary observer.

This same relationship occurs with light waves. If laser light is shone on a stationary metal surface, light reflected from the surface will have the same frequency, or color, as the incident laser light. However, if the surface is moving, the Doppler shift slightly





Laser technician Tony Whitworth adjusts the settings on the digitizer component of the photonic Doppler velocimeter (PDV). The PDV consists of a fiber laser, a detector chassis, and a digitizer with 20-gigahertz sample oscilloscopes. In this setup, the laser light is split into seven beams, with four feeding a detector and digitizer, and another three feeding a second detector and digitizer. The yellow optical fibers at the top of the case (see inset) are routed to an adjoining room and secured to the back end of a target assembly. In the experiment, a projectile from a gas gun hits a sample of aluminum placed on the opposite side of the target assembly.

changes the frequency (color) of the reflected light. As the surface moves, the shift in frequency of the reflected light is proportional to the change in velocity of the illuminated surface. The greater the velocity, the greater the Doppler shift and frequency change.

Livermore researchers use several types of velocimeters that measure the Doppler effect. The most sophisticated is the multibeam Fabry–Perot velocimeter, developed in the mid-1990s by physicist David Goosman, who leads the Advanced Diagnostics Group. This device splits a laser light into five individual beams with very high efficiency, and five streak cameras then record the reflected laser light. In this way, the time history of material at five different spots on a metal's surface is recorded with extreme accuracy. (See *S&TR*, July 1996, pp. 12–19.)

"The multibeam Fabry–Perot is a robust system that really tells us what is going on," says Livermore physicist Ted Strand, who also is a member of the Advanced Diagnostics Group. Unfortunately, the Fabry–Perot instrument must be custom manufactured, it takes up a lot of space, and several people are needed to operate it—all of which limit the number of channels that can be fielded on an experiment. In addition, many experimenters cannot afford to build a Fabry–Perot system.

Another diagnostic system, the commercially available VISAR (Velocity Interferometer System for Any Reflector), is less expensive than the Fabry–Perot and performs well for measuring a single velocity. However, a VISAR is inadequate for many of the experiments that could potentially produce multiple velocity signatures.

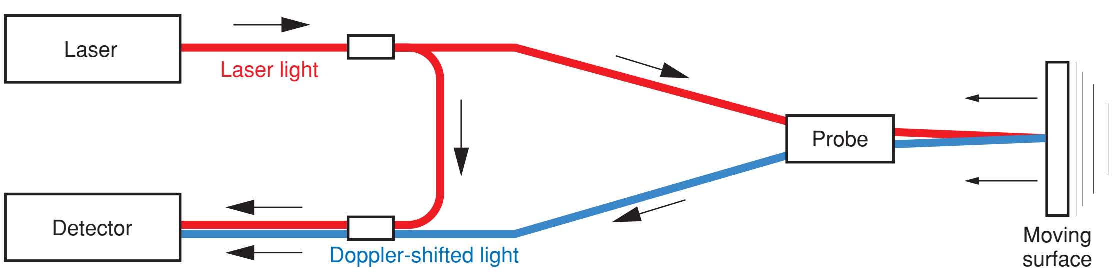
To overcome these problems, Strand searched for a more cost-effective method to measure velocity—one that would offer about the same accuracy as Fabry–Perot. That search led him to the beat frequency.

Beat Frequency a Matter of Subtraction

The beat frequency is the difference in frequency between two waves. It is easily evident in sound waves: Strike two tuning forks, each tuned to a slightly different frequency. The sound from the two forks will go up and down in volume rather slowly. In a similar manner, two guitar strings tuned almost identically and struck at the same time will also produce a beat frequency identified by an up-and-down volume. The "beats" are caused by the constructive interference, or combined amplitude, of two different waves as they pass the same point—in these examples, the listener's ear. When the two waves are in phase, their combined amplitude is larger—or the noise is louder—than it is when the waves are out of phase.

The PDV detects the beat frequency from two slightly different frequencies of light by shining laser light at 1,550-nanometer wavelength (in the infrared spectrum) on the surface of a moving target. The Doppler-shifted laser light reflected off the target surface is collected and sent to a detector. At the same time, some of the original light is sent back to the same detector. The incident laser light has a frequency of 1.93×10^{14} hertz, or 193,414.49 gigahertz. If the target is moving at 1,000 meters per second, the Doppler-shifted laser light will have a frequency of 193,415.78 gigahertz. Both frequencies are so rapid that no existing detector can directly measure them. However, high-speed detectors can measure the difference in frequencies—the beat frequency—because it is much slower than either the original laser light or the Doppler-shifted light.

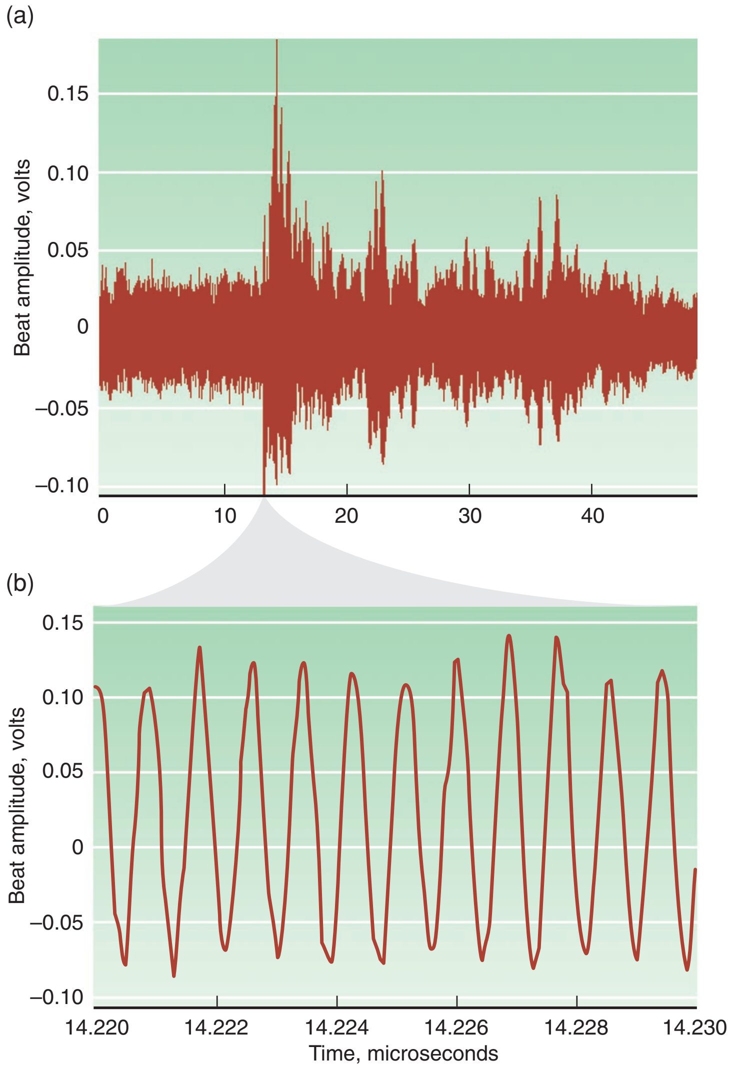
In this example, the beat frequency measures 1.29 gigahertz, or less than 1/200,000 of the original frequency. "Once we know the beat frequency," says Strand, "we can infer the velocity of the metal surface. Then we have data to construct a graph of velocity versus time."



The photonic Doppler velocimeter detects the beat frequency between two slightly different frequencies of light. Laser light (red) from a probe is shone on a moving surface. The Doppler-shifted light (blue) is collected and sent to a detector. At the same time, some of the original light is sent to the same detector. The difference in frequency between the two—the beat frequency—is much slower than either the original laser light or the Doppler-shifted light, allowing researchers to infer the velocity of the metal surface and construct a graph of velocity versus time.

Goosman had once considered using the beat frequency as the basis for a velocimeter, but developing such an instrument for an explosive experiment was impractical until about a year ago. That's when Strand noticed two new and relatively inexpensive telecommunication devices: an extremely fast digitizer and a compact fiber laser.

The digitizer used in the PDV can measure 20 billion samples per second. "That's an extraordinary sampling rate, but it's just barely fast enough to follow an exploding metal sample," says Strand. The 20-gigahertz sampling rate generates 1 million data points in a 50-microsecond experiment, which is fast enough to provide at least 4 data points for every recorded beat-frequency wave. (See the figure below.)



(a) This example shows the beat frequency (converted to amplitude) recorded during 50 microseconds of a high-explosive experiment. (b) The waves from a 10-nanosecond period of the beat frequency are extracted from (a).

Fiber Laser Keeps Things Simple

Another telecommunications product featured in the PDV is compact and affordable high-power fiber lasers. The optical fibers in these lasers, which have 9-micrometer-diameter cores, are doped with rare-earth metals to amplify the laser light. In addition, the laser power can be adjusted over a broad range. Livermore researchers use light of 1,550-nanometer wavelength because that wavelength is used by the telecommunications industry. "The fiber becomes the laser," says Strand. "This design does away with a lot of optics and other components that traditional lasers require."

In the PDV, the originating laser light can be split into as few as four beams or as many as eight. The four to eight fibers deliver light from the control room out to the experiment area, where they have been placed between a few millimeters to 25 centimeters away from the target. During the fleeting experiment, some of the reflected light returns to the control room on these same fibers. The reflected light and a sample of the original light are converted to an electrical signal. This beat signal is then amplified and digitized.

The PDV has been used in more than 20 experiments conducted at Livermore's remote experimental site and its High Explosives Applications Facility. It has also been used at the Big Explosives Experimental Facility, located at the Nevada Test Site (NTS). Plans are under way to use the diagnostic at the underground U1a complex, also at NTS, where subcritical experiments involving small amounts of plutonium are performed. Tests conducted in April 2004 at Livermore's small gas-gun facility demonstrated that PDV would be a valuable diagnostic at JASPER—the much larger Joint Actinide Shock Physics Experimental Research Facility gas gun at NTS. (See *S&TR*, June 2004, pp. 4–12.)

PDV is promising to become a standard element in the arsenal of diagnostic techniques available to Livermore researchers. Commercial products make the technique easy to set up, simple to operate, and cost effective. If the early successes are any indication, more Livermore experiments will focus on the beat.

—Arnie Heller

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