Velocity Measurement of Slowly Moving Surfaces Using an He–Ne Laser Heterodyne System*

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A simple and compact laser Doppler radar system capable of high resolution velocity measurements of a slowly moving surface is described. The system is nondestructive and does not contact or interfere with the object whose speed is to be measured. All required beam splitting and reflective surfaces are integrated in a solid crystal block, greatly simplifying alignment. Experiments are performed using a rotating scattering wheel in which velocities as low as 0.21 ± 0.02 mm/sec have been measured.

USING an He–Ne laser in a simple Doppler heterodyne setup, we have accurately measured velocities of diffuse surfaces as low as 0.21 mm/sec. Heterodyne detection of diffuse[1–3] and reflective[4,5] surfaces has been discussed previously by several workers. The object of the experiments reported here, however, was to obtain a bound on the system's ability to measure *low* velocities. This setup is similar to that used previously in the infrared.[6] Doppler velocity measurements in the optical provide superior resolution to those at lower frequencies because of the large Doppler shift. Furthermore, a light beam may be easily directed to an otherwise inaccessible location.

In the experiments performed, approximately 1 mW of radiation at 6328 Å was incident on a modified Michelson interferometer (Fig. 1). One mirror of the interferometer was replaced by the target, an off-center rotating disk with a sandblasted circumference. The radiation scattered from the surface of the wheel was recombined at the (internal) beam splitter with the unshifted or local oscillator (LO) radiation reflected from the stationary surface of the other interferometer leg.

Instead of separate beam splitter and reflectors, two right angle isosceles prisms were glued together to form a solid block. This integral device eliminated the need for alignment of each individual component, and also minimized the effect of acoustic vibrations. No reflective coatings were used on the surfaces, since the ordinary glass–air interfaces reflected adequate LO power for efficient heterodyne detection. In fact, unshifted laser radiation was reflected from both the surface facing the target and that at right angles to it. Slight misalignment caused these beams to diverge and they were resolvable 5 ft or more from the beam splitter. To avoid excess noise resulting from surface vibrations, only one of these was allowed to pass through the detector aperture and mix with the Doppler scattered signal.

A 50 mm focal length lens was used to converge the incident beam to a spot on the target. The purpose of this lens was twofold. Since the different sections of the spinning wheel have different velocity components parallel to the laser beam, the beam size on the moving surface was made small to minimize this velocity spread. The lens also provided spatial coherence at the detector, resulting in an improved signal-to-noise (S/N) ratio.

It was found that the scattered signal power, and thus the S/N ratio, could be increased substantially by focusing the lens slightly behind the target surface. In this configuration the lens gathered the scattered radiation within several degrees of the laser beam and converged it on that portion of the detector aperture illuminated by the LO beam. Since the signal and LO beams must be nearly parallel to each other for efficient heterodyning, the detector was moved about 5 m away from the rest of the system. This lowered the convergence angle of the collected radiation. Alternatively, a collimation system of some kind could have been used.

A 2 mm iris and an interference filter centered at 6328 Å shielded the photomultiplier detector from ambient radiation. No irises were used for angular alignment of the LO and signal beams since this was controlled by proper use of the convergence lens and orientation of the prism block. It was not necessary to use a polarizer.

A bias voltage of 1340 V was used on the RCA 7102 photomultiplier tube. This setting was not critical, however, and a simple photodiode detector could probably have been used in its place. The output from the phototube was fed through an adjustable bandpass low noise amplifier (Princeton Applied Research CR-4) to an oscilloscope.

The passband of the amplifier was adjusted for each target velocity to provide a fairly clean signal. Too narrow a passband would shift the signal frequency or even make noise appear to be a signal. The validity of each signal

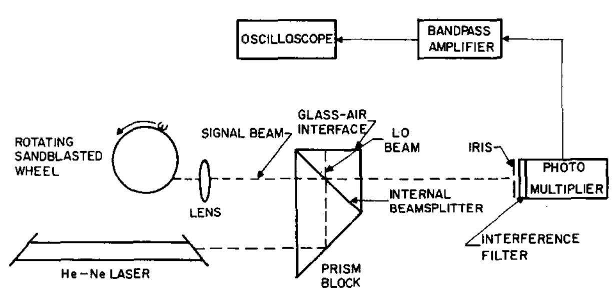

FIG. 1. Block diagram of experimental setup.

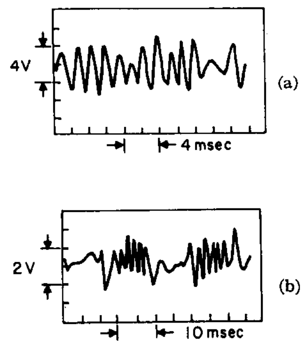

FIG. 2. (a) Oscilloscope trace of a typical heterodyne signal from the scattering wheel. Approximately 8 cycles may be seen in a time of 12 msec, corresponding to a Doppler frequency of about 670 Hz. Thus the radial velocity of the target was 0.21±0.02 mm/sec. (b) Oscilloscope trace of a heterodyne signal with a more compressed time scale. This illustrates the amplitude modulation of the signal due to laser noise and the granularity of the target, and limits the accuracy of the measurement.

was checked by turning the wheel off and observing the frequency decrease as the wheel gradually came to a stop.

The laser itself was noisy, as expected, with sharp spikes at 60 and 120 Hz and lower spikes at harmonics up to 480 Hz. Transmission through the system (with the wheel stopped) spread these sharp harmonics into a fairly continuous noise spectrum from 0 to 500 Hz. It should be mentioned that occasionally the laser became extremely noisy. At these times, no measurements were possible. It is this low frequency noise, of course, which provides the lower bound on the velocities which may be measured.

A typical heterodyne signal from the oscilloscope is traced in Fig. 2(a). We have plotted the magnitude of the amplified heterodyne signal as a function of time, with a horizontal scale of 2.0 msec/div and a vertical scale of 2 V/div. The observed frequency is approximately 670 Hz, which corresponds to a surface velocity of 0.21 mm/sec from the well known Doppler formula

$$v_r = \nu_D c / 2\nu_L. \quad (1)$$

Here, v_r is the radial velocity of the target, c is the speed of light, and ν_D and ν_L are the Doppler and laser frequencies, respectively.

In Fig. 2(b) we illustrate an oscilloscope trace with a compressed time scale, which reveals slight frequency variations and a pronounced amplitude modulation of the signal. This is due to the fact that the movement of the slowly turning gear-driven wheel is not truly uniform and also to the speckled nature of the diffusely scattered laser light, which effectively amplitude modulates the signal.[6] Because of this chopping up of the signal, the triggering and stability adjustments on the oscilloscope are very critical in obtaining recognizable *multiple-trace* signals from such a target. A 'scope camera or a 'scope capable of storage should therefore be used to provide single traces which yield good accuracy and resolution of the measurements.

Using sophisticated filtering and signal processing techniques, speeds lower than 0.2 mm/sec could certainly be measured since the form of the laser noise can be determined. Aside from this, the system may be improved substantially by reducing the line voltage modulation of the laser intensity, while acoustic insulation would probably be of additional help. Improvements may also be obtained by increasing the power of the scattered radiation with the help of a semicooperative backscattering surface such as Scotchlite. In such experiments, a substantial increase in signal power resulted. It is pointed out that the velocity of a target with arbitrary surface characteristics may be obtained by simply applying a bit of Scotchlite to it.

Although the S/N ratio is degraded at lower velocities (as the Doppler frequency approaches the laser noise spectrum), it has been possible to measure accurately target velocities as low as 0.21 mm/sec with a simple, easy to use, and inexpensive setup. The accuracy of the measurement at the lowest velocities (where the S/N ratio was about 3) was approximately 10%. An improvement of about an order of magnitude might make the system suitable for velocity measurements in Mössbauer experiments.

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[1] G. Gould, S. F. Jacobs, J. T. LaTourrette, M. Newstein, and P. Rabinowitz, Appl. Opt. **3**, 648 (1964).
[2] R. D. Kroeger, Proc. IEEE **53**, 211 (1965).
[3] G. A. Massey, Appl. Opt. **4**, 781 (1965).
[4] S. F. Jacobs, Electronics **36** (No. 28), 29 (1963).
[5] M. E. Lasser, IEEE Spectrum **3**, 73 (1966).
[6] M. C. Teich, Proc. IEEE **56**, 37 (1968); **57**, 786 (1969).