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Technique for measuring very high surface velocities

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Abstract

An interferometric technique for measuring displacements of surfaces moving at velocities in the range of a few millimeters per microsecond is presented. The Doppler shift of frequency of light scattered from such surfaces is too high to be detectable by known devices. The present technique is based upon monitoring the signal resulting from the interference between two beams reflected from the surface at different incidence angles. Measurement systems for specularly as well as diffusely reflecting surfaces are described. Light source with very modest temporal coherence delivering about 100 mw power is required. The accuracy of the technique is discussed.

1. Introduction

Continuous measurement of surface velocities in the range of several millimiters per microsecond is a common need in studies of high explosives, shocked materials behaviour, high intensity electron beam-target interactions and other phenomena involving shock waves. In such experiments the various characteristics of the moving surface are usually not constant over a large area of the surface. Hence, a measurement of the velocity of a small area, of about 1 mm^2 is desirable. The displacements considered at such experiments are several millimeters. Interferometric measurements, using visible light, usually make possible a continuous and precise monitoring of the velocity of the illuminated area of the surface. However, such methods are not useful when too high velocities are considered. For example, consider a light beam, in the visible range, reflected from a surface moving with a velocity of 0.3 mm/μs. The Doppler frequency shift of such a beam is around 1 GHz. When such a beam interferes with the local oscillator, in a heterodyne receiver, an interference signal results which has the same frequency, very much near the highest signal frequency that is trackable by the known electronic devices. On the other hand, it is well known that the velocities involved in shock wave experiments are very often higher by more than one order of magnitude.

A well established device for monitoring high velocities is that based upon the velocity interferometer technique[1] . The VISAR[2] , which is a more advanced device, can also be utilized for determination of velocities of diffuse surfaces. In this method, the beam reflected from the moving surface at a time t interferes with the beam reflected at a time $t - \tau$, while τ is a time interval which is fixed prior to the measurement by choosing the length of a delay leg. From the resulting interference signal velocity changes are inferred with τ as the averaging time of the system[1] . The values of τ generally in use[2-8] are several nanoseconds.

Although the VISAR is advantageous for recording velocity changes, it does not solve the problem stated above. Surface accelerations which take place during the time interval τ and induce too high a frequency to be recorded are still not measurable. Assume that Δv_τ is a velocity change which occurs during a time interval less or equal to the delay time τ. Velocity changes which do not fulfill the requirement

$$\Delta v_\tau < 0.3 \text{ mm}/\mu\text{s} \qquad (1)$$

are not observable. Rapid velocity changes higher than this value are very common in shock wave experiments. Also, the choice of a specific value of τ for each experiment raises some difficulties in measurements of accelerations which fulfill the above criterion. In a shock wave experiment the velocity history, in many cases, includes different velocity changes at different rates. When the velocity change is relatively high a small τ is desirable, in order to increase the time resolution of the measurement and to enable a larger range of measurements according to the criterion 1. However, the smaller τ the lower the fringe count1), which consequently causes a larger error in the determination of smaller velocity changes and actually puts a lower limit for the observable velocity changes. Also, when the moving surface is diffuse, etalons should be inserted into the delay leg which practically limits the delay time τ to a low value of 1-2 nanoseconds[2].

In the work presented here a technique for monitoring the motion of surfaces at high velocities is introduced and discussed. The technique (patent protection has been applied for) is based upon the incidence of two coherent beams upon the surface at different incidence angles. The interference of the reflected beams while the surface is moving, produces a signal of a detectable frequency even if the surface velocity is very high. Both cases of specular as well as diffuse reflection by the surface are considered. The signal to noise ratio and the main errors occurring in the proposed measurements are estimated.

2. Proposed method for measuring high velocities of surfaces

The principle of the system proposed here is demonstrated in Fig. 1. Using the beam splitter b_1 and the mirror m_1 two monochromatic plane waves, emerging from a laser are brought to the point P of a surface s, the velocity v of which is being measured. The angles of incidence of the incident beams are different. For simplicity, it is assumed that one beam ℓ_1 is normally incident while the incidence angle of the other is θ. For the time being, it is also assumed that the surface s is specularly reflecting.

Suppose that the surface s moves with a velocity v parallel to the beam ℓ_1. Denoting light velocity and angular frequency by c and ω, amplitudes and phases by A's and ϕ's, respectively, the reflected plane waves are classically described by

$$A_1 e^{i((\omega+\omega_1)t+\phi_1)}$$

and

$$A_2 e^{i((\omega+\omega_2)t+\phi_2)}$$

where, ω_1 is the Doppler frequency shift of the normally incident beam, given by $\omega_1 = 2\omega \frac{v}{c}$, and $\omega_2 = 2\omega \frac{v}{c} \cdot \cos\theta$ is that of the obliquely incident beam. The reflected beam ℓ_1' is brought to the detector D by the beam splitter b_1, and the beam ℓ_2' reaches the detector with the aid of the mirror m_2 and the beam splitter b_2.

Both reflected waves interfere at the photodetector surface. Paths of the reflected beams from the surface s to the photodetector should be of equal lengths in order to prevent a time delay between the beams. The current signal produced is given by

$$I(t) = \alpha[A_1^2 + A_2^2 + 2A_1A_2\cos(\omega_1-\omega_2)t+\phi_1-\phi_2)] \qquad (2)$$

$$= \alpha[A_1^2 + A_2^2 + 2A_1A_2\cos(\omega_1(1-\cos\theta)t+\phi_1-\phi_2)],$$

implying that the signal frequency is smaller than the Doppler shift ω_1 by a factor (1-cosθ). For $\theta \sim 20°$ one obtains nearly a 20 times reduction in the interference signal frequency. The reduction in the signal frequency may be varied by varying the angle θ. Thus, when too high velocities are considered, the interference signal frequency may be reduced to a detectable value by an appropriate choice of θ. Using this principle a continuous measurement of displacements when high surface velocities are involved is achieved. Here, no averaging time needs to be fixed prior to the experiment. In order to obtain the surface velocity the averaging time at any instant can be chosen while analysing the signal I(t) on the recording film. Small variations in the current signal may be made observable by averaging over a longer time interval. Hence, smaller changes in velocity may be determined while sacrificing time resolution. For larger velocity variations averaging time may be taken smaller, thus a better time resolution is obtained. It should be noted that the reduction in the signal frequency, which results in a smaller fringe count, is chosen for each measurement according to the maximum velocity expected. The smaller the fringe count the larger the reduction of either the accuracy or the time resolution in the velocity measurement.

3. System design in the specularly reflecting surface case

It is clear from Fig. 1, that when the surface s moves, the incident point P of beam ℓ_2 shifts on the surface. This causes the reflected beam ℓ_2' to shift while remaining parallel to its initial direction. The incidence point of beam ℓ_2 on the surface s is shifted by $x tg\theta$ where x is the displacement parallel to beam ℓ_1. Apart from that, any tilt of the surface s during its motion causes a deflection of both reflected beams. In order that the interference between the beams will not be hindered by these effects, one may use lenses as suggested in Fig. 2. The beam expander C expands the laser beam to a convenient diameter. Following an adequate broadening by the beam expander C_1 the normally incident beam is focussed on the surface s and is then reflected back into lens L_1. The other beam is focussed on the surface s by lens L_2 and reflected into lens L_2'. The normally reflected beam is directed by the beam splitters b_1, b_2 and b_3 towards detectors D_1 and D_3, while the obliquely reflected beam reaches detectors D_2 and D_3 through beam splitters b_2' and b_3.

Detectors D_1 and D_2 monitor the intensities of each beam while detector D_3 measures the interference signal. In the case that the reflected intensities are not constant, monitoring the intensities of each of the interfering beams may help in evaluating phase changes smaller than 2π. Evidently, one has to ensure an adequate focal depth of the gathering lenses in order to enable a measurement over a displacement of a few millimeters. A lens of 500 mm focal length and f-number of 20 should be quite adequate. Using such lenses, a tilt of less than 2° of the reflecting surface becomes acceptable. Tilts are less than this figure in most shock experiments. The parallel shift of the obliquely incident beam is not disturbing if the lens apertures are large compared to a few millimeters.

It should be pointed out that a possible tilt of the specular surface causes an uncertainty in θ and consequently in the reduction factor $(1-\cos\theta)$ in the signal frequency. For example, if θ equals 25° and the probable tilting degree is 0.5°, the error in this factor is 4%. This would cause a 4% error in the absolute value of the velocities inferred, without affecting relative velocity measurements.

Velocity determination may be improved by adding a measurement similar to that of the velocity interferometer technique. One of the reflected beams, ℓ_1' for instance, is delayed by a time interval τ relative to the other reflected beam ℓ_2' before both beams interfere on the photosurface of an additional detector D_4. By a similar derivation to that given in ref. 4 it is easily shown that the total number of fringes $F_4(T)$ counted at detector D_4 from the beginning of the motion at $t=0$ to the time T is given by

$$F_4(T) = \frac{2}{\lambda} \int_0^{T-\tau} v(t)(1-\cos\theta)dt + 2\frac{\tau}{\lambda}\,\bar{v}_\tau(T-\frac{\tau}{2}) \qquad (3)$$

where, λ is the wavelength of light and $\bar{v}_\tau(T-\frac{\tau}{2})$ is the velocity at $T-\frac{\tau}{2}$ averaged over τ. The first term in Eq. 3 is the fringe count in detector D_3 up to the time $T-\tau$. This result should be subtracted from $F_4(t)$ to enable evaluating the velocity $\bar{v}_\tau(T-\frac{\tau}{2})$ with an accuracy similar to that of the velocity interferometer technique. Choosing a large τ improves the determination of small velocity changes. This is important since the reduction in the fringe count in detector D_3 specially degrades the accuracy in inferring small velocity changes.

4. Diffuse surface case

An illuminated diffuse surface may be treated as an assembly of random phase scattering elements$^{9)}$, separated by at least the incident light wavelength$^{10)}$. A monochromatic coherent light which is reflected by a diffuse surface produces a stationary diffraction pattern which consists of needle-like lobes projecting out of the surface$^{11,12)}$. When such a granular pattern interferes with another beam, the phase difference between both beams over the detector surface may not be well defined, and therefore interferometric measurements are not useful. However, when the receiver is operating at its diffraction limit, only one lobe is observed by the detector, so that phase coherence is preserved$^{13)}$. A usable interference signal is likely to occur when the illuminated spot diameter d_o, the light wavelength λ and the receiver f-number F fulfill the relation $d_o = 1.22\,\lambda F$ $^{13)}$.

For a diffuse surface, the lenses L_1 and L_2' in Fig. 2 may gather light from each of the two incident beams. Therefore, the signal produced at detector 3, may be of no value. To account for this deficiency the system shown in Fig.3 is suggested. Two narrow plane waves, ℓ_1 and ℓ_2, are incident on the point P of the surface. The diffusely scattered light is collected by the lens L and then directed towards the detector D by the beam splitter b and the telescope T. Whenever the diffraction limit criterion is fulfilled the lens L observes one lobe of each of the diffusely reflected beams. The incident beams are preferred to be nearly plane waves in order to prevent broadening of the illuminated spot during the surface motion.

Assume that the surface is moving with a velocity v towards the lens L and that its velocity is constant over the illuminated area of the surface. The light gathered by the lens L is Doppler shifted, with the shift being, respectively, $\omega_D = 2\omega v/c$ and $\omega v(1+\cos\theta)/c$ for light originally belongs to beam ℓ_1 and ℓ_2. The resulting signal frequency produced at the detector is $\omega_D(1-\cos\theta)/2$, a factor of two smaller than the signal frequency for the specular reflection case for the same θ.

A difficulty arises from the fact that the surface area illuminated by beam ℓ_2 shifts during the motion causing the scattering elements to be substituted by neighbouring ones. Thus, the lateral shift of the spot leads to a change of the phase of the lobe scattered towards the lens L, originating from beam ℓ_2. Hence, measurement accuracy will be degraded. For example, consider an incidence angle $\theta = 25°$ and diameter $d_o = 70\ \mu m$ for beam ℓ_2. This necessitates an f-number around 100 for the receiving lens, assuming $\lambda = 6000 \mathring{A}$. The surface area illuminated by beam ℓ_2 is replaced by a neighboring one when the surface moves about 150 µm. Since the phases of the lobes scattered from different areas are not correlated, this may result in a maximum error of one in the fringe count. The fringe number counted when such a displacement takes place is $x(1-\cos\theta)/\lambda$ which is nearly 25. Hence, for this case, the maximum resulting uncertainty is nearly 4%. The reduction factor in signal frequency here, relative to the Michelson interferometer case, is more than 20. One may demonstrate that when a smaller reduction factor is needed a larger θ is chosen which makes the error discussed above smaller. Also, a more intense light source makes the use of a higher f-number lens possible, which permits a larger illuminated spot. This, in turn reduces the error due to spot shift.

Let us consider again the system depicted in Fig. 2. Such a system fits the case of a diffuse surface too. As explained above, the dimensions of the spots projected upon the surface by the lenses L_1 and L_2 should be around 70 µm. In order to prevent significant widening of the spots with surface motion over several millimeters, the f-number of the lenses should be around 100. Spots dimensions are thus determined by the diffraction limit of the lenses. Also, the receiving lenses L_1 and L_2' should have approximately the same f-number in order to observe only one lobe of the diffused light.

When an adequate amount of light, belonging to each of the incident beams, is scattered towards the receiving lenses each of the detectors D_1 and D_2 records an interference signal, practically in the same manner as demonstrated in Fig. 3. However, when a considerable amount of the reflected light is scattered in the specular direction most of the light collected by each of the lenses L_1 and L'_2 originates from only one of the incident beams, so that an interference signal is recorded at detector D_3, and interfering waves intensities at D_1 and D_2. Evidently light intensities recorded in this case are far higher than in the case where the specular direction is not preferred. It ought to be mentioned that when the reflecting surface is diffuse the displacement measurement is not sensitive to tilt. Hence, in some experiments, it would be more appropriate to use diffuse surfaces. One may point out that in the system depicted in Fig. 2 the incident beams are convergent leading to a widening of the illuminated spot during the motion. When the reflection is diffuse this effect is disturbing, and in fact it imposes an upper limit on the measurable displacement, depending upon the receiver f-number. Again, assuming $F = 100$, a displacement of 7 mm causes the spot diameter to double its size.

5. General remarks

The minimum signal to noise ratio of the detector current signal in the measurements discussed above is estimated by assuming an isotropic scattering of the incident beams. In this case, the average power incident upon the photodetector surface, due to one of the scattered beams, assuming surface reflectivity of 1, is

$$P = P_i/8F^2 \tag{3}$$

where P_i is the power carried by the incident beam. A high speed photomultiplier may be used as a detector. Considering, firstly the noise which results only from the fluctuations of the light, the signal to noise ratio, following the formulation given by Oliver[14], is given by

$$SNR = i_1 i_2 / qB(i_1+i_2) \qquad (5)$$

where, i_1 and i_2 stand for the direct currents that would be produced at the detector by each of the interfering waves alone, q for the charge of the electron and B for the bandwidth of the receiving system. Assuming $i_1 = i_2$, one obtains

$$SNR = i_1 / 2qB \qquad (6)$$

Denoting the quantum efficiency of the detector by η one gets, using Eq. 3,

$$i_1 = \eta q \lambda P_i / 8hcF^2 \qquad (7)$$

Putting $\eta=0.1$, B=500 MHz and F=100 in these equations a SNR equal to one is achieved with a beam power P_i of slightly more than 0.2 mW. In order to attain a resolution of fractions of a fringe a SNR around 100 is needed. Thus, a laser power of at least 20 mW is necessary, when the surface is totally reflecting. The power incident on the photomultiplier using such lasers (see Eq. 4), exceeds the internal noise power, at the mentioned bandwidth, of the photomultipliers attainable today by more than 100. C.w. lasers, suitable for interferometric measurements, as well as with a pulse duration of about 10 μs, in the 1W range, are commercially available.

The temporal coherence of the light needed for the technique suggested here is likely to be relatively small, since the path lengths of the interfering waves can be made nearly equal. Therefore, available pulsed lasers producing beams of a few centimeters coherence length are suitable. It may be noted that the VISAR requires beams coherent during a time at least equal to the delay time.

Another remark which may be made is related to the fact that in most shock wave experiments the direction of motion is not reversed although velocity variations change sign. Employing the present technique, displacements are measured, thus no ambiguity in fringes counting is possible. In the VISAR this ambiguity is eliminated by polarizing the reflected beam and producing two orthogonal interference signals[2]. However, a difficulty arises from a possible rotation of the polarization of the light reflected from the surface[5].

In summary, an optical interferometric technique for measuring high velocities of surfaces is suggested. The technique should be especially useful in various shock wave experiments involving high surface velocities.

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Figure Captions

Fig. 1. Schematic diagram of the measuring arrangement for a specularly reflecting surface. L_a-laser ; b_1,b_2-beam splitters ; m_1,m_2-mirrors ; s-reflecting surface ; ℓ_1,ℓ_2-incident beams ; ℓ_1',ℓ_2'-reflected beams; θ-incidence angle of ℓ_2.

Fig. 2. Schematic diagram of an improved system for the specularly reflecting surface. C,C_1,C_2,C_2' - beam expanders ; b_1,b_2,b_2',b_3-beam splitters ; L_1,L_2,L_2'-lenses ; D_1,D_2,D_3-detectors. Other notations as in Fig. 1.

Fig. 3. Schematic diagram of the system for measuring the velocity of a diffuse surface. L_a-laser, b-beam splitter, m-mirror, L-lens, T-telescope, D-photodetector, s-diffuse surface, ℓ_1,ℓ_2-incident narrow beams,θ-incidence angle of ℓ_2, P-incidence point.

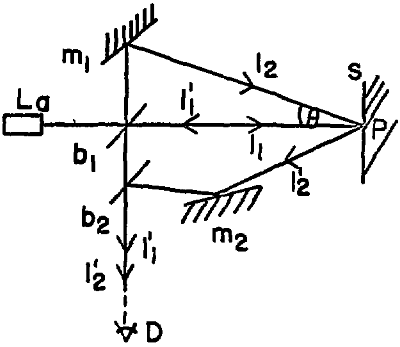

Fig. 1.

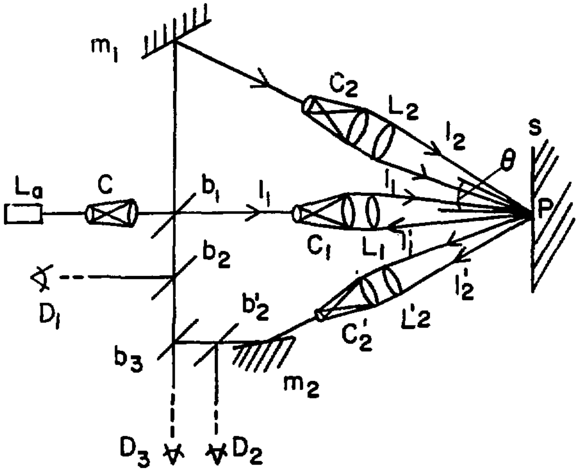

Fig. 2.

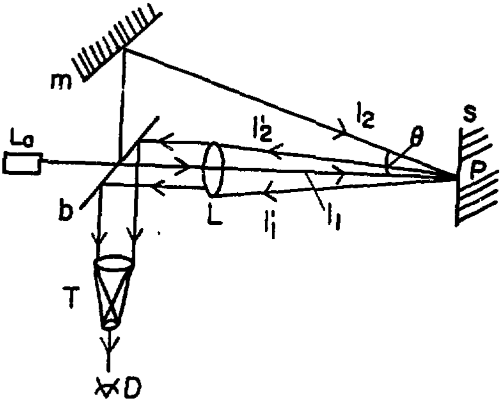

Fig. 3