Chapter 10
Heterodyne Diffracted Beam Photonic Doppler Velocimeter (DPDV) for Pressure-Shear Shock Experiments

M. Mello, C. Kettenbeil, M. Bischann, Z. Lovinger, and G. Ravichandran

Abstract We present details on the design and validation of a heterodyne diffracted beam photonic Doppler velocimeter (DPDV) for pressure-shear plate impact (PSPI) shock experiments. The fiber optic interferometer collects symmetrically diffracted 1st order beams produced by a thin, specular, metallic grating deposited on the rear surface of the impacted target plate and separately interferes each of these beams with a reference beam of a slightly increased wavelength. The resulting interference signals contain an upshifted carrier signal with a constant frequency at zero particle velocity. Signal frequency content in recorded waveforms from PSPI experiments is extracted using a moving-window DFT algorithm and then linearly combined in a post- processing step to decouple and extract the normal and transverse velocity history of the rear target surface. The 0th order (normally reflected) beam can also be interfered in a separate heterodyne PDV configuration to obtain an additional, independent measurement of the normal particle velocity. An overview of the DPDV configuration is presented along with a discussion of the interferometer sensitivities to transverse and normal particle velocities. Results from a normal impact experiment conducted on Y-cut quartz are presented as experimental validation of the technique.

Keywords Heterodyne · Diffraction · Pressure-shear · Transverse particle velocity · Y-cut quartz

10.1 Introduction

Pressure-shear plate impact (PSPI) experiments have traditionally relied on free space beam interferometers such as the transverse displacement interferometer (TDI) and normal displacement interferometer (NDI) or normal velocity interferometer (NVI), to measure transverse and normal velocities at the rear surface of the target plate [1]. Alternative interferometer schemes feature a dual beam VISAR arrangement [2] and a recently developed all fiber-optic TDI-NDI configuration [3]. We present details on the development, and experimental validation of a heterodyne diffracted beam photonic Doppler velocimeter (DPDV) system for simultaneous measurement of normal and transverse particle velocity components in pressure-shear plate impact (PSPI) shock experiments. A source probe produces a thin collimated beam which is normally incident to the rear surface of the target plate. The 0th order (normally reflected) beam is collected by the same source probe, and a pair of fiber-optic side probes receive the symmetrically diffracted 1st order beams. Each beam is then passed through a fiber-optic circulator and then combined with a reference beam of a slightly higher wavelength to create a heterodyne interference signal with an upshifted carrier frequency at zero particle velocity. The frequency content encoded within the recorded DPDV waveforms corresponds to a scaled linear combination (sum or difference) of the normal and transverse particle velocity components. A moving-window discrete Fourier transform (DFT) algorithm is applied to extract the DPDV signal frequencies $f^+(t)$ and $f^-(t)$ from the recorded signals, which also contain the constant user-selected carrier frequency. Normal and transverse particle velocity components are subsequently decoupled in a post-processing algorithm through addition or subtraction and appropriate scaling of the extracted signal frequencies. The normally reflected (0th order) beam is also interfered in a heterodyne PDV arrangement to obtain an additional independent measurement of the normal particle velocity. The fiber-optic DPDV system has been configured with a powder gun capable of achieving impact velocities of 1.8 km/s and has enabled PSPI shock impact investigations on the strength and failure properties of novel materials at shear strain rates approaching $10^8\ s^{-1}$.

M. Mello (✉) · C. Kettenbeil · M. Bischann · Z. Lovinger · G. Ravichandran
California Institute of Technology, Pasadena, CA, USA
e-mail: mello@caltech.edu

J. Kimberley et al. (eds.), *Dynamic Behavior of Materials, Volume 1*, Conference Proceedings of the Society for Experimental Mechanics Series, https://doi.org/10.1007/978-3-319-95089-1_10

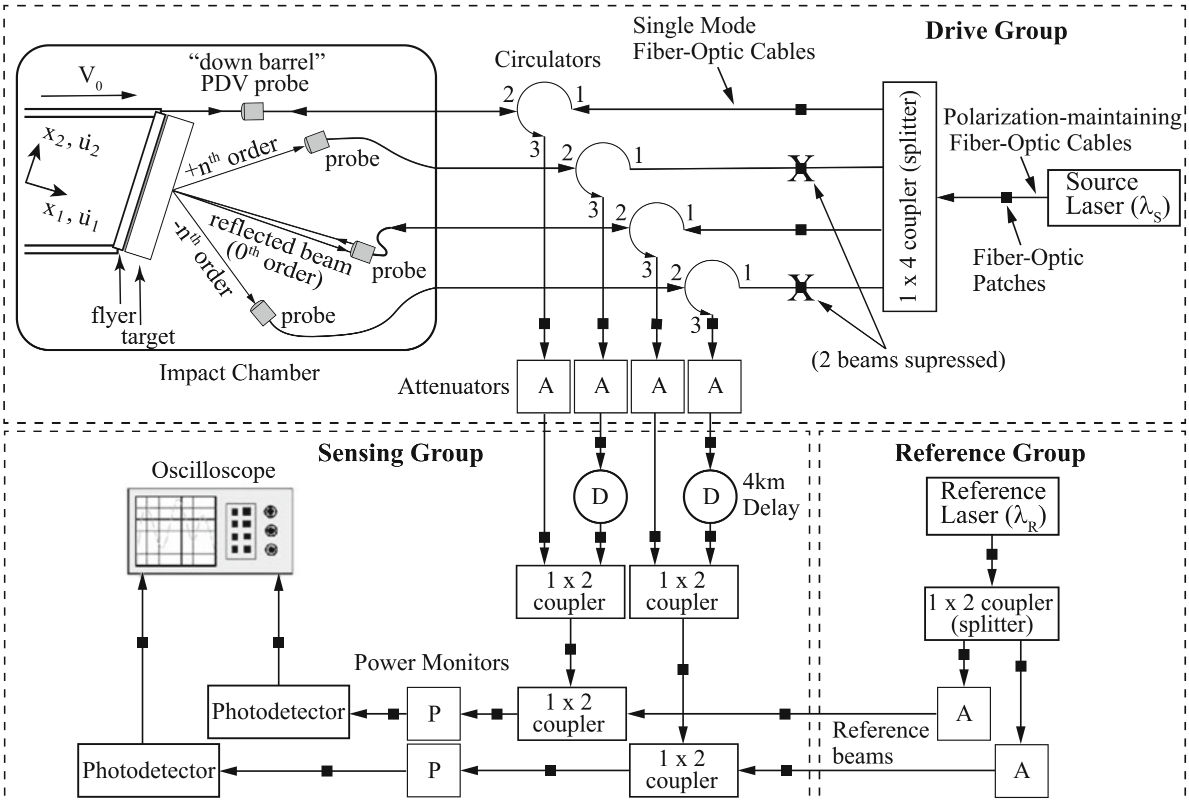

Fig. 10.1 DPDV optical configuration for the combined measurement of normal and transverse particle velocity history in PSPI shock experiments

10.2 Interferometer Configuration

The fiber-optic DPDV arrangement is comprised of the drive, reference, and sensing groups as depicted in Fig. 10.1. The source light is produced by a KOHERAS BOOSTIK model E15 fiber laser by NKT Photonics with a Lorentzian linewidth of 0.1 kHz, an adjustable center wavelength between 1550 nm and 1570 nm, and a maximum output power of 2 W. The drive group hardware elements include a 1 × 4 fiber-optic splitter, fiber-optic circulators, attenuators, and fiber-optic probes. Fiber optic side probes are designed to efficiently collect the diffracted beams even as they rotate due to tilt and decenter from the optical axis as a consequence of accumulated normal displacement of the target plate rear surface. Reference group hardware elements depicted in Fig. 10.1 generate the reference beams, which are interfered with the drive group source beams diffracted and reflected by the target. Sensing group hardware elements depicted in Fig. 10.1 interfere the collected source light with the reference light and convert the resulting interference signals into digitized fringe records for analysis.

10.3 Interferometer Measurement Sensitivity and Analysis of Recorded Waveforms

DPDV measurement sensitivity is derived by invoking the two beam, time-averaged interference equation given by

$$I^{\pm}(t) = I_S^{\pm} + I_R^{\pm} + 2\sqrt{I_S^{\pm}\, I_R^{\pm}}\, \cos\left[\frac{2\pi}{\lambda_S}\left(u_1(t)(1-\cos\theta_n) \pm u_2(t)\sin\theta_n\right) + 2\pi(\nu_S - \nu_R)t - \phi^{\pm}\right]. \qquad (10.1)$$

Here $I_S^{\pm}$ and $I_R^{\pm}$ respectively represent the time-averaged background intensity of the source and reference beams and the ± symbols designate interference of the $n = +1$ or $n = -1$ diffracted order with its respective reference beam [1].

Application of a moving-window discrete Fourier transform (DFT) algorithm to the pair of recorded DPDV waveforms extracts the encoded signal frequencies corresponding to

$$f^{+}(t) = \frac{1}{\lambda_S}\left(\dot{u}_1(t)\left(1 + \cos\Theta_n\right) + \dot{u}_2\left(t\right)\sin\Theta_n\right) + \left(\nu_S - \nu_R\right) \tag{10.2}$$

$$f^{+}(t) = \frac{1}{\lambda_S}\left(\dot{u}_1(t)\left(1 + \cos\Theta_n\right) - \dot{u}_2(t)\sin\Theta_n\right) + \left(\nu_S - \nu_R\right) \tag{10.3}$$

where λ_S represents the wavelength of the source laser, $\dot{u}_1$, $\dot{u}_2$ are the normal and transverse particle velocity components, ν_S and ν_R correspond to the optical frequencies of the source and reference laser light beams, and $\phi^{\pm}$ is a constant arbitrary phase term in each interference signal. Subtracting Eq. (10.3), from Eq. (10.2) and substituting from the grating equation $sin\Theta_n = n\lambda/d$ yields an expression for the transverse particle velocity expressed in terms of the grating pitch (d), diffraction order (n), given by

$$\dot{u}_2(t) = \frac{d}{2n}\left(f^{+}(t) - f^{-}(t)\right) \tag{10.4}$$

The frequency scaling factor d/2n effectively represents the fundamental measurement sensitivity of the DPDV to changes in transverse velocity and is equivalent to the sensitivity of a TDI [1]. Using the 1st order beams from a 400 lines/mm grating in the current DPDV configuration results in a transverse velocity measurement sensitivity of 1.25 m/s/MHz. Addition of the two DPDV signal frequencies given by Eqs. (10.2 and 10.3) yields an expression for the normal particle velocity in terms of the measured signal frequencies and the independently measured carrier frequency ($\nu_C = \nu_S - \nu_R$) given by

$$\dot{u}_1(t) = \frac{\lambda_S}{2\left(1 + \cos\Theta_n\right)}\left(f^{+}(t) + f^{-}(t) - 2\nu_C\right). \tag{10.5}$$

The scaling factor $\lambda_S/2(1 + \ cos\ \Theta_n)$ represents the fundamental measurement sensitivity of the DPDV to changes in normal velocity. DPDV is therefore, $(1 + \ cos\ \Theta_n)$ times more sensitive to changes in normal velocity compared to a standard PDV, which has a sensitivity of $\lambda_S/2$ [4]. Using the 1st order beams from a 400 lines/mm grating in the current DPDV configuration results in a normal velocity measurement sensitivity of 0.434 m/s/MHz, which represents a 1.78× increase over the sensitivity of the PDV when using the 0th order beam at the same source wavelength.

10.4 Experimental Validation – Normal Impact of Y-Cut Quartz

A normal plate impact experiment was conducted using a borosilicate glass flyer plate and a single crystalline Y-cut quartz target plate as a means of validating the new DPDV system. Single crystalline Y-cut quartz was selected as a target material because of the strong anisotropic coupling exhibited between longitudinal and transverse particle motion when impacted along its x_2 axis. Quasi-longitudinal (QL) and quasi-transverse (QT) waves emerge as the only nonzero eigenvalues of the elasto-acoustic tensor which governs the problem [1]. Sharp velocity jumps registered in the normal and transverse directions upon arrival of the QL and QT waves at the rear surface of the target present an ideal scenario for evaluating various attributes of the DPDV system such as predicted velocity measurement sensitivities and the optical heterodyne feature for automatic, accurate detection of sharp velocity reversals. A 300 nm thick, 400 lines/mm ($d = 2.5\ \mu$m) gold diffraction grating was fabricated onto the backside of the polished Y-cut quartz target plate using standard photolithography procedures in a cleanroom environment. The grating was deposited on the target plate with its grooves aligned parallel to the x_1 axis of the Y-cut quartz substrate. The grating produced sharp, specular 0th order and 1st order diffraction beams along 1st order diffraction angles $\Theta_n = \pm 38.32^{\circ}$ per the grating equation. No additional diffraction orders are produced by a 400 lines/mm grating at the source wavelength $\lambda = 1550$). DPDV probes were physically aligned to the $\pm 1^{st}$ order diffraction angles by optimizing the light return from each diffracted beam until the maximum light returns were achieved.

Normal and transverse velocity profiles measured at the rear surface of the Y-cut quartz target plate using the DPDV system are plotted in Fig. 10.2. The velocity profiles were obtained from the acquired fringe records using a Hamming window of 50 ns with the window shifted by a 50 ps time step for every analysis. The dashed lines represent the predicted

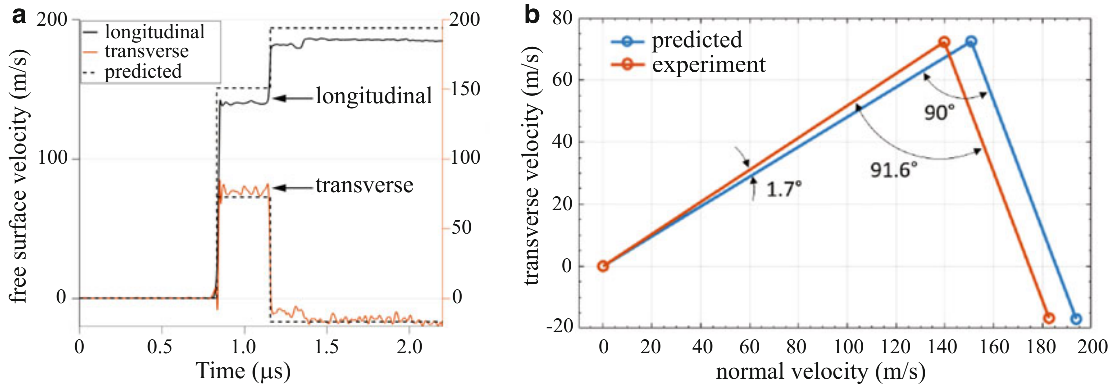

Fig. 10.2 (**a**) Measured longitudinal and transverse velocity profiles compared to predicted values based on the measured impact speed of $V_0 = 212$ m/s (**b**) Orthogonality of the measured velocity jumps during the arrival of the QL wave, and the QT wave

velocity jumps of each respective motion component. The measured steady initial and final transverse particle velocity levels are in excellent agreement with theory while the measured normal velocity jumps are within 6–7% of their respective predicted values. The observed deviation is attributed to a small impact tilt angle of ~1mrad, which caused the QL wave to deviate from the x_2 axis (quartz crystal y-axis) by an amount consistent with the observed deviation. The observed deviation is also partly attributed to uncertainties in the values of the elastic constants of Y-cut quartz and borosilicate glass.

References

1. Kim, K., Clifton, R.J., Kumar, P.: A combined normal- and transverse-displacement interferometer with an application to impact of Y-cut quartz. J. Appl. Phys. **48**, 4132–4139 (1977)
2. Chhabildas, L.C., Sutherland, H.J., Asay, J.R.: A velocity interferometer technique to determine shear-wave particle velocity in shock-loaded solids. J. Appl. Phys. **50**, 5196 (1979)
3. Zuanetti, B., Wang, T., Prakash, V.: A compact fiber optics-based heterodyne combined normal and transverse displacement interferometer. Rev. Sci. Instrum. **88**, 033108 (2017)
4. Dolan, D.H.: Accuracy and precision in photonic Doppler velocimetry. Rev. Sci. Instrum. **81**, 053905 (2010)