Optical distance measurements to recover the material approach missed by optical velocimetry

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Abstract. Optical velocimetry is limited to measuring the component of the target velocity along the axis of the optical beam, thereby allowing a laterally moving tilted surface to approach a probe undetected. We are not discussing the detection of the lateral motion, but rather the detection of material approaching the probe due to lateral motion of a surface that is not perpendicular to the beam. This motion is not measured in optical velocimetry, and consequently, integrating the velocity will in general give an incorrect position. We will present three approaches to overcome this limitation: Tilted wave-front interferometry, which maps time of flight into fringe displacement; pulse bursts for which we measure the change in the average arrival time of a burst, and amplitude modulation interferometry, in which a change in path length shows up as a change in the phase of the modulation. All three of these have the potential to be integrated with existing velocimetry probes for simultaneous velocity and displacement measurements. We will also report on initial tests of these approaches.

1. Velocimetry does not detect the longitudinal approach of material due to the lateral motion of a tilted surface

Briggs et al., and Dolan et al., [1-3] showed in 2009 that Photon Doppler optical velocimetry (PDV) does not measure the full approach of material toward the probe, even though PDV is a displacement interferometer, but only measures the portion of the motion arising from the component of velocity along the beam. This is actually a good thing, because it allows an unambiguous interpretation of a velocimetry measurement. However, it limits the applicability of velocimetry in situations where the distance to the material is needed. Only the normal velocity v in figure 1, and the Bore Probe in figure 2 will integrate to give the correct change in distance. The most obvious example of missed motion is the result of the Perpendicular probe measurement in figure 2, which gives a constant speed of 0, despite the approach of material along the ramp. The above experiments were a follow on to Goosman’s original demonstration of this effect in 1986, for Fabry-Perot velocimetry [4]. Note that even if one uses multiple probes to resolve the velocity vector, the approach of material due to the lateral motion of a tilted surface is missed. In our demonstration experiment shown in figure 2, the perpendicular probe reports a constant zero, and the angled probe a constant V Cos(45°); neither notice the approach of the ramp.
**Figure 1.** Single beam optical velocimetry will give the same result for all four velocities shown.

**Figure 2.** Integrating the velocimetry from the probes in this figure will give the correct distance to the projectile only for the bore probe, which is aligned with the velocity vector.

Of course, for a simulation or model of an explosively driven system to be complete it must predict the material location. Currently, workers must rely on assumptions or simulations to supply this missing information; no experimental technique exists with the required spatial and time resolution. The standard cylinder test shown in figure 3 is one of many standard tests for which the integrated velocimetry will not give the correct constraint on material location. The details of how much motion is measured and how much is missed are shown in figure 4.

**Figure 3.** An expanding cylinder test is an example of an important test in which the velocimetry is measured from a tilted surface undergoing lateral motion, and will therefore give incorrect material location.

**Figure 4.** The approach of material to a velocimetry probe can be divided into the above two components, one arising from the component of velocity along the beam (which is measured), and the other from the lateral motion of a tilted surface, which is missed.

2. **To measure the full motion, we need an effective wavelength large compared to the surface roughness**

Many applications of optical velocimetry measure the backscattered light from a surface that is not normal to the beam, as described in the examples in the previous section. In order for a surface that is
not normal to the illumination beam to scatter light backwards, the surface must rough compared to
the wavelength of light. Such a surface is said to be diffuse or non-specular. If a surface smooth
compared to the wavelength of light would scatter light back into the probe (the dots in figure 5), the
approach of the lateral motion shown would presumably be measured. However, we must roughen the
surface in order to get non-specular back scattering (the Xs shown in figure 5), causing the phase
information to be scrambled by random additions of $2\pi$. As a result, this contribution to the motion
goes undetected, and only the beat frequency arising from the Doppler shift of motion along the beam
is detected.

Figure 5. The tilted surface shown is moving to the right, causing material to
approach the probe, while the individual scatterers have no velocity toward the
probe. The approach of the idealized tilted smooth surface shown in red dots would be
measured if back-scattered light could be
detected from such a smooth surface.
However, in order to scatter light from such
a tilted surface back into the probe, the
surface must be rough (Xs). This scrambles
the phase, masking the approach.

So far in this paper we are pointing out things that are widely known. However, the implications
are not widely appreciated: integrating optical velocimetry measurements is in general insufficient to
determine the change in distance or range to a target. To measure the full target approach rate
optically, we must create an effective wavelength greater than the surface roughness.

3. Performance goals and proposed methods
Our desired spatial resolution is 0.1 mm because we know that is adequate from the historical
performance of electrical shorting pins. We picked a measurement frequency of 1 MHz to give one
measurement every millimeter for a typical speed of 1 mm/$\mu$s. The time for light to travel 0.1 mm is
about 0.33 ps. We assume that the measurements are round-trip measurements, i.e., the beam travels to
and from the target on the same path, which is typical for velocimetry. This means that a motion of 0.1
mm will result in twice that much time elapsed, so the time resolution we need in our measurement
strategy is 0.67 ps. We propose three methods for achieving this performance, all of which share some
variation on creating an effective wavelength greater than the surface roughness of a typical target,
typically ~ 0.05 mm.

3.1. Pulse burst method
Current state-of-the-art oscilloscopes have a rise time of about 20 ps, too slow to resolve the round trip
time to the resolution that we need. We propose instead to measure the average arrival time of a burst
of 100 pulses: a 20% noise on a 20 ps rise-time will give 4 ps resolution on an individual pulse edge
arrival time. That would reduce to 4 ps/$\sqrt{100}$ pulses * 2 edges/pulse) = .3 ps for an average of 100
pulses if the errors are random. The average is the same as the time at the center of the pulse stream if the velocity is constant over the 10 ns burst, which will usually hold. The next burst arrives at a time $T \pm .3$ ps later. As the target location changes by $\Delta x$, $T$ reduces by $2\Delta x/c$, which we can now resolve with twice the required precision (allowing room for other errors).

A variant of the pulse burst method is suggested by the fact that the wavelength of the pulses is longer than the surface roughness, and so the frequency of the pulses should be Doppler shifted on their return, $2\cos(\theta-\Phi)/\cos(\Phi)/c$. For a 10 GHz amplitude modulation, and a full target approach rate of $v \sim 1000$ m/s, $2v/c = 6.7$ ppm, or 67 KHz out of 10 GHz, a small but discernible shift.

Figure 6. The angles used to describe the full target approach rate, and the pulse burst method. To resolve an optical round-trip-time to better than 0.67 ps, use the average of a burst of 100 pulses.

Figure 7. In the amplitude modulation approach, we propose recovering the gain provided by the local oscillator in PDV by creating two nearby amplitude modulation frequencies, where the motion will show up as a Doppler shift in the beat frequency between these two.

3.2. Amplitude modulation

The preceding solution lacks the amplification that interferometry obtains from mixing the signal with the local oscillator, so getting enough light could be problematic in the pulse burst method. However, by modulating both the target beam and the local oscillator at wavelengths > surface roughness, we may be able to recover an interferometry approach. We call this amplitude modulation interferometry. We create an illumination beam with a 1 THz modulation by combining the light from two lasers separated by this frequency. We scatter this light off the surface and combine it with a reference beam that is modulated at a frequency 9 GHz below the 1 THz (figure 7). When we square the recorded beat frequency between the reference and target beams, the 9 GHz will appear. The full target approach rate should appear as a Doppler shift in this 9 GHz signal.

3.3. The tilted wave-front method

The concept here is to send a series of femtosecond pulses at the target, and direct the reflected pulses onto a viewing screen from the normal direction (figure 8). Meanwhile, a portion of the pulse stream is picked off by a beam splitter before it encounters the surface, and directed onto the viewing screen from an angle. The time for the reflected pulse to reach the screen is proportional to the distance, while the time for the reference pulse to reach the screen is fixed. As the target approaches the probe, the time between the reflected (normal) pulse and reference (tilted) pulse decreases. This causes the overlap position between the reflected and reference pulse to shift to the left in figure 8. This technique thus converts the change in distance to the target into lateral position on the viewing screen. A 1 MHz camera should be able to resolve a 0.1% spatial shift, which would give the desired 0.1 mm on 100 mm of travel.
The light pulses shown travelling horizontally will reflect from the material location with a time delay proportional to distance. The reflected pulse then travels to the viewing screen, and the timing of its arrival with respect to the tilted reference pulse determines where the interference fringes appear on the viewing screen. We have thus converted the range to the target along the beam to lateral position on the screen.

4. Summary
We have proposed three methods to make optical measurements of the approach of a target with 0.1 mm spatial resolution at 1 MHz. These techniques will measure the full approach, including the approach arising from the lateral motion of a tilted surface, which is not measured by optical velocimetry techniques. The fact that optical velocimetry measures the projection of the velocity along the beam, and not the approach arising from laterally moving tilted surfaces is a strength of velocimetry: it allows for a clear interpretation of velocimetry measurements as arising only from the projection of the velocity vector along the beam. However, it limits the applicability of velocimetry in situations where the approach of material must be measured.

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