A Variable Sensitivity Displacement Interferometer With Application to Wave Propagation Experiments

The present paper introduces a variable sensitivity displacement interferometer (VSDI) used to monitor both normal and in-plane particle displacements in wave propagation experiments. 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 may be achieved through a linear combination of the two VSDI records. Alternatively, it is always possible to decouple the components of motion by combining a VSDI record with an independent measurement of either component. Moreover, it is shown that in the case of pure normal motion, the VSDI system functions as a desensitized normal displacement interferometer (DNDI). Similarly, in situations involving purely in-plane motion, the VSDI is shown to function as a desensitized transverse displacement interferometer (DTDI). The DNDI and DTDI fringe sensitivities are in general shown to depend on the angle θ or equivalently, the frequency σ of a grating manufactured at the observation point and the order n of the diffracted beams. The variable sensitivity feature of the VSDI greatly desensitizes normal displacement measurements and is particularly well suited for wave propagation studies in which normal particle velocities in excess of 100 m/s are generated. Experimental results are presented which demonstrate the application of this technique to monitoring particle motion histories in plate impact recovery experiments.

1 Introduction

Laser interferometry has proven to be a highly reliable and accurate means for measuring particle motion in wave propagation experiments. Particle velocity histories were initially monitored in wave propagation experiments by means of a Normal Velocity Interferometer (NVI) developed by Barker and Hollenbach in 1965. In this technique, normally reflected laser light is collected and split into two separate beams which are subsequently interfered after traveling through different path lengths. The interferometer’s sensitivity is a function of the delay time between the interfering beams, and the resulting fringe signal is related directly to changes in the normal particle velocity.

In 1972 Barker and Hollenbach introduced a significantly improved NVI system termed VISAR (velocity interferometer for any reflecting surface). The VISAR was developed by using the wide angle Michelson interferometer (WAM) concept, resulting in an interferometer capable of velocity measurements from either a speculally or diffusely reflecting specimen surface. Another improvement incorporated into the VISAR was the simultaneous monitoring of two fringe signals 90 deg out-of-phase. Quadrature coding is obtained by adding an eight-wave retardation plate and two polarizing beam splitters. It eliminates ambiguity in the sign of the acceleration and improves accuracy when data reduction is performed using the high resolution regions of the traces. In most VISAR systems, three signals are recorded, the two quadrature optical signals obtained from horizontally and vertically polarized components of light that differ in phase because of the retardation plate, plus the intensity monitoring signal used in data reduction. However, higher signal-to-noise ratios can be obtained by substituting the two s-polarized beams and the two p-polarized beams, both pairs 180 deg out-of-phase (Hemsming, 1978). This feature known as push-pull significantly reduces the noise introduced by incoherent light entering the interferometer. The VISAR has been successfully used to monitor normal particle velocity histories in shock wave experiments for over two decades and remains a principal tool of the field.

Another laser interferometer to emerge in that decade was the LDV or (Laser Doppler Velocimeter) developed by Sullivan et al., in 1974. The LDV can be used to monitor in-plane motion but does not lend itself to the simultaneous monitoring of normal motion. The need to measure both normal and in-plane displacements prompted the development of the TDI (transverse displacement interferometer) by Kim et al. in 1977. The TDI takes advantage of diffracted laser beams generated by a grating deposited or etched onto the specimen rear surface. In this technique, the 0th-order reflected beam is used to monitor longitudinal motion in a conventional way by means of an NVI, or NDI (normal displacement interferometer) while any pair of n-th-order symmetrically diffracted beams may be interfered to obtain a direct measure of the transverse particle displacement history. The sensitivity of the TDI is given by 1/2n σ [mm/fringe] where σ is the grating frequency and n represents the order of the interfering diffracted beams.
In 1979, Chhabildas et al. presented an alternative interferometric technique particularly suited for monitoring in-plane particle velocities in shock wave experiments. The technique employs two VISARs which monitor specific diffracted laser beams from a target surface. Since one or both of the resulting signals contains a linear combination of the normal and in-plane components of surface motion, it is always possible to decouple the transverse velocity from the normal velocity through a linear combination of the two fringe records.

Both techniques, the two VISAR and the NDI-TDI, have advantages and disadvantages. The combined NDI-TDI system has a much better resolution at low velocities, but requires the deposition of grids on the free surface of the target plate. On the other hand, the two VISAR technique provides velocity profiles directly without the need to differentiate displacement profiles. Although the two VISAR technique is simpler to use when optical windows are needed, it was shown by Espinosa (1996) that a combined NVI-TDI with window interferometer is feasible. In contrast to the embedded electromagnetic gauge technique to measure velocity histories, both of these interferometers can be applied to a wide variety of materials, metallic or nonmetallic. Moreover, the noncontact feature of the measurement system makes these techniques ideal for high-temperature studies of materials.

A common feature of all interferometers discussed in this section is that successful signal acquisition requires good fringe contrast during the time of the experiment. Contrast loss arises from two main causes, interferometer imperfections and target motion (displacement and tilt). These losses can be in general time varying. For instance, a beamsplitter that does not split light equally will produce a constant loss of contrast, while unevenly curved surfaces will produce a variable contrast change as a function of the light path in the interferometer. Target rotations that change the light path can be very detrimental to most interferometers. In this respect, interferometers that use scatter light from the target and fiber optics to transfer the laser light will minimize the loss in fringe contrast because the light path in the interferometer is fixed. Furthermore, even target rotations of a few milliradians will not result in signal loss in such systems. By contrast, standard interferometer set ups, without fiber optics, require tilts smaller than 1 milliradian to avoid a change in the light path that can offset the beam from the optical components of the interferometer. This feature is particularly relevant in Two-Dimensional and Three-Dimensional wave propagation problems, e.g., penetration experiments, in which significant surface rotations are expected at diagnostic points. Recently, Barker developed a VISAR with these features (Valyn VISAR User's Handbook, 1995).

2 Motivation

Need for a Desensitized Normal Displacement Interferometer. The development of the normal velocity interferometer (NVI) was motivated by the relatively small range of velocities that can be measured by the normal displacement interferometer (NDI). The latter interferometer is a derivative of the original Michelson interferometer in which a light beam reflected from a moving target is interfered at a beamsplitter with a stationary reference beam. The sensitivity of the NDI is given by λ/2 [mm/fringe] where λ represents the laser light wavelength. Multibeam NDI systems (Mello et al., 1991) have been successfully employed in the recording of normal displacements in impact soft-recovery experiments performed on ceramic composites (Espinosa and Clifton, 1991). The experimental configuration and the stress-time history at the specimen-momentum trap interface are given in Espinosa and Clifton (1991). The important feature to be noted in their stress histories is that the displacement interferometer can resolve slow changes in velocity with very high accuracy and hence provide very valuable information for damage identification. 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.

The "velocity limit" for such an interferometer may be approximated by \( V_{max} = \lambda/2 f_{max} \) where \( f \) represents the frequency cutoff of the light detection system. The velocity limitation is best illustrated by considering a fast light-detection system (photodetector, amplifier, shielded BNC cables, and a 2 G/s digital storage oscilloscope) possessing a system 3 db analog frequency response of 400 MHz. Such a system is reasonable to consider in light of recent advances in the electronics industry and is representative of present day systems having large storage capacity. Next, consider an interferometer signal having 1 400 MHz frequency component generated by a particle velocity of 0.103 mm/\( \mu \)sec at the target surface. It is clear that a 400 MHz signal falls well within the bounds established by the Nyquist sampling theorem and that such a signal sampled at 2 G/s is deemed fully reconstructible. Observe, however, that a 400 MHz fringe when sampled at 2 G/s will at most be represented by only five bits of data. In light of system noise and undesirable amplitude fluctuations, it would be difficult to extract displacement information beyond this frequency even after applying filters and correcting for amplitude variations. It, therefore, seems reasonable to regard a particle velocity of 0.1 mm/\( \mu \)sec as an upper bound for the NDI in wave propagation experiments. Studies of damage and inelasticity in materials may at times require much higher particle velocities making quite impractical the use of normal displacement interferometers having such a high fixed level of sensitivity.

A normal velocity interferometer (NVI) or a VISAR on the other hand, has a variable sensitivity given by \( \lambda/(2(1+\delta)) \) [mm/\( \mu \)s/fringe] whereby \( \tau \) 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. A quite appealing feature of this interferometer is that the fringe record is a direct measure of particle velocity, thereby alleviating the need for differentiation of the reduced signal. Moreover, signal frequencies generated by an NVI are proportional to particle acceleration and are therefore lower than equivalent signal frequencies generated by an NDI. However, during an initial time period \( \tau \), an NVI is functioning as an NDI since the delayed light arriving at the detector from the delay leg or etalon is reflected from a stationary target (Clifton, 1970). Ironically, it is the interpretation of the NVI in the interval where it operates as an NDI that limits the usefulness of the NVI in the low-velocity range (0.1–0.25 mm/\( \mu \)sec). In this velocity range, values of \( \tau \) in the neighborhood of 5 nsec or more are required in order to obtain records with at least three or four fringes. This in turn leads to a greater averaging of the velocity measurements. Furthermore, elastic precursors causing velocity jumps of more than 0.1 mm/\( \mu \)sec in a time less than \( \tau \) cannot be detected because the early time NDI signal frequency may exceed the frequency response of the light detection system. This feature is described as lost fringes in the Valyn VISAR User's Handbook (1995).

Clearly, the NDI and VISAR principles described above indicate that there is a velocity range between 0.1–0.25 mm/\( \mu \)sec over which particle velocities may not be measured with the desired accuracy. Barker and Hollenbach (1972), have investigated the accuracy of the VISAR experimentally. They found that measurements with two percent accuracy can be obtained when a delay time of approximately 1 nsec corresponding to a velocity per fringe constant equal to 0.2 mm/\( \mu \)sec is used. Certainly, velocities below 0.2 mm/\( \mu \)sec can be measured, but the uncertainty of the measurement increases because only a fraction of a fringe is recorded. In this case, signals in quadrature have to be recorded immediately before the experiment and assume the amplitude remains the same during the experiment (Valyn VISAR Data Reduction Program, 1995). It should be
pointed that the VISAR data reduction is very sensitive to the position and shape of the Lissajous, Valyn VISAR Data Reduction Program (1995). In both interferometers it might appear that sophisticated light detection systems having several GHz of bandwidth are required. Such systems, although currently attainable, remain for the most part prohibitively expensive.

The particle velocity limitation is particularly relevant in the case of soft recovery experiments (Kumar and Clifton, 1979; Espinosa, 1992, 1996) in which impact velocities below 0.2 mm/μs are utilized. In these experiments, damage (microcracking, interfacial failure) and inelasticity (plasticity, phase transformations) are identified based on the recorded velocity histories and on microscopy studies of the recovered samples. It is clear that information about the early stages of inelasticity is contained in the first few nanoseconds of the velocity signal. Furthermore, velocity jumps occurring within a few nanoseconds may result from inelastic and failure events. Therefore, if the information is not captured, the experiment is only partially successful.

The variable sensitivity displacement interferometer (VSDI) presented here has been designed to overcome the inherent high-frequency requirement of the NDI and VISAR within the noted velocity range of interest. Furthermore, it does not require the utilization of very expensive optical components and oscilloscopes. The sensitivity of such an interferometer is fully variable; thus, it can be adjusted to operate over a wide range of particle velocities without exceeding the frequency response of the light detection system.

3 VSDI Theory

To derive the governing equation for a variable sensitivity displacement interferometer, consider Fig. 1 in which a normally incident laser beam impinges on the rear free surface of a target plate. Diffraction beams are generated by a diffraction grating either written into a layer of photoreact or directly etched into a metallic coating. High-quality photoreacts are now available which make it quite feasible to write holographic phase gratings of 600–1600 lines/mm with high diffraction efficiencies. Furthermore, “lithographic techniques” may also be applied to photoreact gratings which yield etched gratings on metallic coatings (Espinosa, 1992). Such gratings, although more difficult to produce, are more durable than photoreact gratings and can be used in severe environments such as elevated temperatures. Alternatively, the specimen rear surface may be preferentially roughened in which case light will be scattered back in all directions. In the latter case, light may be

\[ d \sin \theta = n \lambda \quad n = \pm 1, 2, 3, \ldots \]  

(1)

where \( d \) is the grating period, \( n \) is the beam order, and \( \lambda \) is the wavelength of the laser source.

The target free surface may undergo only normal motion as depicted in Fig. 1(a), or it may have combined normal and in-plane motion as in Fig. 1(b). Far from the target surface, e.g., at the photodetector, the reflected and diffracted beams can be represented as plane waves, i.e.,

\[
E^0(r, t) = A^0 e^{i[kl^0 - \omega t - \Phi^0(t)]} \\
E^\pm(r, t) = A^\pm e^{i[kl^\pm - \omega t - \Phi^\pm(t)]} \\
E^\mp(r, t) = A^\mp e^{i[kl^\mp - \omega t - \Phi^\mp(t)]} 
\]

(2)

where \( k = 2\pi/\lambda \) is the wave number, \( \omega \) is the angular frequency, and \( l^\pm, l^\mp \) 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; \( A^\pm \) and \( A^0 \) are vector quantities which characterize the amplitude and polarization of the diffracted and reflected light beams, respectively. The functions \( \Phi^0, \Phi^+, \Phi^- \), are the phase terms which are related to the target free surface motion by

\[
\Phi^0(t) = 2kU\left(t - \frac{l^0}{c}\right) + \phi^0 \\
\Phi^+(t) = k\left[U\left(t - \frac{l^+}{c}\right)(1 + \cos \theta^+\right] + V\left(t - \frac{l^+}{c}\right) \sin \theta^+ + \phi^+ \\
\Phi^-(t) = k\left[U\left(t - \frac{l^-}{c}\right)(1 + \cos \theta^-\right] - V\left(t - \frac{l^-}{c}\right) \sin \theta^- + \phi^- 
\]

(3)

where \( U(t) \) and \( V(t) \) represent the normal and in-plane displacements of the point of observation from its position at time \( t = 0 \), and where \( \phi^0, \phi^+, \phi^- \) represent constant arbitrary phase terms.

Next, consider the effect of interfering the normally reflected beam with a beam diffracted at an angle \( \theta^\pm \) with respect to the specimen normal as shown in Fig. 2. The normally reflected beam is split at beamsplitter BS1. Each half of the normal beam is then made to interfere with one of the diffracted beams via beamsplitters 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 is

\[
E^\pm(r, t) = E^0(r, t) + E^\pm(r, t) \]

(4)

from which the time-averaged intensity relation

\[
I(t) = E^\pm(r, t)E^{\pm*}(r, t) \]

leads directly to a classical interference expression of the form

\[
I(t) = I^0 + I^\pm + 2\sqrt{(I^0I^\pm)} \cos \beta \cos \Psi^\pm(t) 
\]

(5)

(6)

Here, \( I^0 \) and \( I^\pm \) represent the time-averaged intensities of the respective contributing light fields, and \( \beta \) is the angle between their respective polarization vectors. Normal and transverse par-
VARIABLE SENSITIVITY DISPLACEMENT INTERFEROMETER (VSDI)

![Diagram of VSDI system]

Fig. 2 Optical layout of VSDI system. The \( \Theta^\pm \) VSDI system is obtained by combining a normally reflected beam and a diffracted beam at an angle \( \theta^\pm \).

Particle motion introduce frequency modulation through the time-varying phase term

\[
\Psi^\pm(t) = \frac{2\pi}{\lambda} \left[ 2U(t - \frac{\theta^\pm}{c}) - U(t - \frac{\theta^\pm}{c}) (1 + \cos \theta^\pm) \right]
\]

\[
+ V \left( t - \frac{\theta^\pm}{c} \right) \sin \theta^\pm + (l^2 - l^\pm) \right] + \phi^\delta - \phi^\pm. \quad (7)
\]

Observe that the transverse motion phase term is subtracted for the case where the \( \theta^+ \) beam is employed and otherwise added when interfering with the \( \theta^- \) beam. Next, setting \( l^0 = l^+ = l^- \) and \( \theta^+ = \theta^- = \theta \) leads to a more simplified and useful form, i.e.,

\[
\Psi^\pm(t) = \frac{2\pi}{\lambda} \left[ U \left( t - \frac{l}{c} \right) (1 - \cos \theta) \right]
\]

\[
+ V \left( t - \frac{l}{c} \right) \sin \theta \right] + \phi^\delta - \phi^\pm. \quad (8)
\]

Equation (8) shows that each VSDI system will generate a different signal frequency when used to monitor the same given combined state of motion. This effect is confirmed in pressure shear experiments at the time corresponding to the arrival of the shear wave at the target rear surface. Initially, each VSDI system functions as a desensitized normal displacement interferometer (NDNI) having a fringe sensitivity \( \lambda/(1 - \cos \theta) \), see derivation of Eq. (10) below. With the delayed arrival of the shear wave, the signal now represents a linear combination of the two motion components. Consequently, the signal frequency is altered as indicated by Eq. (8) and each VSDI system exhibits a sudden increase or decrease depending upon whether the \( \theta^+ \) or \( \theta^- \) beam is being interfered.

Case of Purely Normal Motion: (NDNI). For \( V(t) = 0 \), a full fringe shift associated with a normal displacement \( \delta U \) satisfies

\[
\Delta \Psi(t) = \frac{2\pi}{\lambda} \left[ \delta U(t - l/c) \right] (1 - \cos \theta) = 2\pi. \quad (9)
\]

Rearrangement of this expression and use of Eq. (1) gives the fringe constant relation

\[
\frac{\text{normal displacement}}{\text{fringe}} = \frac{\lambda}{1 - \cos \theta}
\]

\[
= \frac{\lambda}{1 - \sqrt{1 - (n\lambda \sigma)^2}} \quad (10)
\]

where \( \sigma = 1/d \) represents the frequency of the diffraction grating and \( \theta \) is used for \( \theta^\pm \) since both the \( \Theta^+ \) and \( \Theta^- \) VSDI systems will function as identical desensitized normal displacement interferometers. The effect of \( \theta \) (or equivalently the grating frequency \( \sigma \)) on the interferometer's sensitivity is summarized in Fig. 3. The fringe constant varies from infinity at \( \theta = 0 \) deg to \( \lambda \) [mm/fringe] at \( \theta = 90 \) deg. As an example, using the second-order beam from a diffraction grating with \( \sigma = 600 \) lines/mm, the DNI is found to have a fringe constant of 4.697\( \lambda \); for light of wavelength \( \lambda = 514.5 \) nm the fringe constant is 2.4 \( \mu \)m/fringe, which is nearly an order of magnitude less sensitive than that of a conventional NDI which has a fringe
constant of 0.2572 μm/fringe. Frequencies will likewise be reduced by an order of magnitude, thereby extending the applicability of the normal displacement interferometer to wave propagation experiments in which particle velocities in excess of 0.1 mm/μs are generated.

**Case of Purely In-Plane Motion: (DTDI).** Referring to Eq. (8), we may consider the case where \( U(t) = 0 \), i.e., the case of pure in-plane motion. In this case, the variable phase is

\[
\Psi(t) = 2\pi \left[ \mp V \left( t - \frac{l}{c} \right) \sin \theta \pm \right] + \phi^\pm - \phi^\pm
\]

and the \( \Theta^+ \) and \( \Theta^- \) VSDI systems now act as identical transverse displacement interferometers. A full fringe shift associated with a transverse displacement \( \delta V \) corresponds to

\[
\delta \Psi(t) = 2\pi \left[ \frac{\delta V \left( t - \frac{l}{c} \right) \sin \theta}{\lambda} \right] = 2\pi
\]

which may be rearranged and combined with Eq. (1) to give the fringe constant relation

\[
\text{transverse displacement} = \frac{\lambda}{\sin \theta} = \frac{\Lambda}{\sigma_n}
\]

The DTDI sensitivity ranges from a complete loss of sensitivity at \( \theta = 0 \) deg to a theoretical sensitivity limit of \( \lambda / \text{mm/fringe} \) at \( \theta = 90 \) deg (see Fig. 4). 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).

**Case of Combined Normal and In-Plane Motions (VSDI System).** When the material point exhibits both normal and in-plane components of displacement, for instance, in pressure-shear experiments or in normal impact experiments of anisotropic crystals, frequency modulation results through a linear combination of both motion components as dictated by Eq. (8). Decoupling of the normal motion component \( U(t) \) from the in-plane component \( V(t) \) is obtained through one of two possible schemes. Both schemes involve the simultaneous application of two interferometers and the use of Eq. (8) to decouple the two components of motion. In the first option, two VSDI systems are employed. The normally reflected beam is split into two beams, one of which interferes with the \( \Theta^+ \) beam to form the \( \Theta^+ \) VSDI system and a second one which is made to interfere with the \( \Theta^- \) beam to form the \( \Theta^- \) VSDI system. The two resulting signals may then be linearly combined through use of Eq. (8) to solve for the longitudinal motion \( U(t) \) and the transverse motion \( V(t) \), respectively. Addition of the phase terms of the \( \Theta^+ \) and \( \Theta^- \) VSDI signals provides an expression for a new phase term associated solely with a normal displacement \( U \) given by

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

Hence, the fringe constant relation of this new signal is

\[
\frac{\text{normal displacement}}{\text{fringe}} = \frac{\lambda}{2(1 - \cos \theta)}.
\]

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 \( \Theta^+ \) and \( \Theta^- \) VSDI signals, an expression for a phase term associated solely with an in-plane motion \( V \) is obtained, viz.,

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

The fringe constant of this new signal is given by

\[
\frac{\text{transverse displacement}}{\text{fringe}} = \frac{\lambda}{2 \sin \theta}.
\]

This sensitivity is the same as the one exhibit by the transverse displacement interferometer (TDI, Kim et al., 1977). 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.

It is conceivable, however, that in some cases frequency limitations may render this option impractical. This might be the case if the “combined motion” signal frequency associated with the \( \Theta^- \) VSDI system suddenly exceeds the frequency response of the light detection system. Yet another possibility might involve the “combined signal” frequency associated with the \( \Theta^+ \) VSDI system, suddenly decreasing to the point where too few fringes are counted thereby rendering the measurement too insensitive. Clearly then, the decision to employ the dual VSDI arrangement in a pressure-shear experiment should be based upon some a priori knowledge of the frequency range that will be spanned.

In cases where the dual VSDI arrangement is ruled out due to frequency considerations, it is always possible to independently monitor one of the motion components through the simultaneous employment of an alternative technique. For example, the corresponding transverse displacement history \( V(t) \) may be obtained through the employment of a transverse displacement interferometer (TDI). In this technique, the transverse displacement history is obtained by interfering two symmetrically diffracted laser beams. It was shown by Kim et al., 1977, that if the path lengths \( l^+ \) and \( l^- \) of the diffracted beams are kept equal, then the resulting fringe record remains unaffected by the presence of normal motion and is solely a measure of the in-plane displacement. The transverse displacement history \( V(t) \) determined in this way can be combined with a VSDI record to decouple the normal displacement \( U(t) \) through the use of Eq. (8). For instance, by subtracting the time-varying phases of a \( \Theta^- \) VSDI system and a TDI system we obtain an expression

![Fig. 4 DTDI and TDI sensitivities as a function of diffraction angle](image-url)
for a phase term associated solely with the normal displacement $U(t)$, namely,

$$2\Psi(t)_{\phi_{\text{VSDI}}} - \Psi(t)_{\phi_{\text{TDI}}}$

$$= \frac{4\pi}{\lambda} \frac{U(t)}{c} \left[ 1 - \frac{1}{c} (1 - \cos \theta) \right] \phi_{\text{VSDI}}.$$

This equation shows once more that the normal motion can be recorded with the sensitivity given by Eq. (15). The in-plane motion $V$ can be directly obtained from the TDI signal.

4 VSDI Applied to Pressure-Shear Recovery Experiments

In this section we examine the applicability of the VSDI system to pressure-shear soft-recovery experiments (Espinosa, 1992, 1996; Yadav et al., 1993). This experiment is particularly suitable to investigate the usefulness of the variable sensitivity displacement interferometer (VSDI) because it requires the measurement of both normal and in-plane motions. The configuration is shown in Fig. 5(a). Compression-shear loading is accomplished by inclining the flyer and target plates with respect to the axis of the projectile. By varying the angle of inclination a variety of loading states can be obtained.

Pressure-shear recovery experiments offer several advantages over other experimental techniques in the study of damage and inelasticity in metals, ceramics, and composite materials. The stress amplitudes and deformation rates obtained in these experiments allow the identification of microcracking and shear localization. Furthermore, the information obtained from these experiments is substantially increased by correlation of real-time velocity profiles and microstructural features associated with the mechanisms of inelasticity and damage.

The principal difficulties of the pressure-shear recovery experiment are thought to be (1) simultaneous trapping of the longitudinal and shear momentum by a back plate, and (2) satisfactory mitigation of radial release waves at the stress levels and pulse durations required in these experimental studies. Such mitigation can be accomplished by means of a star-shaped flyer design (Espinosa et al., 1992). A design that meets the first requirement is obtained by means of a multiplate flyer. Such a flyer consists of a thin film made of material with very low shear flow stress, e.g., a polymer, sandwiched between two thicker hard plates. The selection of given materials for the flyer plates is a function of the application. As in the case of the normal soft-recovery experiment, and for the same reasons, the flyer plate is backed by a low impedance material and the projectile is stopped by an anvil.

The elastic wave fronts for a plane wave analysis of a pressure-shear recovery friction experiment are given in a Lagrangian $x$-$t$ diagram in Fig. 5(b). At impact, plane compression waves and shear waves are produced in both the impactor and the target. Since the shear wave velocity is approximately half the longitudinal wave velocity, a thin film with very low shear resistance needs to be added to the flyer plate such that the arrival of the unloading shear wave to the impact surface precedes the arrival of the unloading longitudinal wave generated at the back surface of the second flyer plate. Certainly, the thickness of the target plate must be selected so that the arrival of longitudinal unloading to the impact surface, from the target back surface, does not prevent the transfer of the main shear pulse to the target plate. It should be noted that a residual shear wave remains trapped into the flyer plate for two reasons: (1) the small but finite shear resistance of the thin film, and (2) the possibility of interfacial sliding in the case of friction experiments.

Due to mismatch in impedances between the thin film and the bounding plates, a few reverberations within the polymer film are required for the achievement of the normal stress imposed at the impact face. This feature imposes another requirement in the design and manufacturing of the thin polymer film. The thickness of the thin film needs to be minimized such that the time required to achieve a homogeneous state is only a small fraction of a microsecond. We have manufactured such a multiplate flyer by bonding two hard plates with a uniform 1- $\mu$m-thick polymer layer (photoresist AZ 1350J-HOECHST CELANSE). We have observed that the uniformity of the thin film prevents tilt between the flyer plates which would otherwise perturb the interferometric measurements.

A pressure-shear recovery friction experiment was performed in a 3.0-in. gas gun at Purdue University to test the new interferometer. A combined $\Theta$ VSDI-TDI system was utilized to monitor the normal and transverse velocities at the target free surface. The target rear surface was polished and then a thin layer of photoresist was deposited using a spinning machine. A holographic phase grating was created by interference of two laser beams. The angle between the beams was selected such that a sinusoidal profile with 600 lines/mm was obtained. The zero-order reflected beam was combined with the negative first-order diffracted beam to produce a $\Theta$ VSDI. A TDI interferometer was obtained by mixing the two first-order diffracted beams.

The multiplate impactor and target plates were made of 4340 steel. The plate surfaces were mirror-polished to examine friction and wear in the recovered samples. 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 deg. An aluminum back with two rubber O-rings was mounted in the rear end of the tube to seal the wrap-around breech. A key was mounted on the middle of the fiber glass tube to prevent rotation of the projectile. The projectile velocity was measured, just before impact, by recording the times of contact of four wire pins placed in the path of the projectile.

Plates 2.25 inches in diameter were chosen to maximize the arrival time of the first unloading wave, from the plate periphery to the displacement recording point. The two steel plates used as multiplate impactor were 2.68 and 3.25 mm thick, respect-
tively. The target plate was 6.99 mm thick. The plates were lapped flat using a lapping machine and 15 μm alumina powder. A flatness better than three rings was measured by means of a Newton interferometer.

After the target plate was mounted in a holder ring, it was aligned to the impactor surface within 0.5 milliradians using an optical technique developed by Kumar and Clifton (1977). In order to check the angle of misalignment at impact, the times of contact at four voltage-biased pins were recorded. Through a logical circuit, contact of the four pins gave four voltage steps, in the ratio of 1:2:4:8, which were recorded in an oscilloscope. A tilt of 1.7 × 10^{-7} radians was measured in the experiment.

The signals produced by the combined Θ^- VSDI-TDI system, recorded in a Tektronix DSA 602A oscilloscope, are plotted in Figs. 6(a) and 6(b). 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. (8). The TDI trace (see Fig. 6(b)) shows an initially strong fringe contrast. A contrast reduction follows probably due to a change in intensity in the diffracted beams caused by the grating motion and/or target tilt. 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 Eq. (18). To eliminate electronic noise, the interference fringes were filtered using a Fast-Fourier Transform method and a cut-off frequency higher than the maximum fringe frequency. Furthermore, since the signal amplitude does not contain displacement information, it is customary to scale the signal to a constant amplitude prior to the displacement calculation. Hence, the filtered fringes were then scaled to obtain uniform fringe amplitude. Based on the displacement interferometer principles, one can assume that the interferometer signal consists of fringes in a sine-like function of voltage versus time, e.g., y(t) = a(t) \sin(f(t)) + b(t), where a(t) is the amplitude, b(t) is the zero offset, and f(t) is the phase function. In general, a(t) and b(t) are not constant. They can be evaluated by finding the envelopes, h(t) and l(t), formed by peaks and valleys, respectively. These functions are given by a(t) = 0.5(h(t) - l(t)) and b(t) = 0.5(h(t) + l(t)) (Tong, 1991). The amplitude corrected signal, y_0(t), is then determined by y_0(t) = (y(t) - b(t))/a(t). The signal phase function can be obtained from f(t) = arcsin(y_0(t)). Then the displacement can be computed from d(t) = d_0f(t)/2π. The constant d_0 is a function of the interferometer and is defined by Eqs. (15) and (17) for the VSDI and TDI systems, respectively. Velocities were obtained by differentiating the displacement histories numerically. All the calculations were automatically performed with MATLAB. The functions MENU, GINPUT, INPUT, and STRCMP were used to input the data files. The functions FFR1 and FFTFILT were used to perform the fast Fourier transform filtering. The function INTERP1 was employed to fit the peaks and valleys with cubic splines. The function GRADIENT was utilized to perform the numerical differentiation.

In Fig. 7, the normal free surface velocity history is plotted together with the Θ^- VSDI amplitude corrected signal. Upon arrival of the longitudinal wave to the target free surface, the normal velocity exhibits an increase in velocity to a level.
of approximately 80 m/sec followed by a reduction and increase in velocity due to wave reverberations in the thin polymer layer used in the multiplate flyer. A few bumps are observed in the first 900 nanoseconds of the normal velocity history. These variations in normal velocity are likely the result of the low signal to noise ratio in the early part of the record (see Fig. 6(a)). They are also in part due to errors in data reduction arising from the insensitivity of the displacement interferometer at the peaks and valleys of the trace (Espinosa and Clifton, 1991). Experience suggests that signals with higher frequency are less sensitive to errors caused by signal noise. The noise level can be observed in the part of the record preceding the longitudinal wave arrival. In later experiments we have increased the angle $\theta$ used in the $\Theta^{-}$ VSDI with good results. An approximately constant velocity of 115 m/sec is monitored in the next 1.8 $\mu$s which is in agreement with the elastic prediction. It should be noted that this normal velocity would lead to a frequency of 450 MHz in an NDI, while in the VSDI system a much smaller frequency is recorded.

In Fig. 8 the transverse velocity history and the TDI amplitude corrected signal are shown. A transverse velocity well below the impact shear velocity is measured indicating interface sliding. Small fluctuations in the transverse velocity are due in part to errors in data reduction arising from the insensitivity of the TDI at the peaks and valleys of the trace (Espinosa and Clifton, 1991). An in-plane wave release is observed at approximately two microseconds. This wave release is in agreement with the wave release predicted by one-dimensional elastic wave theory. It should be noted that the reduction in in-plane motion is progressive. A residual transverse velocity of 5 m/sec is recorded likely due to the shear resistance of the thin polymer film used in the multiplate flyer. Modeling of the experiment including the frictional behavior of the steel interface, and the nonlinear behavior of the polymer thin film is required to fully interpret the transverse velocity history. Further evidence on the shear wave duration can be observed in Fig. 9 in which an optical micrograph shows sliding marks, approximately 50 $\mu$m in length. From the transverse velocity history, an average sliding velocity of 26 m/sec is computed. This velocity during 2 $\mu$s leads to a sliding length of 52 $\mu$m, which correlates very well with the sliding marks observed on the micrographs.

5 Concluding Remarks

We have presented a novel variable sensitivity displacement interferometer obtained by interfering a normally reflected beam with a beam diffracted at an angle $\theta$ with respect to the specimen.
normal. A wide range of sensitivities 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 (Espinosa and Clifton, 1991). Moreover, it should be possible to extend the technique to the case where scattered light from a preferentially roughened surface is collected by three fiber optic probes: a central one for illuminating the specimen and collecting normally reflected light, and two side probes for collecting diffracted light at $\theta^\circ$. In this case, the light is transported to the interferometer through optical fibers, thereby increasing the versatility of the system. Observe that in normal impact experiments the DNDI can be combined with other interferometers, for instance a VISAR, to produce optimal velocity histories. For example, the sensitivity of the DNDI can be adjusted so that a high resolution of the elastic precursor is obtained while the measurement of very high velocities is accomplished with the VISAR system. A similar result can be obtained if two DNDI’s at different diffracted angles are utilized. Hence, it appears that the VSDI exhibits promise as a new tool for monitoring particle displacements in wave propagation experiments, particularly within the previously noted problematic velocity gap spanning 0.1–0.2 mm/\mu sec.

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References