LA-UR-14-21042
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Intended for: NEDPC 2013, 2014-03-10 (Livermore, California, United States)

Issued: 2014-04-24 (rev.1)

(U) Optical Ranging as a Complement to Velocimetry

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Abstract. (U) ***Photonic Doppler Velocimetry (PDV) is a powerful diagnostic for material shock experiments. However, its physical observable is not the same as shorting pins. In this contribution, we discuss our motivation, ideas, and early proof-of-concept work regarding the development of an optical ranging diagnostic. Our general idea is to send an amplitude modulated (AM) laser beam to a target, and to use the phase measurements of the send and return AM signals as an indication of the true, relative surface position along the beam. As a proof-of-principle, we successfully tracked an apparent surface approach due to the transverse motion of an object. Such a surface approach is not observable with PDV. We demonstrated a 10 MHz bandwidth and the possibility to achieve 100 μm resolution. We view optical ranging as a complement to PDV; we are investigating fielding both PDV and optical ranging on the same probe using the same laser light.***

1. Introduction

Optical Doppler-shifted Velocimetry (a.k.a. Photonic Doppler Velocimetry (PDV)) is a high fidelity diagnostic for measuring the motion of material driven by high explosives, flyer plates, etc.

One subtlety of PDV is that, in general, the integral of a PDV signal does not give the relative position of a surface along the beam direction (this occurs when the object is moving transverse to the PDV beam). For this reason, the data from modern optical hydros and historical pin shots cannot be trivially compared. To more firmly connect modern and historical tests, it is useful to pursue a high fidelity optical ranging diagnostic. That is, an optical diagnostic that measures the true, relative surface position along a line-of-sight that can be fielded in a fashion similar to PDV. In this paper, we describe our efforts in this regard.

In Section 2, we describe the attributes of PDV and motivate the idea of an optical ranging diagnostic. In Section 3, we present a general approach to optical ranging that complements velocimetry. In Section 4, we describe our first proof-of-principle design and some early results. We conclude the paper with a summary.

2. Attributes of PDV

The physics of PDV is similar to continuous wave (CW) Doppler radar. In PDV, coherent light from a CW laser operating at ~1.5 μm is transmitted to a target. After reflection from the target, the light is Doppler shifted by $\Delta F = 2vF/c$, where v is the instantaneous longitudinal velocity of the illuminated material, F is the frequency of light, and c is the speed of light. For light at 200 THz (1.5 μm), the rule is: ΔF = 1.3 GHz/ (km/s).

This Doppler-shift is measured with an interferometric technique. The reflected beam is collected and combined with an unshifted reference, and the combined beam heterodynes at ΔF. The combined beam is measured by a photo-diode, and ΔF is extracted with frequency-space analysis methods.

PDV has several attributes.

- It gives an accurate and unambiguous indication of the instantaneous longitudinal (i.e., along the beam direction) velocity of the material illuminated by the beam. It can be argued that velocity is the more natural observable in dynamic tests such as material-shock experiments.

- PDV is a practical diagnostic to field. For example, it is possible to field hundreds of PDV beams from a probe head that measures <1 cm is radius.
- With current multiplexing techniques, up to 8 beams can be recorded on one oscilloscope channel.
- PDV is capable of high bandwidth (e.g., tens of millions of measurement per second).
- PDV can measure multiple velocities simultaneously (e.g., the break-up of a surface).
- PDV can measure velocities from a cloud of particles (i.e., several surfaces at different distances).

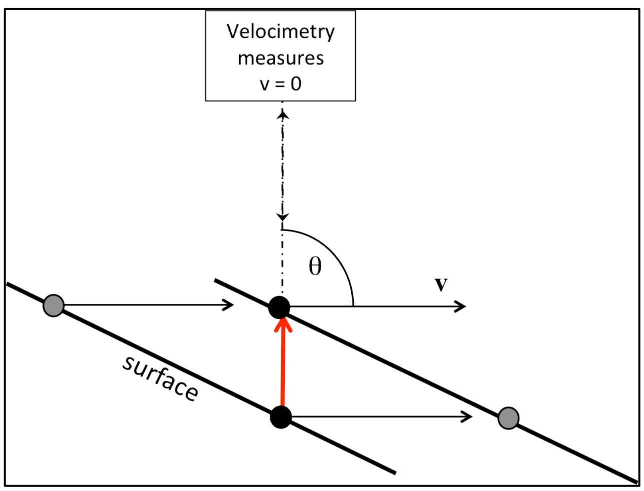

Figure 1: An inclined plane moving transverse to the beam direction with velocity *v*. In this case, PDV does not indicate that the surface has an approach velocity due to transverse motion (red arrow). The reason is that the transverse motion of the surface causes the surface approach to be discontinuous at the scale of the surface roughness. Because the discontinuities are greater than the wavelength of light, there is no Doppler shift.

A subtlety of PDV is that it does not indicate the approach of a surface due to the transverse motion of an inclined plane. Consider an inclined plane that is moving 90 degrees from the beam direction at velocity v as shown in Figure 1. Two instances in time are shown.

In the first instance, a particular point on the inclined plan is illuminated. The instantaneous longitudinal velocity of the illuminated material is $v_{\text{long}} = 0$. Thus, there is no Doppler-shift and a PDV indicates no longitudinal velocity.

However, in the second instance a new spot on the material is illuminated, and this spot is closer to the probe. The surface approaches the probe (red arrow) even though the individual points on the object have no velocity toward the probe.

In general, a Doppler-shift will be produced only if a component of the instantaneous velocity of the illuminated material is along the probe direction. That is, if the surface approach is only due to the transverse motion of an inclined plane, PDV indicates zero velocity.

In Figure 2 we show why this is true. For light to be Doppler-shifted, there must be smooth longitudinal motion of the surface. By smooth, we mean that any discontinuities in the motion have to be much smaller than the wavelength of light. However, because of surface roughness, the surface approach due to transverse motion is not smooth. It comes in steps on the scale of the surface roughness and so does not create a continuous Doppler-shift, only a series of discontinuous phase shifts. Note that polishing the surface does not help because the surface would become specular and there would be no return light.

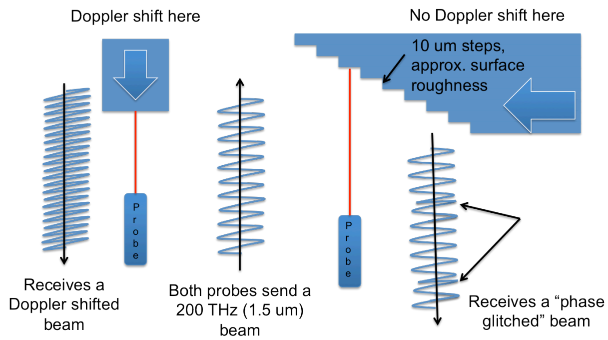

Figure 2: Longitudinal motion of an object will create a Doppler-shifted return beam. Transverse motion of an inclined plane will not because the surface approach comes in steps and glitches that are larger than the wavelength of light.

A simple experiment makes this subtlety clear. Figure 3 shows an actual gun experiment[1]. An odd shaped bullet is fired from a powder gun. Three PDV probes interrogate the motion of the bullet: 1.) A Longitudinal Probe, 2.) An Angled Probe, and 3.) A Perpendicular Probe.

The longitudinal probe measures the true longitudinal velocity of the bullet, which is shown by the dot-dash red line. The integral of this velocity gives the relative position of the surface along the beam.

The perpendicular probe measures zero velocity at all times during the test, shown by the dot-dash green line. In this case, the integral of the PDV signal does not give the surface position along the beam (shown as the solid green line). The same is true for the angled probe. The conclusion is that the integral of a PDV signal does not, in general, give the relative surface position along the beam direction.

Even so, we believe that with a large number of PDV measurements and with knowledge of the general material flow, the position of the material can be constrained throughout a test.

Computationally, this statement has been verified for certain experiments in the presence of uncertainty in the material flow[2].

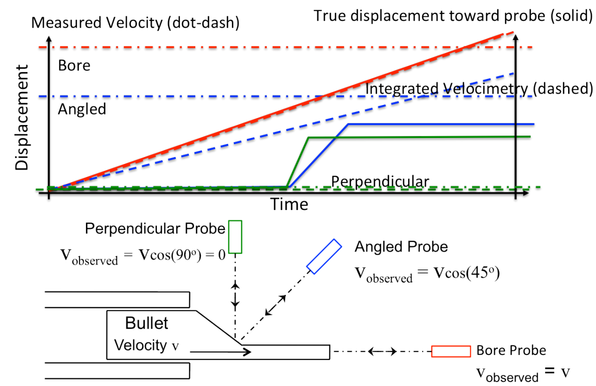

Figure 3: A schematic of a real experiment. Three PDV probes at different angles interrogate the motion of a shaped bulleted fired from an air gun. In general, the integral of the PDV signal does not result in the relative position of the surface along the beam direction.

Experimentally, verification of this statement is not trivial. For example, a PDV beam and a shorting pin cannot be made spatially coincident. Also, debris from the pin affects the PDV signal.

Our main motivation to develop an optical ranging diagnostic is to perform experiments to answer robustly the question of material position with PDV in certain experiments (i.e., to firmly connect historical pin measurements with modern velocimetry).

3. A General Approach to Optical Ranging

Our goal has been to create a diagnostic that can measure surface position along a beam with 100 μm resolution and 10 MHz bandwidth. A resolution of 100 μm on an approach of 1 km/s is equivalent to a 100 ns (10 MHz) time blur.

The general approach we are pursuing is to amplitude modulate a GHz signal on to a 200 THz (1.5 μm) CW laser. We refer to the 200 THz wave as the carrier. The GHz signal has a wavelength of several mm or more.

The carrier wavelength is much smaller than the surface roughness. This is helpful to produce a diffuse reflection from of the surfaces of interest. On the other hand, the signal wavelength is much greater than the surface roughness. This prevents the phase of the signal from being scrambled during transverse motion of the surface, allowing us to track the full surface approach.

As shown in Figure 4, the phase difference between the send and return GHz signals indicate the position of the surface along the direction of the beam. The general rule is that the change in phase is $\Delta\phi = 4\pi x/\lambda$, where x is the change in position and λ is the signal wavelength.

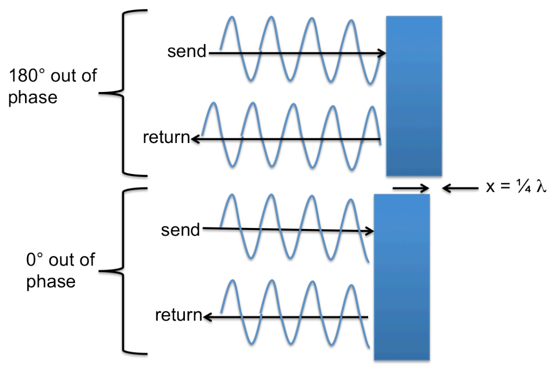

Figure 4: Schematic of the GHz signal, riding on a 200 THz carrier, reflecting off a surface. The phase difference between the send and return signals indicate the relative position of the surface.

This measurement technique will track the surface position regardless if the object is moving longitudinally or an inclined surface is moving transverse to the beam direction.

The upper limit of the measurement bandwidth is the AM frequency. In practice, we will average over many cycles so that a GHz AM signal will result in an MHz measurement bandwidth.

The spatial resolution depends on several things including: the bandwidth of the phase comparator, the AM frequency, the signal-to-noise ratio at the AM frequency, and the presence of non-linearities in the electronics. The method should be relatively insensitive to noise at all frequencies other than the AM frequency.

In Table 1 we discuss the complementary of PDV and optical ranging.

Table 1: The complementary of PDV and Optical Ranging

PDV	Optical Ranging
Measures velocity. A natural observable in dynamic experiments.	Measures position. Cannot tell the difference between dynamic and static surfaces in a single measurement.
Not sensitive to surface approach due to the transverse motion of an inclined surface.	Indicates true, relative surface position along a beam direction.
Can measure multiple velocities and/or a cloud of particles. Useful measurements can be made even with relatively large reflections in the probe/fiber.	Only applicable to one surface. Reflections from multiple surfaces may be problematic. Strong reflections within a probe/fiber can cause problems.

Proof-of-Principle

We show a diagram of our first proof-of-principle test in Figure 5. A CW fiber coupled laser operating at 1.5 μm is split with a 1x2 splitter (not shown). One beam passes through an acousto-optical downshift module. This decreases the light frequency by 1 GHz. The beams are recombined in a 2x2 splitter. After recombination, the beams are amplitude modulated with a 1 GHz signal. A 1 GHz signal has a wavelength of 30 cm in air.

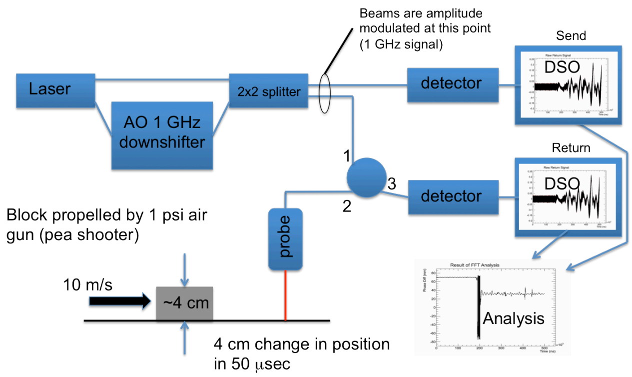

Figure 5: Schematic of our first proof-of-principle test for optical ranging.

One AM beam (termed the reference or send beam) is sent directly into a photo-diode, and the photo-diode signal is recorded by a digital storage scope.

The other AM beam (termed the target or return beam) is sent out to a target via an optical circulator and a collimating probe. The same probe collects light reflected from the target. The return light passes through the circulator again and then to a photo-diode. The signal from this photo-diode is recorded by a digital storage scope.

The target consists of a plastic rectangular block moving transversely through the beam. As the block moves through the beam, the change in surface position along the beam direction is 4 cm. The block is propelled by a low-pressure air gun to a velocity of ~10 m/s.

At the exit of the collimating probe, the beam diameter is ~0.5 mm. Thus, the 4 cm change in surface position occurs in ~50 μsec for an apparent surface approach of 800 m/s. As discussed early, PDV would not indicate this surface approach because it is discontinuous.

The data analysis consists of comparing the phase of the send and return signals. We wrote a computer program to do this analysis in both frequency domain and time domain. We found no significant differences in the results between the two methods.

Our result using a frequency domain analysis for one particular test is shown in Figure 6. The 4 cm surface transition occurs at ~ 200 μs and is tracked successfully.

During the surface transition, for ~25 μsec the AM signal is so low that useful phase information cannot be extracted. This region is label "lost signal" in Figure 6. The lost signal is likely caused in part by the two surfaces, about 40 degrees apart in phase, being simultaneously present in the beam.

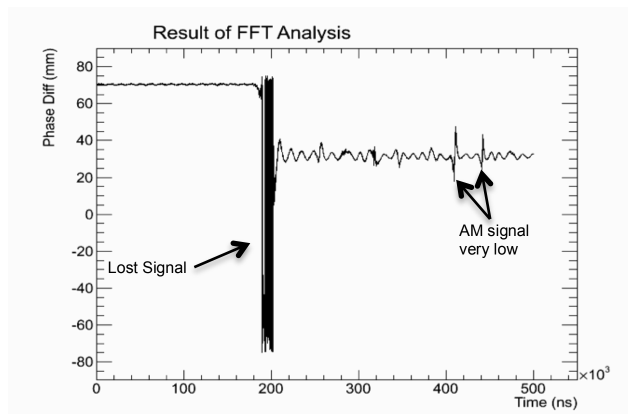

Figure 6: Phase vs. Time for one particular test. The analysis used a frequency domain technique.

There is a ~100 kHz oscillation in the phase measurement. The oscillation is present both before the surface transition and after, though it is more pronounce after. This cannot be a real mechanical vibration based on simple energetics (i.e., if the 100 kHz oscillation was real motion there would be thousands of times more kinetic energy in this motion than the motion of the bullet along the barrel direction). When the AM signal drops out (see arrows), the phase of the oscillation changes.

One possible cause of the oscillation is the presence nonlinearities in the electronics (i.e., phase delays that are a complex function of the signal strength). We plan on investigating the source of this oscillation in the near future. If the 100 kHz oscillation can be remedied, the accuracy of the measurement appears to be near 100 μm.

The implementation of this first proof-of-principle test was far from ideal. For example, the AM signal had an unexplained low frequency oscillation, the wavelength of the AM signal (30 cm) was perhaps ~10x longer than what will eventually be used, and the AM signal power was relatively weak.

Despite these issues, the results of our first proof-of-concept test were encouraging. A surface approach due to the transverse motion of an object was successfully tracked. If the cause of the 100 kHz oscillation can be mitigated, we will achieve our goals of 100 μm resolution and 10 MHz bandwidth.

Variations

Our first proof-of-principle test was a single realization of our general idea for optical ranging. As future work, we want to investigate variations of the general idea.

The amplitude modulation can be created in various ways, such as:

- By combining two highly stable lasers (their frequency difference is the AM frequency), or
- By frequency modulating (FM) a laser and combining it with an unmodulated beam.

If the second method is used, the mixing of the FM beam and the unmodulated beam can occur before or after the beam is sent to the target.

The phase comparison can be accomplished with either digitally or with analog circuitry.

We are also investigating the possibility of fielding both PDV and optical ranging on the same probe using the same laser light. This would be a particularly powerful diagnostic because of the aforementioned complementary of the methods. We currently believe this is possible, though the total laser power would have to increase.

Summary

Our main motivation for developing an optical ranging diagnostic has been to experimentally connect modern optical hydros with historical pin shots.

Our proof-of-concept for optical ranging was successful. We have not yet achieved our goals of 100 μm resolution and 10 MHz bandwidth, but our early results are encouraging. For continued work, we have several lines of investigation planned. We believe optical ranging will be highly complementary to PDV.

Acknowledgments

The authors would like to acknowledge support from the LANL subcritical program, Steve Hare for technical support in the laser lab, and Kevin Rainey for useful discussions.

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