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New developments in photon Doppler velocimetry

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Abstract. Photon Doppler velocimetry (PDV) has made the transition among many experimental groups from being a new diagnostic to being routinely fielded as a means of obtaining velocity data in high-speed test applications. Indeed, research groups both within and outside of the shock physics community have taken note of PDV's robust, high-performance measurement capabilities. As PDV serves as the primary diagnostic in an increasing number of experiments, it will continue to find new applications and enable the measurement of previously un-measurable phenomena. This paper provides a survey of recent developments in PDV system design and feature extraction as well as a discussion of new applications for PDV. More specifically, changes at the system level have enabled the collection of data sets that are far richer than those previously attainable in terms of spatial and temporal coverage as well as improvements over PDV's previously measurable velocity ranges. And until recently, PDV data have been analyzed almost exclusively in the frequency-domain; although the use of additional data analysis techniques is beginning to show promise, particularly as it pertains to extracting information from a PDV signal about surface motion that is not along the beam's axis.

1. Introduction and background

Photon Doppler velocimetry (PDV) was introduced by Ted Strand in 2004 [1] and again in 2006 [2]. Although a similar architecture had been previously introduced for laser Doppler velocimetry in 1965 [3], it was Strand who refined the design around the use of optical fibres. The inclusion of optical fibres and fibre coupled optics contributes to the relative ease with which PDV is implemented and its robustness to experimental variation. Strand's modern PDV architecture is shown in figure 1. Although several variations on this architecture exist [4-6], the basic principle of heterodyning a reference field with a measurement field remains the same. When the two fields are combined and converted to an intensity measurement (figure 1), they yield a beat frequency, which is based on their phase difference (or optical path length difference). Each of the interferometer's fringes corresponds to a surface displacement of $\lambda/2$, for light at wavelength λ . The beat frequency (or fringe rate) f_b observed at the mixing of the two signals indicates a surface velocity v along the beam axis, according to the relationship [2]

$$v = \left(\frac{\lambda}{2} \right) f_b \quad (1)$$

Today, PDV is no longer considered a new diagnostic, but rather, its implementation is becoming routine. As a testament to this observation, 10-20 channels of PDV returning good quality data was considered a big effort a few years ago, but today, more than 100 channels of PDV have been fielded for measuring a single dynamic experiment [7]. PDV is robust to changes in signal levels that are caused by changes in surface reflectivity, self-light of high explosives during detonation, surface tilt,

etc. In addition to its robustness, the relative success of PDV is the result of its remarkable ability to measure a broad range of velocities (a few m/s up to roughly 50 km/s), with high accuracy (10 m/s) and time resolution (10 ns) for long durations [4]. The fundamental tradeoff between time resolution and frequency resolution is governed by the sampling rate of the digitizers, which are currently capable of several tens of gigasamples per second. In technical discussions on high-speed velocimetry for shock physics applications, PDV is often compared to the velocity interferometer system for any reflector (VISAR) [8]. Note, that a fundamental difference exists between the two sensing methodologies, inasmuch as PDV is a frequency measurement technique while VISAR is an intensity measurement technique. Consequently, the two have their own relative strengths and weaknesses. For example, PDV requires several data points to generate an estimate of the signal's power spectral density, while VISAR generates a velocity measurement from every measured point. This tradeoff reduces the measurement rate of PDV compared to VISAR (in terms of measuring velocity as a function of time), but it enables PDV to measure velocities at lower signal to noise ratios than VISAR.

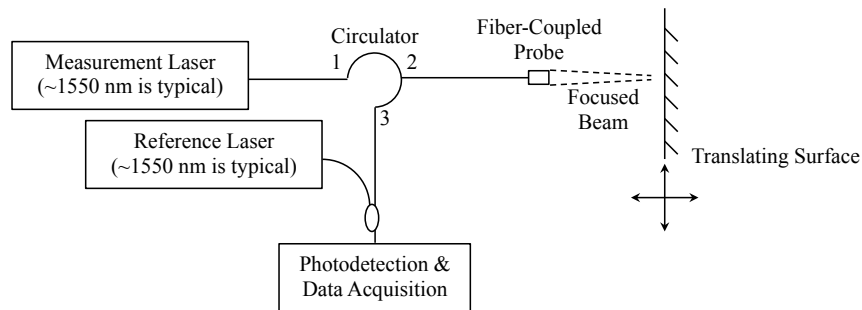


Figure 1. A typical, heterodyned PDV architecture is shown.

Past test series performed at Los Alamos National Laboratory (LANL) [10-11] and Sandia National Laboratory (SNL) [12] were designed to investigate precisely what types of surface motion PDV measures. The results of these tests indicated that optical probes used in PDV measure only the component of the surface's velocity that lies along the probe's beam axis. In other words, PDV entirely misses the approach of an angled surface whose trajectory is transverse to the beam axis. This characteristic may be viewed as an advantage, in the sense that one can be sure of what PDV does measure, although it imposes a limitation on applications that seek to track an approaching surface (e.g., PDV does not directly measure a surface's position). Further, this characteristic is exploited through the use of multi-probe arrangements, where each of a number of probes views the same point on the target surface at a unique angle with respect to the surface normal [10]; thereby enabling a rigid surface's velocity vector to be reconstructed (each probe contributes one-dimension of information regarding the surface's velocity). Limitations imposed by the multi-probe approach, as well as the intrinsic dimensional limitation have motivated research into alternate methods for measuring position in conjunction with PDV or otherwise detecting the approach of laterally moving surfaces [13].

The brief overview in this section provides a high-level introduction to PDV. Readers who are interested in gaining detailed insight into the history, functionality, and capabilities of PDV are encouraged to read the references cited in this section. The remainder of this manuscript concentrates on new developments in PDV, as they relate to the system level, to frequency-based data analysis, to analysis of speckle dynamics, and new applications for PDV.

2. System Level Developments

2.1. Multiplexed photon Doppler velocimetry

Multiplexed photon Doppler velocimetry (MPDV) constitutes, perhaps, the single most influential development in PDV in recent years [7, 14-15]. This is evidenced by the fact that in addition to the

popularity MPDV is gaining among hydrodynamic test groups, the developers of MPDV were recently acknowledged with an R&D 100 Award [16]. MPDV makes use of multiplexing, both in the frequency-domain and in the time-domain, to combine several velocity histories (i.e., several probes' measurements) onto a single digitizer channel. A common configuration is to frequency multiplex four channels onto a single optical fibre, and to multiplex this configuration twice in the time-domain [14]. This configuration results in eight velocity histories recorded on a single digitizer channel, as opposed to standard PDV, which records one velocity history per digitizer channel. A four-channel digitizer is therefore capable of measuring 32 distinct velocity histories measured by 32 separate optical probes. A general schematic of the first generation MPDV architecture developed by National Security Technologies, LLC (or NSTec) is shown in figure 2. The system shown in figure 2 consists of eight lasers – four measurement lasers at unique wavelengths (designated in figure 2 as ITU bands) and four local oscillators which are detuned a few GHz from these measurement lasers. All four measurement lasers are multiplexed onto a single mode optical fibre, and their signals are transmitted via a circulator toward a division wavelength demultiplexer, where the four signals are separated to their respective optical probes. The measurement signals (reflected by the target surface) reenter the probes, where they are multiplexed again and sent to attenuators and combined with their respective local oscillators.

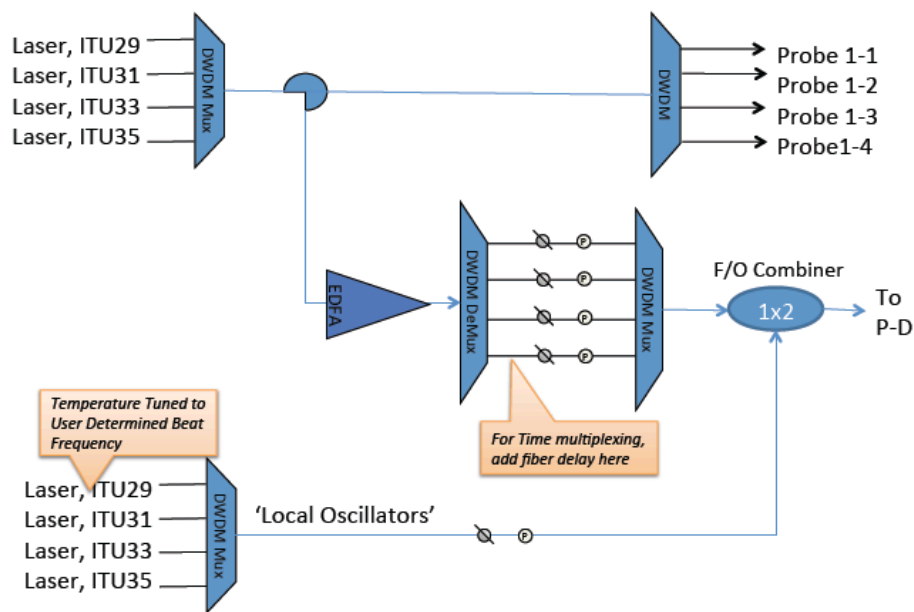


Figure 2. An MPDV system is shown (used with permission, E. Daykin, NSTec).

The nominal frequency differences between each measurement laser and its local oscillator are tuned such that each pair's beat frequency is distinguishable in the resulting spectrogram (figure 3). In this example, the eightfold increase in probe number requires only a marginal increase in hardware cost, since the digitizer demands are the same as in standard PDV. MPDV takes advantage of bandwidth and time/memory that were otherwise being wasted, in the sense that the digitizers record them even if no new information is present. The increase in spatial coverage that MPDV affords is, by itself, pushing the diagnostic into a new regime where it is capable of measuring a data richness that was previously unattainable. Using the previous example, MPDV enables an eightfold increase in the number of probes allowed per digitizer, and this results in a denser spatial sampling of the target surface. Probe designs, such as those from NSTec have made it possible to accurately map over a hundred distinct channels to locations on a target surface [17], thereby taking more complete advantage of MPDV's capabilities.

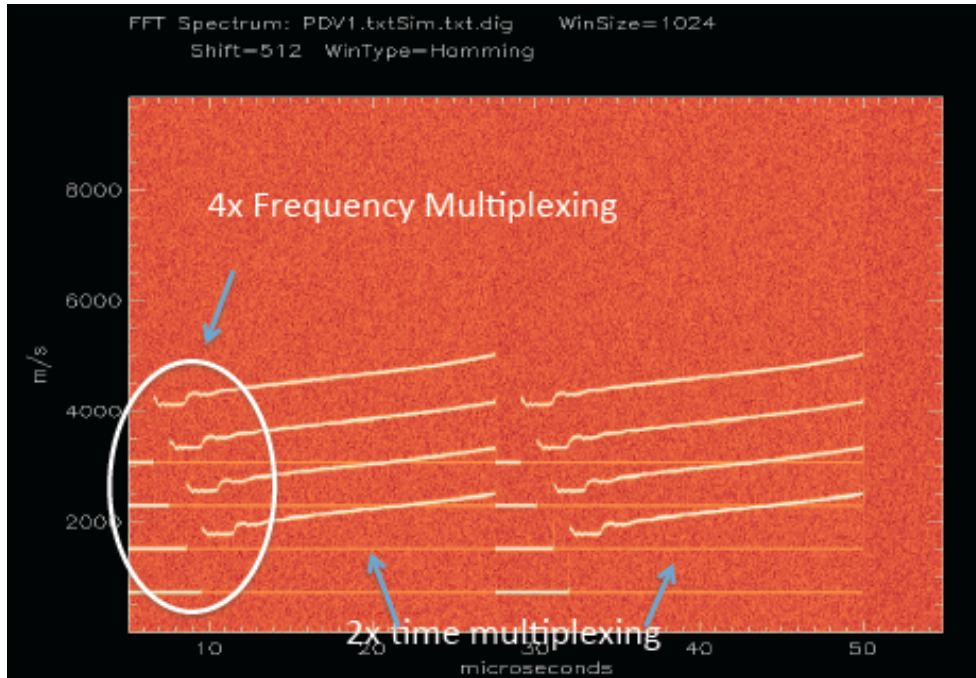


Figure 3. Simulated MPDV data demonstrates the manner in which frequency-domain and time-domain multiplexing exploit the digitizer's bandwidth and memory resources (used with permission, E. Daykin, NSTec).

2.2. Leapfrogged photon Doppler velocimetry

Dolan *et al* of SNL recently demonstrated a technique they refer to as “leapfrogged PDV”, where several laser/photodetector pairs are used in parallel (figure 4) to increase PDV's velocity range [18]. The reference laser of each laser/photodetector pair is tuned such that it measures a specific velocity range (similar to MPDV in the sense that $v = 0$ yields a tuned beat frequency for each pair; refer to figure 3). The multiple pairs are analyzed during different intervals of the surface response, and together they provide a mosaic of the surface's velocity history. A digitizer with 25 GHz of bandwidth is capable of measuring velocities from rest up through nearly 20 km/s (according to equation (1), 1.3 GHz of bandwidth corresponds to 1 km/s of velocity for $\lambda = 1550$ nm). The recent work by Dolan *et al* demonstrated the capability to measure an imploding cylinder from rest through velocities exceeding 43 km/s, by using a 25 GHz digitizer, leapfrogging three laser/photodetector pairs, and tuning each reference laser with respect to the measurement laser (Laser 1 in figure 4). This research constitutes the highest velocity measurements made with PDV, which is especially relevant to work at SNL, where the Z Machine can implode cylinders with velocities exceeding 50 km/s [18]. Dolan *et al* claim they could have tuned their three-channel leapfrogged system to measure velocities up to 97 km/s.

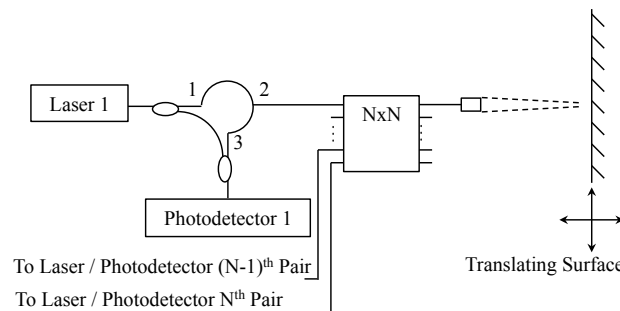


Figure 4. The leapfrogging architecture was recently demonstrated by Dolan *et al*.

3. Data analysis

As PDV gains in popularity, and as MPDV becomes more widely utilized, the volume of velocimetry data that a typical dynamic experiment generates continues to increase. Different research groups have their own tools for estimating the power spectral densities of PDV data and calculating velocity histories from the peaks in the spectrograms. For example, Dolan and Ao at SNL published a report on SIHREN [19], the MATLAB® based computational tool they have developed specifically for PDV and MPDV data analysis. Similarly, researchers at NSTec have developed their own PDV data analysis tools [20], as have researchers at LANL. Analysis software tools like these aid tremendously in velocity extraction. However, a large degree of user-input is still required, and user input raises questions regarding the subjectivity of the analysis procedure and the accuracy of the final results. Figure 3 is an example of how velocity traces can cross reference bands, and in experimental data they often cross one another as well. Regions where velocity traces overlap and change drastically in short time-periods are often challenging to resolve.

Dolan recently investigated the effects of uncertainty on the PDV, where he simulated noisy data and propagated it through the velocity extraction process [21]. His general conclusions were that (1) the Fourier analysis utilized for PDV experiences a bias at low frequencies and that (2) at high frequencies precision-limitations dominate PDV's performance. That is to say that performance at high frequencies is fundamentally governed by the limitations of the discrete Fourier transform, which are rooted in a tradeoff between time-resolution and frequency-resolution. Briggs studied the uncertainty effects on PDV in the case of experimental data with a non-constant velocity [22]. His conclusion was that the second moment of the fit (centroid or Gaussian) on the peak in the Fourier domain provides a conservative approximation of the uncertainty in the process.

4. Laser speckle dynamics

The coherent illumination of an optically rough surface results in a grainy, speckle pattern. The speckle pattern is caused by constructive and destructive interference in the backscatter contributions from neighbouring surface features, as seen by an observer [23]. Speckle patterns can translate, meaning a pattern shifts intact as a result of surface motion. Speckle patterns can also boil, meaning the speckle pattern decorrelates and its bright and dark regions randomly appear and disappear as a result of surface motion. Practically, either case of speckle dynamics results in random amplitude fluctuations as measured by PDV's optical probes (figure 5). As a consequence of the small number of speckles that influence a PDV measurement at a particular instance, these fluctuations often result in the loss of the signal, making velocity extraction difficult if not impossible (two to four speckles on average is typical, depending on the probe in use). These fluctuations are of a time-scale that is generally 50-1000 times slower than the Doppler-induced beating typically measured in PDV. Autocorrelation analysis has been shown to be effective at relating the time-scales associated with speckle dynamics with transverse motion of the target surface [24]. An example of speckle boiling, that is produced by a probe and setup that are representative of PDV, is shown in figure 6. The results in figure 6 also illustrate how a measurement probe sees a limited spatial region of the speckle pattern, and it is this region that is imaged by the lensed probe in PDV.

Moro and Briggs recently demonstrated the simultaneous measurement of axial velocity and transverse speed using a single optical probe using a PDV setup [23]. In the optical far field, the surface's transverse speed $|v|$ is related to the speckle-induced coherence time τ_c (measured using autocorrelation analysis) according to the relationship

$$|v| \approx \frac{w_0}{\tau_c}, \quad (2)$$

where w_0 is the waist (radius) of the illuminating beam. This technique holds promise for extracting more information from PDV data without requiring any system-level changes. Widespread implementation of this and related speckle analysis techniques in a variety of PDV test environments

will require a high-degree of confidence in the measured output as well as a thorough understanding of the relationships between structural responses and speckle dynamics. A complex parameter-space relates the optical probes' parameters, the target surface dynamics, and the measured speckle dynamics. Further, the majority of point-measurement speckle velocimetry research (such as the relationship derived in equation (2)) has focused on a subset of this parameter space. Recently, efforts by Moro and Briggs have been directed toward understanding the dependencies of speckle dynamics on probe-parameters, as well as understanding the effect that speckle boiling has on the time-scale of the speckle dynamics (most models of speckle dynamics address only the time-scales associated with translation). In addition to these efforts to utilize speckle dynamics, there still remains a great interest in the PDV community in mitigating speckle effects entirely, so as to eliminate undesired signal dropouts from PDV data.

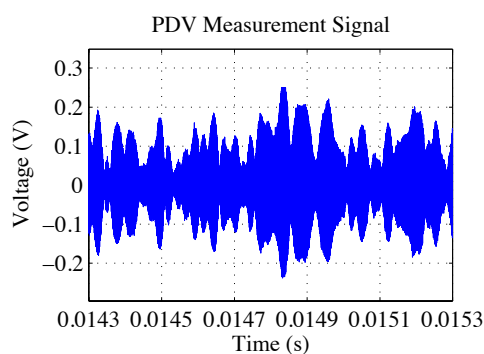


Figure 5. Speckle results in amplitude fluctuations in the measured PDV data.

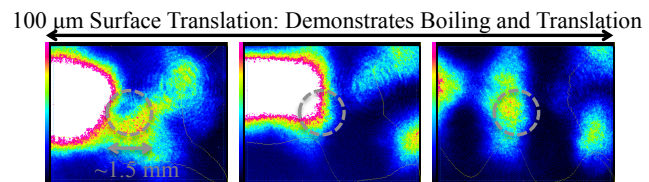


Figure 6. Speckle boiling is shown as a result of surface translation over 100 micrometers. The dashed circle indicates a region 1.5 mm in diameter, which indicates the probe's aperture at the image plane.

5. New applications

5.1. Transparent media, particle clouds, and particle size estimation

Mercier *et al* have recently demonstrated that an optical probe used for PDV is capable of measuring distribution of particle velocities that exist within transparent media and particle clouds [25-27]. One implication of this research, which they have also demonstrated, is that a probe that is angled with respect to a particle cloud is capable of measuring the cloud's profile as it propagates through space. This research group has gone further, to demonstrate that individual particle trajectories may be inferred from a cloud's velocity data, and that a particle's acceleration may be used to calculate its particle diameter (using a nonlinear optimization routine) [28].

5.2. Other applications

Shinas recently demonstrated the use of fibre optic "pins" for measuring the time of arrival and velocity of detonation waves [29]. As a shockwave traverses the face of an Aluminium-coated single mode fibre, it destroys the coating and the fibre (which contains light) transmits an increased percentage of the light as the coating is destroyed. At the same time, the detonation wave's velocity is also inferred from Doppler shifting in the measured data. This technique has been demonstrated within a PDV architecture, where the coated fibre is essentially a dedicated PDV channel. Utilizing this approach, Shinas has demonstrated sub-nanosecond time of the detonation wave's arrival.

Various university-based research groups are demonstrating an interest in using PDV for slow (less than 1 km/s) measurements of mechanical vibrations. As an example, researchers at Ohio State University are applying PDV to manufacturing applications, where the velocity history of a metal plate during a laser welding process is indicative of the quality of the weld [30]. This research team

has demonstrated that they are able to distinguish between high-quality welds and low-quality welds using PDV data, where measured velocities are on the order of a few hundreds of meters per second. Researchers will continue to find new applications for PDV as they identify applications that suit its ability to robustly and accurately measure a broad range of velocities, without necessitating contact with the target surface.

6. Summary

PDV was originally introduced nearly 10 years ago, and since that time it has seen a tremendous increase in use and popularity. MPDV is perhaps the biggest development to PDV in recent years, and it enables collection of data sets, whose spatial- and temporal-coverage during a dynamic test are unparalleled in optical velocimetry. On-going MPDV research will address, among other things, the reduction in dynamic range limitations imposed by the MPDV architecture and the need for automated velocity extraction. Leapfrogging also constitutes a significant, system-level development for PDV, and it has enabled the highest velocity measurements on record for PDV (43 km/s).

There is interest in developing the capability for PDV (or a related diagnostic) to measure either the absolute position of a surface or the approach of a laterally moving angled surface. Both scenarios constitute a weakness for PDV, since it only measures displacement of a surface along beam axes. Along the same lines, speckle analysis of PDV data holds promise for enabling a PDV probe to simultaneously measure motion along its beam axis as well as motion perpendicular to its beam axis. Future work will include modeling of the speckle's coherence time in regions where speckle boiling dominates the speckle dynamics (as opposed to regions where translation dominates the speckle dynamics). Also with regard to laser speckle effects, the issue of signal dropouts remains a pressing one. Even in the case that speckle dynamics may be related to surface dynamics, it is non-ideal for the signal to disappear entirely, getting in the way of velocity extraction.

Researchers continue to find new applications for PDV, such as the measurement of multiple velocities in transparent media, the measurement of particle cloud profiles, and the calculation of particle sizes from their trajectories. The use of a PDV probe for measuring detonation wave timing also constitutes a recent extension PDV's capabilities, where its fast rise time and large dynamic range make it very suitable for these sorts of measurements. PDV will continue to find new applications as people decide its trade-offs suit their particular needs.

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