A desensitized displacement interferometer applied to impact recovery experiments

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A variable sensitivity displacement interferometer (VSDI) used to monitor both normal and in-plane particle displacements in stress wave propagation experiments is introduced. The general system consists of two interferometers working in tandem. Normally reflected light is interfered with each of two symmetrically diffracted light beams generated by the specimen rear surface. In cases where the surface motion simultaneously exhibits both in-plane and normal displacements, the fringes represent a linear combination of the longitudinal and transverse components of motion. Decoupling of the normal and in-plane displacement histories can be achieved through a linear combination of the two VSDI records. The variable sensitivity feature of the VSDI greatly desensitizes normal displacement measurements and is particularly well suited for wave propagation studies. Experimental results are presented which demonstrate the application of this technique to monitoring particle motion histories in pressure-shear *recovery* experiments. © *1996 American Institute of Physics.* [S0003-6951(96)05347-8]

In shock wave propagation experiments two interferometers are commonly used in the measurement of normal particle velocities. In the case of low velocity impact experiments, a normal displacement interferometer (NDI), having a fixed sensitivity of $\lambda/2$ [mm/fringe], where λ represents the laser light wavelength, is frequently used because this interferometer can resolve fast and slow changes in velocity with very high accuracy. Nonetheless, the extreme sensitivity of this interferometer severely limits its application in wave propagation experiments due to the inordinately high signal frequencies which may be generated. It is reasonable to regard a particle velocity of 0.1 mm/μs as an upper bound for the NDI. In order to overcome this limitation, Barker[1] developed a normal velocity interferometer (NVI). A more versatile velocity interferometer for any reflecting surface (VISAR) was later developed by Barker and Hollenbach.[2] The VISAR has a variable sensitivity given by $\lambda/[2\tau(1+\delta)]$ [mm/μs/fringe], whereby τ represents a time delay between the interfering light beams introduced by an air delay leg or etalon in the interferometer. The factor $(1+\delta)$ is a correction term to account for the refractive index of the etalon. During the initial period τ, an NVI is functioning as an NDI since the light arriving at the detector from the delay leg originated from a stationary target (see Clifton[3]). As a result, the interferometer may not resolve elastic precursors involving velocity jumps of more than 0.1 mm/μs in a time less than τ because the early time NDI signal frequency may exceed the frequency response of the light detection system. This feature concerning true velocity jumps is discussed in relation to lost fringes in Barker and Hollenbach.[2]

In 1977, Kim, Clifton, and Kumar[4] introduced the transverse displacement interferometer (TDI) to simultaneously monitor in-plane and out-of-plane particle displacements in pressure shear plate impact experiments. In 1979, Chhabildas *et al.*[5] introduced a dual VISAR arrangement in which each VISAR collected scattered light at a known angle with respect to the specimen rear surface. Each VISAR detector output represents a linear combination of the normal and in-plane velocity histories. Decoupling of the individual motion components is achieved through addition or subtraction of the combined motion phase terms. Additional optical techniques for measuring the surface displacements of solids have been successfully developed, such as a two-channel confocal Fabry–Pérot interferometer (Cand, Monchalin, and Jig[6]).

The variable sensitivity displacement interferometer (VSDI) presented here has been designed to provide an alternative to the NDI, VISAR, and Fabry–Pérot interferometers as applied to plate impact experiments, particularly within the noted velocity range of 0.1–0.3 mm/μs. The sensitivity of such an interferometer is fully variable; thus, it can operate over a wide range of particle velocities without exceeding the frequency response of the light detection system. Moreover, the VSDI system eliminates the need for very expensive optical components and ultrafast oscilloscopes.

VSDI theory: to examine the governing equation for a variable sensitivity displacement interferometer, consider the effect of interfering the normally reflected beam with a beam diffracted at an angle θ with respect to the specimen normal as shown in Fig. 1. The normally reflected beam is split at beam splitter BS1. Each half of the normal beam is then made to interfere with one of the diffracted beams via beam splitters BS2 and BS3. The resulting signals generated by each interfering beam pair are monitored by photodetectors. The combined field for either pair of interfering plane waves leads to a classical interference expression of the form

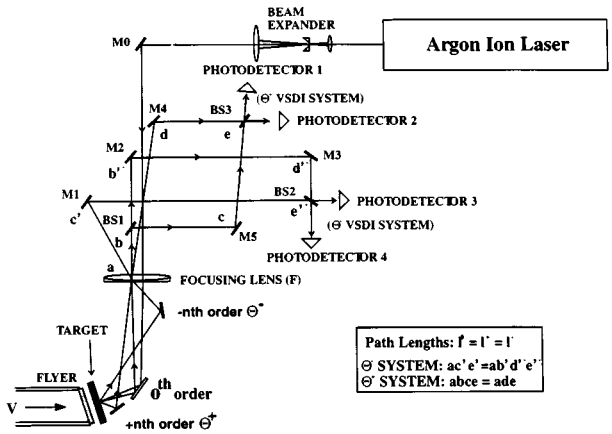

FIG. 1. Schematic of VSDI system. The $\Theta^{\pm}$ VSDI system is obtained by combining a normally reflected beam and a diffracted beam at an angle $\theta^{\pm}$. In this figure, mirrors M0 to M5 and beam splitters BS1 to BS3 are used to obtain the VSDI system. The lens with focal length F is used to focus the beam at the grating plane in the anvil back surface.

$$I(t) \propto I^0 + I^{\pm} + 2\sqrt{(I^0 I^{\pm})}\cos(\beta)\cos\Psi^{\pm}(t). \tag{1}$$

Here, I^0 and $I^{\pm}$ represents the time averaged intensities of the respective contribution light fields and β is the angle between their respective polarization vectors. Normal and transverse particle motion introduce frequency modulation through the time varying phase term, namely

$$\Psi^{\pm}(t) = \frac{2\pi}{\lambda}\left[2U\left(t-\frac{l^0}{c}\right) - U\left(t-\frac{l^{\pm}}{c}\right)(1+\cos\theta) \mp V\left(t-\frac{l^{\pm}}{c}\right)\sin\theta + (l^0 - l^{\pm})\right] + \phi^0 - \phi^{\pm}, \tag{2}$$

where λ is the wavelength of the laser source, $U(t)$ and $V(t)$ represent the normal and in-plane displacements of the point of observation from its position at time $t=0$; ϕ^+, ϕ^- represent constant arbitrary phase terms, and l^+, l^-, and l^0 represent the fixed initial path lengths traversed from target to detector by the $\theta^{\pm}$ diffracted beams and the normally reflected beam, respectively. Observe that the transverse motion phase term is subtracted for the case where the θ^+ beam is employed and otherwise added when interfering with the θ^- beam. Next, setting $l^0 = l^+ = l^-$ leads to a more simplified and useful form, i.e.,

$$\Psi^{\pm}(t) = \frac{2\pi}{\lambda}\left[U\left(t-\frac{l}{c}\right)(1-\cos\theta) \mp V\left(t-\frac{l}{c}\right)\sin\theta\right] + \phi^0 - \phi^{\pm}. \tag{3}$$

Equation (3) shows that each VSDI system will generate a different signal frequency when used to monitor the same given combined state of motion. In pressure-shear experiments, after arrival of the shear wave to the point of observation, each VSDI system exhibits a sudden frequency increase or decrease depending upon whether the θ^+ or θ^- beam is being interfered.

Case of purely normal motion: (desensitized normal displacement interferometer, DNDI). For $V(t)=0$, Eq. (3) gives a normal displacement/fringe$=\lambda/(1-\cos\theta)$. The fringe constant varies from infinity at $\theta=0°$ to λ [mm/fringe] at $\theta=90°$.

Case of purely in-plane motion: (desensitized transverse displacement interferometer, DTDI). For $U(t)=0$, Eq. (3) gives a transverse displacement/fringe$=\lambda/\sin\theta$. The DTDI sensitivity ranges from a complete loss of sensitivity at $\theta=0°$ to a theoretical sensitivity limit of λ [mm/fringe] at $\theta=90°$. The interferometer is ''desensitized'' in the sense that, for the same diffraction orders, it exhibits one-half the sensitivity of the transverse displacement interferometer (TDI[4]).

Case of combined normal and in-plane motions: (VDSI System). When the material point exhibits both normal and in-plane components of displacement, frequency modulation results through a linear combination of both motion components as dictated by Eq. (3). Decoupling of the two motions can be achieved by adding or subtracting the time varying phase terms of the Θ^+ and Θ^- VSDI signals. Addition provides an expression for a new phase term associated solely with a normal displacement U given by

$$\Psi(t)^+ + \Psi(t)^- = \frac{4\pi}{\lambda}U\left(t-\frac{l}{c}\right)(1-\cos\theta) + 2\phi_0 - \phi^- - \phi^+. \tag{4}$$

Hence, the fringe constant relation of this new signal is normal displacement/fringe$=\lambda/2(1-\cos\theta)$. It should be noted that this sensitivity is twice the sensitivity obtained by a single VSDI system for the case of pure normal motion, basically because the signal obtained by addition of two VSDI systems exhibits a double recording of the normal displacement.

By subtracting the phase terms of the Θ^+ and Θ^- VSDI signals, an expression for a phase term associated solely with an in-plane motion V is obtained, viz.,

$$\Psi(t)^- - \Psi(t)^+ = \frac{4\pi}{\lambda}V\left(t-\frac{l}{c}\right)\sin\theta - \phi^- + \phi^+. \tag{5}$$

The fringe constant of this new signal is given by $\lambda/2\ \sin\theta$. This sensitivity is the same as the one exhibited by the transverse displacement interferometer (TDI[4]). This result is not surprising since the signal obtained by subtracting the two VSDI systems eliminates the effect of the normally reflected beam. We can conclude that this resulting signal is nothing other than a TDI signal.

An alternative approach for determining the normal and in-plane motions is to use the phase information of both a TDI system and a Θ-VSDI system. The in-plane motion V can be directly obtained from the TDI signal[4] while the normal motion can be obtained from the Θ-VSDI signal.

We next present results obtained with the VSDI system applied to pressure-shear recovery experiments. The pressure-shear soft-recovery experiment is particularly suitable to investigate the applicability of the variable sensitivity displacement interferometer because normal velocities in the range 0.1–0.3 mm/μs need to be recorded. The configuration is shown in Fig. 2.

In the present study the multi-plate impactor, 57 mm in diameter, was made of two speed-star steel plates (AISI-type M2 tool steel) (Smith[7]), 3.3 and 2.4 mm thick, respectively, bonded by a 1-μm-thick polymer film. The specimen is

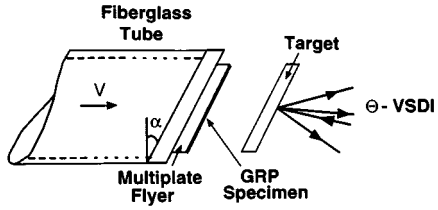

FIG. 2. Schematic of high strain rate pressure-shear configuration.

made of a woven glass fiber-reinforced polyester (GRP), 0.31 mm thick, glued to the two steel plates in the periphery. The impactor was glued to the front end of a fiber glass tube with the impact plane skewed from the axis of the tube at an angle of 18°. A grating with 1000 lines/mm was manufactured in the 6.45-mm-thick target plate back surface to produce the desired diffracted beams. An impact velocity of 0.132 mm/μs was measured in the experiment.

A combined Θ^- VSDI-TDI system was utilized to monitor the normal and transverse velocities at the target free surface. The zero order reflected beam was combined with the negative first order diffracted beam to produce a Θ^- VSDI system. A TDI interferometer was obtained by mixing the two first order diffracted beams.[4] Addition details of the experimental procedure are given by Espinosa *et al.*[8] Decoupling between the normal and in-plane motions was accomplished by first obtaining the in-plane motion, V, directly from the TDI signal and then the normal motion, U, from the Θ^- VSDI signal. Velocities were obtained by differentiating the displacement histories numerically. All the calculations were automatically performed with MATLAB.

The normal velocity–time profiles obtained from the experiment and the amplitude corrected signal are plotted in Fig. 3. Upon arrival of the normal wave, fringes are produced in the Θ^- VSDI channel. A significant frequency increase is observed after arrival of the shear wave in accordance with Eq. (3). The normal velocity exhibits a jump in velocity to a level of approximately 0.05 mm/μs followed by a reduction and increase in velocity due to wave reverberations in the thin polymer layer used in the multi-plate flyer. An approximately constant velocity of 0.095 mm/μs is monitored in the next 1.8 μs, which is in agreement with the elastic prediction.

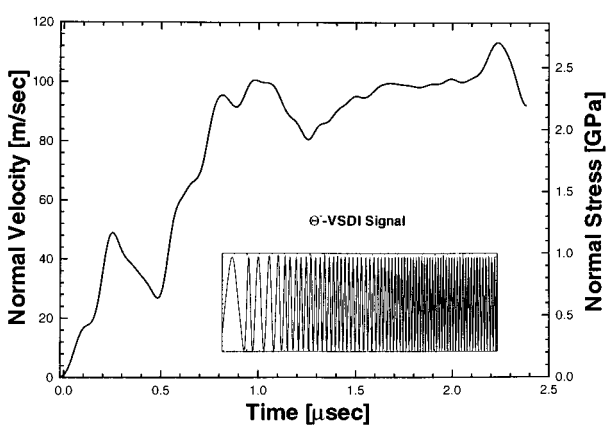

FIG. 3. Normal velocity–time profile from pressure-shear recovery experiment. The plotted time is after arrival of normal wave to the steel target plate back surface.

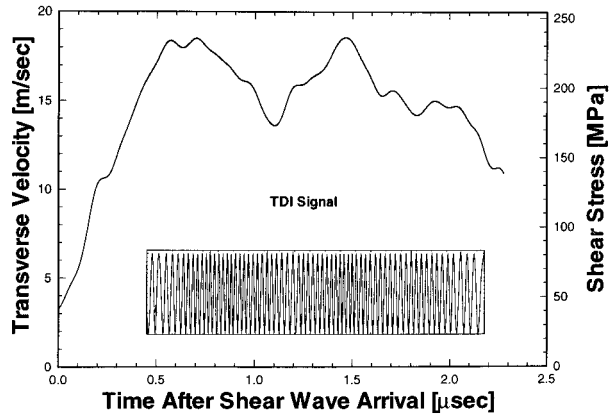

FIG. 4. Transverse velocity–time profile from pressure-shear recovery experiment. The plotted time is after arrival of shear wave to the steel target plate back surface.

The transverse velocity history together with the amplitude corrected TDI signal are shown in Fig. 4. The transverse particle velocity progressively increases to a maximum value of about 0.019 mm/μs corresponding to a shear stress of 240 MPa. In high strain rate pressure-shear experiments, the recorded velocity at the target free surface can be used in the calculation of stresses, at the target-specimen interface, using the method of characteristics. In these calculations, a state of one-dimensional elastic strain is assumed (see Espinosa and Clifton[9]).

In conclusion, we have presented a novel variable sensitivity displacement interferometer obtained by interfering a normally reflected beam with a beam diffracted at an angle θ with respect to the specimen normal. A wide range of sensitivites can be obtained by changing the angle between the two beams. In principle, the VSDI interferometer presented here can be used in wave propagation experiments conducted on metallic and nonmetallic materials in a variety of impact configurations including those in which an optical window is employed. It appears that the VSDI exhibits promise as a new tool for monitoring particle displacements in wave propagation experiments, at room and high temperatures, particularly within the previously noted normal velocity range spanning 0.1–0.3 mm/μs. It should be noted that the variable sensitivity feature of the VSDI system allows the recording of normal velocities in excess of 0.3 mm/μs without requirements of ultrafast oscilloscopes or expensive optical components.

[1] L. M. Barker, Exp. Mech. **12**, 209 (1992).
[2] L. M. Barker and R. E. Hollenbach, J. Appl. Phys. **43**, 4669 (1972).
[3] R. J. Clifton, J. Appl. Phys. **41**, 5335 (1970).
[4] K-S. Kim, R. J. Clifton, and P. Kumar, J. Appl. Phys. **48**, 4132 (1977).
[5] L. C. Chhabildas, H. J. Sutherland, and J. R. Asay, J. Appl. Phys. **50**, 5196 (1979).
[6] A. Cand, J.-P. Monchalin, and X. Jia, Appl. Phys. Lett. **64**, 414 (1994).
[7] W. F. Smith, *Structures and Properties of Engineering Alloys*, 2nd ed. (McGraw-Hill, New York, 1993).
[8] H. D. Espinosa, G. Emore, and Y. Xu, ASME Winter Annual Meeting, San Francisco, 1995 (unpublished), AD Vol. 48, p. 7.
[9] H. D. Espinosa and R. J. Clifton, ASME Winter Annual Meeting, Altanta, Georgia, 1991 (unpublished), pp. 37–56.