Fiber optic velocity interferometry

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ABSTRACT

This paper explores the use of a new velocity measurement technique that has several advantages over existing techniques. It uses an optical fiber to carry coherent light to and from a moving target. A Fabry-Perot interferometer, formed by a gradient index lens and the moving target, produces fringes with a frequency proportional to the target velocity. This technique can measure velocities up to 10 km/s, is accurate, portable, and completely noninvasive.

1. INTRODUCTION

Explosively driven flying plates experience rapid acceleration and are capable of reaching velocities of several kilometers per second (millimeters per microsecond) in fractions of a microsecond. The two velocity interferometry techniques presently used to measure the velocity of these targets, the Velocity Interferometer System for Any Reflector (VISAR)^{1,2,3} and the Fabry-Perot technique,^{4,5,6} measure the Doppler shift of light reflected from the moving targets. The Doppler shift gives rise to a fringe shift proportional to the velocity. These techniques are very accurate, precise, and noninvasive. Unfortunately, they are also very big, expensive, and not portable. Typical VISAR systems use a high power water cooled Argon laser, are constructed on a 4'X 8' optical table, and record the data on four or more expensive high speed digitizers. Fabry-Perot systems use somewhat simpler optics, but require an expensive electronic streak camera to record the data.

In many experiments it is desirable to measure the velocity at several points simultaneously. Many laboratories incorporate a dual VISAR which is capable of measuring the velocity of two points simultaneously, but it is impractical with such a system to increase the number of points beyond two. A velocity diagnostic constructed of fiber optic components would overcome many of the problems with the presently used techniques. It could be constructed relatively inexpensively by using the same components used in the telecommunications industry. It would be small and light-weight, enabling the experimenter to bring the diagnostic to the experiment instead of constructing the diagnostic in the location of the device to be tested. It would also allow for multipoint measurements because of its small size and low cost.

2. FIBER OPTIC VELOCITY SENSOR

A schematic diagram of the sensor is shown in Figure 1.

Light from a coherent laser diode is launched into a 10 μ m core single mode optical fiber, through a 50% coupler, and onto a quarter pitch gradient index lens. Approximately 4% of the light is reflected from the uncoated face of the lens, with the remainder striking the diffuse target. Some of the light reflected from the target, typically between 1% and 20%, is captured by the lens and coupled back into the optical fiber. The amount of reflected light captured by the lens depends on the surface finish and the distance between the lens and the target. This reflected light then travels back through the coupler and is detected by a photodiode.

The lens and target form a reflection Fabry-Perot interferometer. However, the cavity has a very low finesse due to the low reflection coefficients at the lens and target. The light output from the interferometer can be determined by summing the contributions of the electric field from each reflection. Let R_1 be the portion of the electric field reflected by the lens, T_1 be the portion transmitted, and R_2 the portion reflected by the moving target. (Recall that for uncoated glass $R_1^2 = 0.04$ and $T_1^2 = 0.96$.) The

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Figure 1. Schematic diagram of the interferometer. The gradient index lens and moving target form a Fabry-Perot cavity.

electric field transmitted back through the fiber, E' , is given in terms of the input field, E , by the expression

$$E' = \text{Re} \{ (-R_1 + T_1^2 R_2 e^{2ikd} + T_1^2 R_1 R_2^2 e^{4ikd} + \dots) E \} \quad (1)$$

where d is the distance between the target and the lens and $k = 2\pi/\lambda$. Since the detector is capable of responding only to the intensity of the light and not to the electric field itself, the signal is proportional to the square of the electric field. This is given by

$$I' = \frac{\{ [R_1(1+R_2^2) + R_2(1+R_1^2) \cos 2kd]^2 + R_2^2(1+R_1)^2 \sin^2 2kd}{4(1 + R_1^2 R_2^2 - 2R_1 R_2 \cos 2kd)^2} I \quad (2)$$

where I' is the intensity at the detector, and I is the intensity launched into the fiber by the laser. (The 4 in the denominator reflects the 50% loss through each pass of the coupler.)

This equation can be simplified in the case of low reflectivity of each of the surfaces. If $R_1, R_2 \ll 1$ then equation 2 reduces to

$$I' = \frac{[R_1^2 + R_2^2 - 2R_1 R_2 \cos 2kd]}{4} I \quad (3)$$

Figures 2 and 3 show the reflected signals as a function of the lens to target distance for target reflectances of 1% and 25% respectively. As the figures show, the two functions are essentially sinusoidal so that the approximation in equation 3 can almost always be used.

The above analysis holds as long as the distance between the lens and the target is less than or equal to the coherence length of the laser diode. The laser diode used in these experiments has a spectral width of less than 0.1 nm full width at tenth maximum. The coherence length is given by $L = \lambda^2/(2\Delta\lambda)$. This means that the laser is coherent over distances of a centimeter or less. For longer distances, the velocity signal is slightly attenuated, but the period remains the same. Working distance limitations of several centimeters are generally not a problem for most explosive research.

The preceding analysis also implicitly assumed that the lens to target distance remained fixed. A moving target changes the above analysis in two ways. First, the lens to target distance, d , is not constant but changes with time. Thus, the simple summation shown in equation 1 must be modified to account for the different distances for each reflection. However, as figures 2 and 3 and the preceding analysis show, the first two terms dominate so that only one distance is needed. Second, a moving target produces a Doppler shifted wavelength so that the term $2kd$ in the above equation must be modified. This term becomes $2kd + (k+k')d = (1+v/c)2kd$. Even for explosively driven flyer plates reaching velocities of several kilometers per second, this correction is one part in 10^5 and can be completely ignored.

Figure 2. Interferometer signal given by the sensor with a target with 1% reflectance.

Figure 3. Interferometer signal given by the sensor with a target with 25% reflectance.

This interferometer produces a phase shift proportional to a change in distance, unlike the VISAR which produces one proportional to a change in velocity. Thus, the velocity is proportional to the rate of change of phase. To determine the velocity one only needs to count the number of fringes (2π phase changes). Both equations 2 and 3 show that the peaks in the intensity occur at phase $2\pi d = 2\pi d/\lambda$.

Differentiation with respect to time yields

$$v = \lambda f / 2 \quad (4)$$

where f is the number of fringes per time period. If λ is measured in microns and f is measured in number of fringes per microsecond, then the velocity is given in meters per second.

One advantage of sensing the rate-of-phase change instead of the absolute phase is that the initial phase does not have to be known as it does in the VISAR and Fabry-Perot techniques. Often there is a large timing jitter associated with the explosion. In this case it is often difficult to measure the velocity of the target when it first starts to move. Since this sensor determines the velocity from the rate of change in the phase, no error is introduced by missing the start of the velocity history.

Another advantage is that only one recording channel is used instead of the two to four generally used in VISAR systems. Since a VISAR produces fringes proportional to velocity, ambiguity can result if the velocity changes slowly near the extrema of the sinusoidal interferometer signal. Thus all VISARs use quadrature coding to remove the fringe ambiguity, and require at least two recording channels. Many experimenters also use two VISARs with different fringe constants to recover any fringes lost by the extremely rapid acceleration produced by explosives. The one disadvantage of this sensor is that it places a higher bandwidth requirement on the detector and recorder than typical VISAR systems.

3. EXPERIMENTAL TESTS

The movement of a piezoelectrically driven mirror was recorded in order to verify the functioning of the apparatus. A diffuse reflector was applied to the mirror to simulate typical operating conditions. A 2 mW Toshiba TOLD S52S coherent 1.31 μm laser diode was used as the source of light. The detector was a Tektronix P6702 with a response of 1 V/mW of optical power. It was recorded on a Hewlett-Packard 54111D Gigasample digitizer. Both the voltage drive signal and the interferometer signal were recorded simultaneously.

Figure 4 shows the result of one measurement. Notice that the interferometer signal tracks the voltage signal. The voltage supplied to the piezoelectric driver was sufficient to cause the mirror to move through slightly less than one half wavelength so that less than one fringe was recorded.

Figure 4. Piezoelectric transducer voltage drive signal (top) and sensor signal (bottom). The output is approximately proportional to the input because the target moves by less than 1 fringe.

Figure 5 shows the result of driving the mirror with a larger voltage. The mirror traveled forward at one slow velocity, and then backward at a faster velocity. The difference in speeds of the mirror is reflected by the different fringe frequencies in the interferometer signal. Figure 5 also illustrates the fact that the interferometer is insensitive to the direction of motion. For explosive research there is no ambiguity since the direction of motion is known in advance. For more complicated motion it is possible to use two lasers with slightly different wavelengths and use wavelength division multiplexing to determine unambiguously the direction of motion.

A schematic diagram of a more realistic experiment is shown in Figure 6. A .22 caliber lead bullet from an air gun struck an aluminum plunger after first passing through a .5mm pencil lead. The small current passing through the lead was interrupted when the bullet broke the lead. The resultant signal was used to trigger the digitizer.

Figure 5. Piezoelectric transducer voltage drive signal (top) and sensor signal (bottom). The target moves slowly forward (broad fringe) and more rapidly backward (sharper fringe).

Figure 6. Schematic diagram of gas gun experiments. The bullet broke the pencil lead to provide a trigger and then struck the plunger.

Figure 7 shows a typical output from the sensor. The initial part of the trace shows motion on the order of 0.3 m/s. This slow velocity is due to small vibrations in the system. The much higher velocity (signaled by the high frequency fringes in the later part of the trace) was caused by the bullet transferring its momentum to the plunger. Figure 8 shows an expansion of the high frequency section of the signal. The signal is a sinusoidal function with a period of 29.5 ± 0.4 ns, which corresponds to a velocity of 22.2 ± 0.3 m/s.

The velocity of the bullet, v_1 , can be estimated by measuring the time delay from the trigger until the plunger starts to accelerate. Approximately $27.7 \mu\text{s}$ after the bullet broke the lead, the movement of the plunger was detected. It should take approximately $2.4 \mu\text{s}$ for the front surface of the plunger to start moving after the back was struck, yielding, a bullet flight time of $25.3 \mu\text{s}$. The center of the trigger lead was located approximately 1.9 ± 0.3 mm from the plunger. The large uncertainty in the location of the trigger lead is caused by the inability to determine at what point the lead breaks and current stops flowing. Combining the above measurements yields a bullet velocity of 75 ± 12 m/s. The velocity of the plunger, v_2 , can be predicted by dynamics in terms of the mass of the bullet, $m_1 = 0.92 \pm 0.01$ g, the plunger mass, $m_2 = 1.74$ g, and the velocity of the bullet. For an inelastic collision the expected value of the plunger velocity is given by $v_2 = v_1 m_1 / (m_1 + m_2) = 26.4 \pm 4.2$ m/s, if the effects of friction are ignored. The interferometer velocity measurement (22.2 ± 0.3 m/s) is consistent with the plunger prediction to within the experimental error of the bullet velocity measurement.

Figure 7. Sensor output from the experiment shown in Figure 6. The plunger starts to move at approximately 26 μs (at the dotted line).

Figure 8. Sensor signal expanded to show high frequency sign waves. The velocity is directly related to the frequency of the sinusoidal signal.

Further tests were conducted with different pressures in the air gun. The interferometer velocity measurement was consistent with the bullet time-of-flight bullet measurements in all cases although there was much better precision and accuracy in the interferometer measurements than in the bullet velocity estimations.

The alignment of the diagnostic was also found to be very easy. The experimenter adjusted the angle of the gradient lens with respect to the target in order to maximize the reflected light. With practice, the alignment usually takes under a minute.

4. LIMITATIONS OF THE TECHNIQUE

One of the biggest limitations of this diagnostic is the reliance on high speed digitizers to record the signal of rapidly moving targets. The maximum velocity that can be recorded is directly related to the wavelength of the laser and the highest frequency signal that can be recorded by the digitizer.

The choice of wavelength is limited by the availability of optical fiber. In general, only optical fiber of interest to the telecommunications industry at wavelengths 0.83 μm , 1.3 μm , and 1.55 μm can be used. Hence, the maximum velocity that can be measured, v_{max} , is given by

$$v_{\text{max}} \text{ (km/s)} = 0.775 F_{\text{max}} \text{ (GHz)} \quad (5)$$

where F_{max} is the maximum detectable frequency.

The maximum detectable frequency can be higher than the 3db bandwidth of the recorder, as long as it is possible to unambiguously determine the period of the signal. Digital systems impose the Nyquist requirement of at least 2 digitization points per cycle. Thus, the fastest velocity that can be measured (utilizing the 2 gigasample option on the Hewlett-Packard digitizer mentioned above) is 0.8 km/s. Use of a faster oscilloscope, such as a Tektronix 7250 digitizer brings the maximum measurable velocity to approximately 10 km/s. An electronic streak camera can record an extremely high velocity, but a shorter wavelength laser would be needed to better match the spectral response of the streak camera photocathode.

If the experimenter is willing to relax the requirements of ease of use (using fiber optics to transport the laser beam to and from the target) and portability, then lasers with longer wavelengths, such as the 10.6 μm CO₂ laser, could be used. The coefficient in the above equation would be modified from 0.775 to 5.3. Thus, any of the modern gigasample digitizers would be capable of recording velocities of several kilometers per second. An additional approach would be to use heterodyne techniques to offset the frequency. However, this approach usually results in a much lower bandwidth for the system.

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Because of the several centimeter coherence length of the laser diodes, it is necessary that the lens be close to the target. Explosive experiments will generally cause the destruction of the lens and part of the optical fiber. However, since these components are relatively inexpensive (less than \$10 in reasonable quantities) the loss of the detector with each experiment should be a minor inconvenience.

As mentioned above, it is often desirable to measure the velocity at several target positions. Since the lenses are only two millimeters in diameter, it would be simple to place several probes close together. Use of a streak camera as a multichannel data recorder² with several of these interferometers would allow inexpensive simultaneous measurement of the velocity of many points.

5. CONCLUSIONS

The fiber optic velocity interferometer discussed in this paper presents a new diagnostic. It is precise, accurate, portable, inexpensive and easy to use. It is capable of measuring velocities as high as 10 km/s with a high speed digitizer.

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