Optical velocimetry; LA-UR-04-6453

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This work considers current potential uses of laser Doppler velocimetry. A discussion of other optical velocimetry techniques is presented and compared with their practical application to modern shock physics diagnostics, such as VISAR.

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I. INTRODUCTION

Doppler effect concepts were first introduced by mathematician Christian Johann Doppler in the 1800s [1]. Doppler postulated that the frequency of sound, and light, depended on whether the source was moving or stationary, and on the medium through which the sound was carried. As a proof, in 1845 Doppler performed an experiment at a train station in which two identical horns played the same note while one horn was on a moving train and the other was stationary. This result is now generally appreciated by most persons as most have heard the difference between the sound of a car horn, siren, etc., that is travelling toward or away from a stationary listener.

At a later date (~1848), Armand Fizeau independently formalized Doppler’s theory for electromagnetic. Fizeau was unaware of Doppler’s work [1], and his postulates dealt with the red shift of light by moving stars. He postulated that the speed of the star depended on its color, or frequency. Of course, Einstein fully established the relativistic Doppler effect with his *Special Theory of Relativity* in the early 1905 [2].

Presently the Doppler effect is used quite effectively, and regularly, to determine the velocities of many different objects, to answer many different physics questions. Police use the Doppler effect, with optical- and radio-frequencies, to remotely determine the velocity of cars. The military has used Doppler radar for similar purposes. Doppler anemometers are used to measure particle velocities in fluid flow. Laser Doppler velocimeters are used to measure wind speeds [3], etc.

Modern laser Doppler techniques were introduced in the early 1960s by Yeh and Cummins [4]. Shortly thereafter, Forman, *et al.* [5] proved Yeh’s efforts and developed practical applications of laser Doppler velocimetry as a fluid flow diagnostic (see Fig. 1). Since this modern inception, Doppler methods as a diagnostic tool have become popular in atmospheric physics, eavesdropping, etc.

II. OPTICAL DIAGNOSTICS: SHOCK PHYSICS APPLICATIONS

Measurement problems in shock physics present their own special difficulty in determining parameters important for modeling continuous mechanical systems, such as steel or other metals, under extreme pressures. At

![Diagram of optical diagnostic setup](image)

FIG. 1: This schematic shows the basic configuration used by Forman [5]. Its salient characteristic is that it splits off the reference beam and heterodynes it with the Doppler shifted beam. The concept is simple, and the technique sensitive. (Not shown are any attenuators that might be needed to balance the reference beam with the reflected beam intensity; neither is the beamsplitting ratio specified, nor any other detailed optics specifications.)
once Doppler methods looked promising to measure the parameters important in equation-of-state studies, and yet were difficult to practically implement. The largest problems centered on available laser-light frequencies, and detection-and-measurement technologies available at that time. For example, consider the Doppler shift from He-Ne light ($\lambda = 633$ nm) scattered off of a surface shocked up to a velocity on the order of 1,000 m·s$^{-1}$. This shift is represented by a Doppler beat frequency of:

$$\omega_D = \frac{v}{c} \times \omega_0$$

$$\therefore |f_D| = a \cdot \frac{v}{\lambda_0} = 1.58 \text{ GHz.} \quad (1)$$

(The constant, $a$, is determined by the angle of observation, and whether the light is travelling along or against the flow; for normal incidence reflection, $a = 2$.) Thus, one can see quite clearly that in the early stages of Doppler development, that measurement-and-detection technologies at the time limited Doppler techniques to low speed measurements.

Not to be denied, scientists applied some neat optical techniques to measure velocities of this order of magnitude; namely, VISAR (velocity interferometer system for any reflector) [6]. The success of VISAR relies on the Doppler shift to determine a velocity from a reflector, but it does not actually measure the Doppler shift. Rather, VISAR measures the difference in the Doppler shift between two relatively Doppler shifted, reflected light beams. Thus, if you will, VISAR measures the acceleration of a surface as a function of time.

The VISAR concept, essentially, is based on an unbalanced interferometer, i.e., one arm of the interferometer is longer than the other (see Fig. 2). The effect is to interfere early-time reflected light with late-time reflected light. In its simplest concept, detector amplitude measurements are made in quadrature; the amplitude measurements then represent the sine and cosine of the detected amplitude at the last beamsplitter. In this concept, the sine- or-cosine is plotted versus the cosine- or-sine of the measured amplitude—the phase angle between the early- and late-time reflected light. To complete the system, polarizers and waveplates are used to ascertain whether the surface is accelerating in a positive or negative sense. The velocity is determined by integrating (counting) the number of fringes that spin by. The longer the signal is integrated in time, the more uncertain the result.

VISAR was an elegant solution to an intractable measurement-and-detection bandwidth problem in the early 1970s. However, it has also been regularly applied to Asay foil measurements [7] when in fact direct Doppler measurements are more appropriate as the foil velocity in such systems is seldom greater than a few tens of meters per second (a beat frequency on the order of tens of mega-Hertz). It would be much simpler and more cost effective to simply apply Doppler techniques to the Asay foil diagnostic.

Another technique currently in use to measure the free-surface velocity of a projectile, or shocked system of particles, is referred to as Fabry-Perot [8]. Basically, this concept involves directly measuring the change in the wavelength of the reflected light. This is accomplished with a high quality etalon. When properly aligned, the fringe pattern formed when light passes through the etalon forms an Airy pattern. This Airy pattern (a.k.a. Fraunhofer diffraction pattern of a circular aperture) is imaged onto a slit preceding a streak camera that is used for detection. As the surface is shocked, or as the projectile moves, the Airy pattern fringe spacing changes. These changes in the fringe patterns are recorded on the streak camera and relate the velocity of the free-surface similarly as the direct Doppler measurements.

### III. DISCUSSION

We have discussed several methods whereby it is possible to measure the velocity of a free surface, such as a projectile or shocked surface. The techniques commonly

![VISAR Concept](image_url)

Fig. 2: This figure schematically describes the VISAR concept. Early-time reflected light [light that travels the upper (long) path] is “interfered” with late-time reflected light [light that travels the lower (short) path]. The two detectors define the quadrature measurement. [It is worth noting that many of the subsequent improvements to this earlier system are left out of the schematic. The improvements include a quality block of glass (this changes the rate of modal dispersion), and polarizers and waveplates, to name a few of these important improvements.]
in use today at national laboratories in the United States and Europe include VISAR and Fabry-Perot, and the most common technique in use is VISAR (1). A reasonable question to ask, is why consider different techniques today as we have at least two proven diagnostic methods to accomplish this task? To answer this question, it is appropriate to ask the following: what method would we consider today for these measurements if these types of measurements had never been accomplished before, and we were not limited by our technology? The answer for velocities on the order of \( u(t) \lesssim 1,000 \text{ m-s}^{-1} \), is that we would consider Doppler.

Doppler measurements give the instantaneous velocity, so long as certain parameters are known. For example, is the object moving toward or away from the measurement apparatus? Is the angle of incidence normal to the surface or is the angle known?

The Doppler measurement gives the velocity in the absence of a priori information. For example, if the VISAR system is not activated prior to the initial motion of the surface, the all important initial phase angle information is lost and it cannot be recovered. The initial motion of interest must be covered prior to being able to determine a velocity; failure to measure this angle is equivalent to not knowing (measuring) the integration constant. In addition, due to bandwidth limitations, VISAR cannot accurately determine the jump-off velocity as the measurement is sensitive to small differences in the Doppler shift.

Fabry-Perot requires similar information as VISAR. For example, the streak-camera timing must be precise enough to make certain that the recording system is active prior to the initial surface motion, otherwise the motion of the fringes from the static position will not be known, and neither will the velocity.

It is simple to argue that Doppler has other limitations as well. It is clear, however, that it is better to start the recording of the diagnostic prior to projectile motion, or free-surface motion, otherwise it would not be able to specify the position as a function of time, at least not precisely (\( x_0 \) is needed, for the same reasons that the initial phase angle is needed for VISAR, and the initial fringe position is needed for Fabry-Perot: position follows from integrating and the initial constant is required for a quantitative result).

Because VISAR “velocities” represent an integration of the acceleration measurement, it is clear that if each fringe that is integrated is known to within some constant uncertainty, then the uncertainty in velocity increases with time in a non-linear fashion. If velocity is then integrated again, to generate position as a function of time, then those uncertainties again increase in a non-linear fashion. An advantage of an optical Doppler measurement is that it measures velocity directly, and its uncertainty is, for the most part, fixed with each measurement, i.e., the uncertainty is related to how well one can determine the distance between adjacent peaks in the beat frequency, \( f_D \). This is true for each measurement of the beat frequency. The positional uncertainty, of course, increases with time, non-linearly.

### IV. WHAT MAKES SENSE?

As noted earlier, a normally reflected Doppler measurement with a He-Ne wavelength of \( 633 \text{ nm} \) requires a detector and recording bandwidth of \( \gtrsim 3.2 \text{ GHz} \). While this is achievable today with current technology, it would nevertheless remain expensive as the recording-and-detection technologies are expensive; the laser technology is within reach (for example, one might double and Nd:YAG laser to 532 nm). However, these types of bandwidths remain impractical for practical applications (one might imagine that velocities of interest may be one or two times \( 1,000 \text{ m-s}^{-1} \)).

The advent of high-speed optical communications technologies provides a path forward for direct Doppler techniques. For example, if the standard communications wavelength of \( \lambda \approx 1,550 \text{ nm} \) is used, then a bandwidth of \( \approx 1.3 \text{ GHz} \) is needed for a \( 1,000 \text{ m-s}^{-1} \) velocity determination. This leaves room for much higher velocities.

It should also be noted that Doppler will cost much less to field per data set. It can be achieved without laser systems that cost several hundred thousands of dollars, and should not require one or two persons several months to set up, stabilize, and maintain until the measurements are complete. There is no reason that laser Doppler velocimetry cannot be plug-and-play.

The applications include high-velocity measurements at \( 1,550 \text{ nm} \) (single-mode light, erbium doped fiber amplifiers will work well), and Asay foil type measurements with a He-Ne type laser.

Other potentially practical uses include laser Doppler vibrometry (2) to measure strain coefficients in piezoelectric materials. This technique could possibly be used to directly measure the sensitivity of piezoelectric probes fielded as a low-profile companion diagnostic to the Asay foil.

Our current effort includes development of a laser Doppler velocimeter at \( 1,550 \text{ nm} \). All optics have been purchased and measurements on the order of \( \text{mm-s}^{-1} \) velocities have been accomplished; velocities on the order of \( \text{cm-s}^{-1} \) have also been accomplished with a “fast” solenoid. The crude apparatus has been used and initial plans are to test the diagnostic at the Proton Radiography facility powder gun, and other LANL firing sites; fielding the diagnostic at the Bechtel, Santa Barbara, boom-box has also been considered.

Our objective is to develop an alternative optical diagnostic to VISAR techniques where VISAR techniques are not required for success. These situations include velocities up to about \( 3 \text{ km-s}^{-1} \), with a \( \lambda \approx 1,550 \text{ nm} \) laser tool, and a visible He-Ne system for use with Asay foils. The laser technologies are well established and the measurement-and-detection technologies are available.
V. CONCLUSION

We have presented a discussion of current, laser remote velocity determining systems. These systems include VISAR, Fabry-Perot and Doppler. Direct laser Doppler techniques have several advantages over both Fabry-Perot and VISAR. Namely, Doppler techniques are more sensitive than VISAR or Fabry-Perot; Doppler does not suffer from the same visibility issues as either VISAR or Fabry-Perot; Doppler is easier to field with off the shelf components and does not have the expense, nor should it require the continual support required by VISAR or Fabry-Perot.

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