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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. In most applications it is important to know the position of the target surface, and the forgoing means that 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 measure the full material displacement

Velocimetry with a single beam reports only displacement or velocity, not the distance to the target, because we do not measure the absolute phase, only the change in phase. Indeed, single-beam velocimetry does not actually measure velocity; the direction of motion is unknown; all four velocities shown in Fig. 1 give the same measurement.

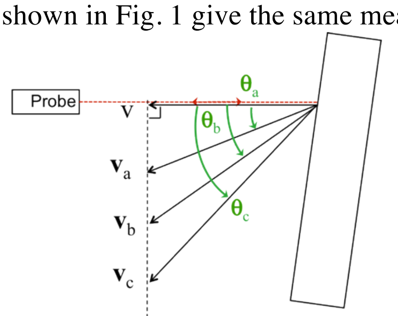

Figure 1. Single beam optical velocimetry will give the same result for all four velocities shown.

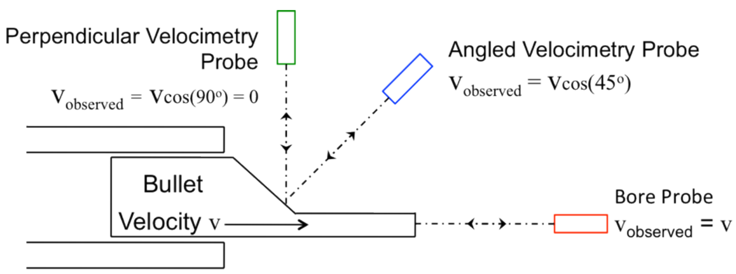

Figure 2. Integrating the velocimetry from the probes in this figure will give the correct distance to the projectile only for the bore probe, which is aligned with the velocity vector.

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Briggs et al., and Dolan et al., [1-3] showed in 2009 that Photon Doppler optical velocimetry (PDV) will 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 was a follow on to Goosman's original demonstration of this effect in 1986, for Fabry-Perot velocimetry [4]. 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. Our demonstration experiment is shown in Fig. 2; the perpendicular probe reports a constant zero, and the angled probe a constant vcos(45); neither notice the approach of the ramp.

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 Fig 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 Fig. 4.

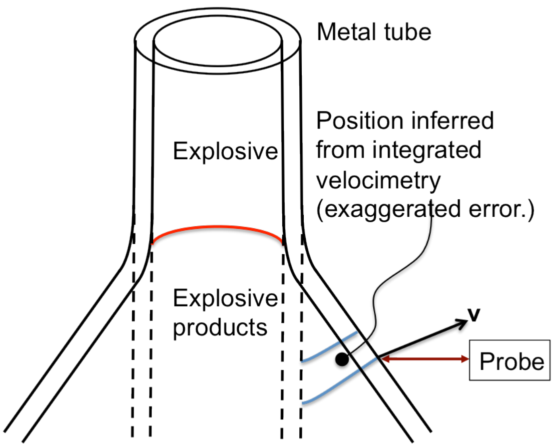

Figure 3. An expanding cylinder test is an example of an important test in which the velocimetry is measured from a tilted surface undergoing lateral motion, and will therefore give incorrect material location.

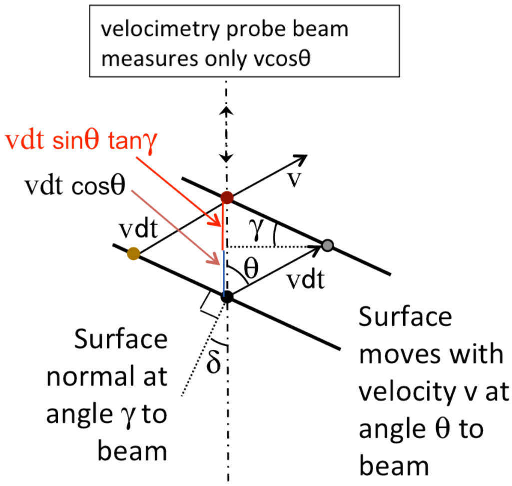

Figure 4. The approach of material to a velocimetry probe can be divided into the above two components, one arising from the component of velocity along the beam (which is measured), and the other from the lateral motion of a tilted surface, which is missed.

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

In this work we are considering the effects of interrogating a surface from a non-normal direction, as described in the examples in the previous section. In order to receive light back from a non-normal surface, the surface must be diffuse, which means that it is rough compared to the wavelength of light. If one could measure light from a smooth surface from a non-specular direction (the dots in Fig. 5), the approach of the lateral motion shown would indeed be measured. However, since we must roughen the surface to get light in the non-specular direction (the Xs shown in Fig. 5), the phase information needed is scrambled by random additions of 2π. 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.

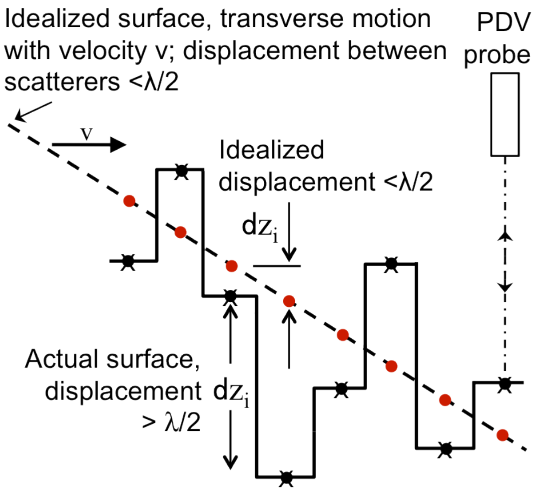

Figure 5. Although the lateral motion of a tilted surface would be measured if light could be detected from a smooth surface (dots), in order to receive light in the non-specular direction inherent in a tilted surface, the surface must be rough (Xs). This scrambles the phase, masking the approach.

So far in this paper we are pointing out things that are widely known. However, the implications are not widely appreciated: *measuring velocimetry alone is insufficient for a complete determination of the motion of an explosively driven metal*. 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/µs. 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. used.

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/√(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 ± .3 ps later. As the target location changes by Δx, 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, $2v\cos(\theta-\Phi)/\cos(\Phi)/c$. For a 10 GHz amplitude modulation, and a full target approach rate of v~1000 m/s, 2v/c = 6.7ppm, or 67 KHz out of 10 GHz, a small but discernible shift.

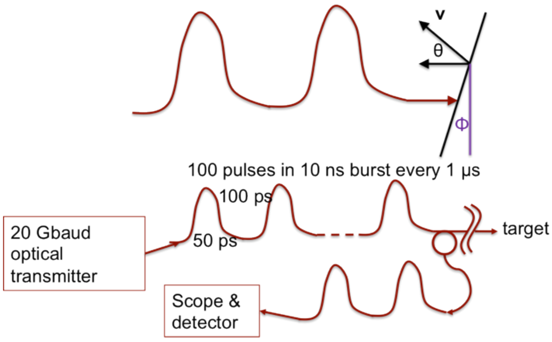

Figure 6. The angles used to describe the full target approach rate, and the pulse burst method. To resolve an optical round-trip-time to better than 0.67 ps, use the average of a burst of 100 pulses.

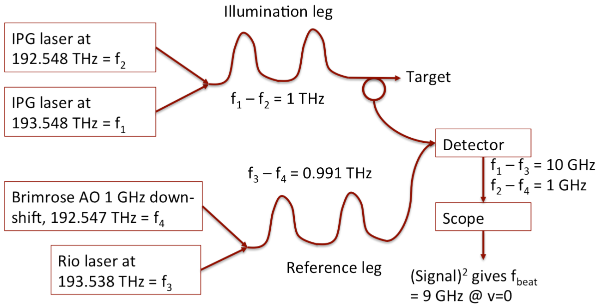

Figure 7. In the amplitude modulation approach, we propose regaining the gain provided by the local oscillator in PDV by creating two nearby amplitude modulation frequencies, where the motion will show up as a Doppler shift in the beat frequency between these two.

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 (Fig. 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. We have done simulations of a laterally moving surface that show exactly this behavior.

3.3. The tilted wave-front method

Here we send a series of femtosecond pulses at the target, and direct the light scattered from the target onto a viewing screen from a normal direction (Fig. 8). Meanwhile, we have picked of a portion of the pulse stream before it encounters the surface, and directed it onto the same viewing screen, but from an angle. As the target moves, the relative time between the pulses changes, and the overlap position on the viewing screen moves sideways. We have converted time into lateral position on the screen. We have a 1 MHz camera that should be able to resolve a 0.1% spatial shift, so that we could resolve our desired 0.1 mm on 100 mm of travel.

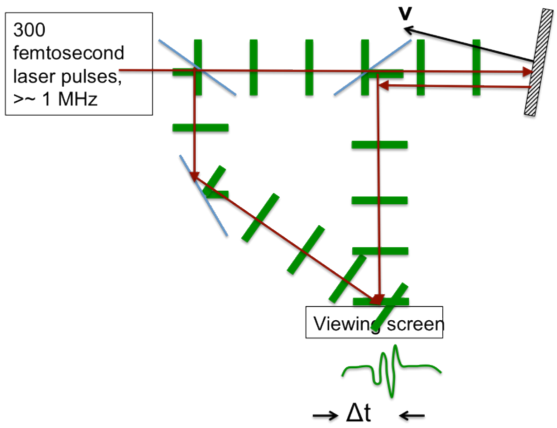

Figure 8. We can convert time to lateral position on the viewing screen of the overlapping target and reference pulse in order to achieve our desired 0.1 mm resolution in target motion at 1 MHz.

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. Calculations of the pulse bust method suggest that the resolution in the average will be good enough, but that the light intensity will need to be near the maximum of what we can do in order to get a signal.

Calculations of the amplitude-modulation interferometry approach tested finding the mixing frequencies and testing whether the Doppler shift associated with the full target displacement showed up in the synthetic signal…these were successful. We have the equipment to begin testing the tilted wave-front approach, and plan to begin that before the end of 2013.

Acknowledgments

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