Note: Phase retrieval method for analyzing single-phase displacement interferometry data


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Formation of x-ray vortex dipoles using a single diffraction pattern and direct phase measurement using interferometry
We present a phase retrieval method (PRM) for analyzing single-phase displacement interferometry measurements on rapidly changing velocity histories, including photon Doppler velocimetry (PDV). PRM identifies the peaks and valleys as well as zero-crossing points in a PDV time series, performs normalization and extracts point-by-point phase and thus velocity information. PRM does not require a wide time window as in sliding window Fourier transformation, and thus improves the effective temporal resolution. This method is implemented in analyzing PDV data obtained from gas gun experiments, and validated against simultaneous measurements with velocity interferometer system for any reflector. © 2014 AIP Publishing LLC. [http://dx.doi.org/10.1063/1.4865113]

Sliding window short-time Fourier transformation (STFT) is a common method in photon Doppler velocimetry (PDV) for measuring the surface or interface velocities in shock wave experiments.\(^1\)\(^-\)\(^3\) Despite its great success, PDV’s capability of measuring rapidly changing velocities is still limited by their low temporal resolutions due to inherent averaging over a STFT time window, and velocity information is smeared to certain extent. This weakness of STFT can be partly compensated with continuous wavelet transformation (CWT).\(^2\)\(^,\)\(^3\) CWT evaluates instantaneous frequencies with an adaptive time window and shows more flexibility than STFT. However, there are a large number of wavelet bases or prototype parent wavelets, and one has to select optimal ones according to a specific interference fringe signal. As a result, the choice of wavelets is not straightforward. Therefore, a simple efficient data processing method for PDV measurements on rapidly changing velocity histories is highly desirable.

Point-by-point phase retrieval is used in data reduction of VISAR (velocity interferometry system for any reflector) measurements; VISAR employs two 90° phase-shifted interference signals with a time delay.\(^4\) Such phase retrieval achieves the maximum temporal resolution allowed by the photomultipliers, oscilloscopes, and interferometer in the system. In all-fiber displacement interferometer system for any reflector (DISAR), three 120° phase-shifted traces are used to measure displacement via point-by-point phase retrieval with two of them, and DISAR achieves nominally better than 50 ps temporal resolution in gas gun experiments.\(^5\) A conceptual analysis method was also proposed for multiphase PDV measurements with 120° phase shifts.\(^6\) With these three phase-shifted signals, it is possible to reduce the effects of intensity variations and incoherent light from the measurement. The three traces are reduced to a pair of quadrature signals, allowing unambiguous calculation of target displacement by evaluating the phase difference.\(^6\) The velocity of a moving surface is obtained via differentiation of the phase evolution.

Here we present a simple phase retrieval method (PRM) for single-phase PDV measurements, as opposed to three 120° phase-shifted channels previously used.\(^5\) It’s advantage lies in its simplicity and high temporal resolution, and the nominal resolution can be as high as the sampling rate during data acquisition.

A PDV is essentially an optical fiber Michelson interferometer. The interferometry signal or light intensities carrying displacement/velocity information are

\[
I(t) = I_0 + I_D + 2\sqrt{I_0 I_D} \sin \left(2\pi \int_0^t f_b(t) dt + \varphi_0\right),
\]

where \(t\) is time, \(I_0\) is the reference light intensity from the probe laser, \(I_D\) is the intensity of the Doppler-shifted light returned from the sample surface, \(f_b\) is the beat frequency of the PDV signal, and \(\varphi_0\) is the initial phase difference between the Doppler-shifted and non-Doppler-shifted light, or the zero-velocity phase.

Data reduction may be performed in either velocity or displacement mode. We can obtain the instantaneous velocity from the beat frequency, \(v(t) = \frac{\lambda_0}{2} f_b(t)\), by

\[
v(t) = \frac{\lambda_0}{2} f_b(t),
\]

where \(\lambda_0\) is the wavelength of the probe laser. Both STFT and CWT use the beat frequency to extract velocity. On the other hand, the phase of an interference signal is related to displacement. PRM assumes that the fringe signal, \(y(t)\), is a sinusoidal function of the fringe count, \(F(t)\), i.e.,

\[
y(t) = y_0(t) + A(t) \sin(\varphi(t) + \varphi_0) = y_0(t) + A(t) \sin(2\pi F(t) + \varphi_0),
\]

where phase \(\varphi(t) = 2\pi F(t)\). Each fringe corresponds to the displacement of the surface by \(\lambda_0/2\), and the velocity \(v(t)\) is related to the phase by

\[
v(t) = \frac{d}{dt} s = \frac{\lambda_0}{2} \frac{dF(t)}{dt} = \frac{\lambda_0}{4\pi} \frac{d\varphi(t)}{dt},
\]

where \(s\) is displacement.
The basic assumption in PRM-PDV is that within a short time period (e.g., a half cycle), \( y_0(t) \) and \( A(t) \) can be regarded as constant. Then the signal as represented by Eq. (3) can be normalized into a sine function with phase information. For a sine function \( y = \sin(x) \) shown in Fig. 1, four representative phases, i.e., \( A_1, A_2, A_3, \) and \( A_4 \) spread over different quadrants, can be calculated as

\[
x = \begin{cases} 
\arcsin(y) & : 1\text{st quadrant } (A_1, A_4), \\
\pi - \arcsin(y) & : 2\text{nd and 3rd quadrant } (A_2), \\
2\pi + \arcsin(y) & : 4\text{th quadrant } (A_3). 
\end{cases}
\]

The boundaries between quadrants are determined with the help of peak and valley positions and zero-crossing points. While the phases evolve from the fourth quadrant of a cycle to the first quadrant of the next cycle, a fringe jump occurs and \( 2\pi \) is added to the phase. Assuming that \( A_1, A_2, \) and \( A_3 \) are in the \((n + 1)\)th period and \( A_4 \) is in the \((n + 2)\)th period, their true phases are, respectively, \( 2\pi n + x_{A_1}, 2\pi n + x_{A_2}, 2\pi n + x_{A_3}, \) and \( 2\pi(n + 1) + x_{A_4}, \) with \( 0 \leq x < 2\pi \). According to the phase unwrapping rules defined above, the time-dependent phases of the whole fringe signal can be recovered unambiguously.

Single-phase PRM is implemented in the analysis of PDV data obtained in plate impact experiments, and validated against an independent VISAR measurement (Figs. 2 and 3). The impact experiments are carried out with a gas gun, in conjunction with PDV and VISAR diagnostics. The PDV signals are recorded at 20 GS/s for 100 \( \mu s \). A MATLAB package is developed for PRM-PDV analysis, and the main processing steps are

- **Noise reduction** in the raw data \( y(t) \) [Figs. 2(a) and 2(b)]. A low-pass fast Fourier Transformation (FFT) filter is used to eliminate the high frequency noise.
- **Normalization** [Fig. 2(c)]. Scan through the smoothed data and search for the maxima \( y_{\text{max}} \) and minima \( y_{\text{min}} \) within a fringe. Normalization is carried out per half cycle (i.e., from \( y_{\text{max}} \) to \( y_{\text{min}} \) or from \( y_{\text{min}} \) to \( y_{\text{max}} \)), i.e.,

\[
y_n = \frac{2(y - y_{\text{min}})}{y_{\text{max}} - y_{\text{min}}} - 1, \quad (6)
\]

where \( y_n \) refers to the signal after normalization. Assuming that \( y_0(t) \) and \( A(t) \) are constant within the half cycle under consideration, Eq. (3) can then be reduced to

\[
y_n(t) = \sin(\varphi(t) + \varphi_0). \quad (7)
\]

- **Phase retrieval** can then be conducted point by point [Fig. 2(d)] with

\[
\varphi(t) = \arcsin(y_n(t)) - \varphi_0. \quad (8)
\]

In VISAR data reduction, the fringe jump is cross-checked with two 90\(^\circ\) phase shifted signals, whereas in PRM quadrant-crossing is utilized.

- **Converting phase into velocity** with Eq. (4). However, noise is introduced due to differentiation [Fig. 2(e)], so a low pass FFT filter is applied to smooth the velocity history [Fig. 2(f)].

The extracted velocity history via PRM shows rich information on dynamic response of the shocked metal owing to its high temporal resolution, including the elastic precursor, plastic shock, elastic and plastic release, and spall pullback [Fig. 2(f)]. We only use a low-pass filter for smoothing the
FIG. 3. Comparison of velocity histories obtained from a gas gun experiment with PRM-PDV and VISAR. The lower panel shows the relative difference between these two methods. The flyer plate is oxygen-free high conductivity Cu (0.78 mm thick) and the target is 2024 Al (1.75 mm thick).

PRM velocity history, while a wide time window of 1024 points (51 ns) is required to obtain a reasonable signal/noise ratio in STFT, for the same raw dataset. The comparison between PRM and STFT demonstrates PRM’s advantage in temporal resolution over STFT [Fig. 2(e)].

VISAR and PDV represent two different ways of using laser interferometry to measure velocity in shock compression experiments. VISAR’s quadrature recording of the fringes and appropriate data reduction method allow velocity measurements accurate to 1% or better as long as two or more fringes are produced in VISAR traces.7 We evaluate the accuracy of PRM-PDV against independent, Barker-type, VISAR4 in the same gas gun experiment. Figure 3 demonstrates excellent agreement between these two methods. Overall, the agreement is within 1%. There are only a couple of instants showing large deviations (∼5%), e.g., near the spall pullback.

We have presented a novel signal processing method for single-phase PDV using data normalization and point-by-point phase retrieval, and implemented and validated this method in gas gun experiments. It may achieve higher temporal resolution and reduces the associated velocity smearing compared to common frequency domain methods. PRM is particularly suitable for measurements on fast changing low velocity histories such as elastic precursors. However, single-phase PRM is sensitive to noise since it analyzes data in time domain, so high signal/noise ratio is required for the raw data. Another limitation of PRM is that multiple velocities cannot be measured at a given instant.