REMOTE SEISMIC DETECTION BY LASER INTERFEROMETER FOR MINING GEOPHYSICS AND TUNNELING OPERATIONS

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A modified laser interferometer system is developed that makes possible the noncontact detection and analysis of dynamic displacements on remote, unprepared rock surfaces. The system is a broadband device and does not suffer from acoustic-impedance-matching problems or frequency-response problems characteristic of conventional contact transducers. The potential applications of such a system include hazard detection in mines, seeing ahead of a working face in tunneling operations, vibration-mode studies of large structures, and examination of vibrating surfaces in hostile environments.

•MANY problems in mining geophysics may be solved by employing seismic techniques. By using geophones or other contact transducers as receivers and various seismic sources, one may perform vibration analyses on rock structures, measure P- or S-wave velocity profiles, and perform experiments such as seismic holography (1, 2) to detect cavities, inclusions, or fracture zones in rock ahead of working faces or in pillars.

Contact measurements of the type described have several drawbacks. First, and most obvious, such measurements always involve the fixing or cementing of a transducer or transducers to the surface of interest. Cables, preamplifiers, and other paraphernalia are often required to transmit and record received signals. These measurements are time consuming, expensive, and obtrusive because they frequently interfere with work in progress. In almost all cases in which a remote observer has line-of-sight access to the surface of interest, one may employ a new technique based on laser interferometry that has none of the forgoing disadvantages and a considerable number of advantages.

Conventional laser interferometric techniques have been applied to the problem of remotely detecting motions of rock or other structural surfaces. However, these conventional techniques invariably use a remote retroreflector fixed to the surface under study. A laser beam from the observer's position is directed toward the retroreflector, and the returned beam is compared interferometrically with the outgoing beam. Phase variations in the returned beam that are due to Doppler shifts resulting from changes in the position of the surface are converted by the interferometer into a series of moving interference fringes that completely characterize line-of-sight motions of the surface. Using an interferometer in this way is clearly disadvantageous because it is not a truly remote measuring system because a retroreflector must be placed and cemented at the point of interest. The potential of interferometry for truly remote noncontact measurements (no retroreflector, geophone, on the like) is thereby lost.

The purpose of this paper is to report on a new interferometric method for remotely detecting vibrations on unprepared rock surfaces and to outline briefly how such a system might be used in various mining or tunneling situations. Our principal goal will be not to provide a detailed account of these applications but rather to demonstrate that such a system is feasible. After demonstrating the feasibility of the system, we will discuss applications, including many that are relevant to tunneling and underground excavation in general.

The method described in this paper is truly remote because the observer located

at the laser interferometer may direct a laser beam to some unprepared remote surface and make measurements of its dynamic behavior. In brief, the action of the remote retroflector in amplifying the returned signal is performed by a 6-in. (15.24-cm) light-gathering telescope located at the position of the interferometer. This telescope amplifies the low-intensity scattered light from the remote surface and focuses the outgoing laser beam in a diffraction-limited spot on the surface to be sampled. The returned light signal is mixed with the outgoing signal as is done in the conventional interferometric devices, and fringes characterizing the motion are detected.

BACKGROUND

In the course of applying acoustic holography to the problem of imaging voids and other discontinuities in rock by using seismic waves (1, 2), we encountered the practical difficulty of recording seismic data when using 2-dimensional detector arrays that involve large numbers of elements. To reduce the time involved in recording such data, we considered various noncontact measurements. In particular, we considered the technique of pulsed laser holographic interferometry, which is a remote technique that involves no prior preparation of the surface. However, to determine the time history of a given surface, we would need a time sequence of holographic interferograms. Apart from the practical difficulties of this requirement, the difficulty of data interpretation that is caused by nonlocalized fringes is also present. However, the fact that holographic interferometry would work in principle meant that any kind of interferometry would work. These considerations led ultimately to the work reported here.

THEORY OF OPERATION

In this section, we present a simple theoretical analysis of the problem of optically detecting and analyzing displacements of moving surfaces. We first examine surfaces moving with a constant velocity along the line of sight; then we take up the general case of sinusoidal and arbitrary motion. Doppler shifts and various effective coherence considerations also are discussed.

Interferometers With Moving "Mirrors"

If a laser beam is directed toward some moving surface of interest, a "mirror" (it can be completely rough), the reflected component returned to the position of the laser will have a circular frequency given by the relativistic Doppler formula

$$\omega = \frac{\omega_0(1 \pm 2v/c)}{\sqrt{1 - v^2/c^2}} \tag{1}$$

where

v = velocity along the line of sight (+v refers to a mirror approaching a stationary interferometer,
ω_0 = stationary laser frequency, and
c = light velocity in vacuum ($\sim$ air velocity neglecting turbulent effects).

Because $v << c$ for most applications, this expression may be approximated by the usual classical result

$$\omega = \omega_o(1 \pm 2v/c) \tag{2}$$

or simply

$$\left|\frac{\Delta\omega}{\omega_o}\right| \sim 2v/c \tag{3}$$

Thus light of 2 different frequencies will mix in the interferometer, and the problem is to determine the observed interference field. If we assume for now that the reference frequency ω_o is time stable and that the reference beam is perfectly monochromatic, then the instantaneous amplitude at the interferometer for a source moving at constant velocity will be

$$A(t) = A_s \exp(-i\omega t) + A_o \exp(-i\omega_o t) \tag{4}$$

Because only square law detectors of light signals are possible, we have the corresponding instantaneous intensity

$$I(t) = A^*(t)A(t) = A_s^2 + A_o^2 + 2A_sA_o\cos[(2v/c)\omega_o]t \tag{5}$$

where, without loss of generality, we have assumed the source amplitude A_s and the reference amplitude A_o to be real numbers, and where v is the line-of-sight velocity as before.

For a given value of v, the observed beat frequency between the 2 light beams $|\Delta\omega| \sim (2v/c)\omega_o$ clearly places limits on the response time of any detector that might be used to record I(t). For constant v, the instantaneous intensity (assuming a perfect detector) would look as shown in Figure 1. In Figure 1, the quantity $(v/c)\omega_o$ is the Doppler or fringe frequency where ω_o is the optical laser frequency and c is the speed of light. The period of I(t) is $\tau \sim (2\pi/|\Delta\omega|) \sim (\pi c/v\omega_o)$, and if the response time of the detector, call it T, is 0.1τ or less, such a detector clearly would be capable of recording I(t) directly. We shall discuss this point in more detail later. For the present, that $T \leq 0.1\tau$ and that I(t) is measured directly will be assumed. The important feature about Figure 1 is that the beat frequency or Doppler frequency shift $|\Delta\omega|$ is directly proportional to the magnitude of the line-of-sight velocity v.

Sinusoidally Moving " Mirrors"

Consider a surface moving with a sinusoidal line-of-sight particle velocity given by

$$v = v_o' \sin(\omega_o' t) \tag{6}$$

where

v_o' = peak particle velocity of the surface, and
ω_o' = circular frequency of the surface vibration.

The corresponding Doppler shift of the light beam that samples this motion is (equations 3 and 6)

$$\Delta\omega \sim 2(\omega_o/c)\, v_o' \sin(\omega_o' t) \tag{7}$$

In this case, $\Delta\omega$ is not a constant, and the formula of equation 5 for intensity is no longer valid. Writing the total complex amplitude in the interferometer as

$$A = A_o \exp[-i\theta_o(t)] + A_s \exp[-i\theta_s(t)] \tag{8}$$

where $\theta_o(t)$ and $\theta_s(t)$ = phase angles to be determined, we note as before that $\theta_o(t) = \omega_o t$. However, the phase angle $\theta_s(t)$ is now a more complicated time-varying phase because $\Delta\omega$ is a function of time. Therefore, because

$$\frac{d\theta_s(t)}{dt} = \omega_s(t) \tag{9}$$

and

$$\omega_s = \omega_o + \Delta\omega \tag{10}$$

$\theta_s(t)$ is given by

$$\theta_s(t) = \int \omega_s dt = \int \omega_o dt + \int \frac{2\omega_o}{c} v_o' \sin(\omega_o' t)\, dt \tag{11}$$

$$\theta_s(t) = \omega_o t - 2\,\frac{\omega_o v_o'}{c\omega_o'} \cos(\omega_o' t) \tag{12}$$

or

$$\Delta\theta = \theta_s(t) - \theta_o(t) = -2\,\frac{\omega_o v_o'}{c\omega_o'} \cos(\omega_o' t) \tag{13}$$

By using equations 8 and 13, one finds the time-varying fringe signal for a sinusoidally moving surface to be

$$I(t) = A_s^2 + A_o^2 + 2A_s A_o \cos\left|\frac{2\omega_o v_o'}{c\omega_o'}(\cos\omega_o' t)\right| \tag{14}$$

Figure 2a shows this intensity $v_s t$; Figures 2b, 2c, and 2d show corresponding Doppler shift, surface velocity, and surface displacement respectively. Two principal features of I(t) should be noted. First, I(t) is a periodic function having a period $2\pi/\omega_o'$ where ω_o' = circular frequency of the oscillating surface. Second, the maximum beat frequency contained in I(t), namely $v_o' \omega_o/c$, will occur when v reaches its maximum value or when $\sin\omega_o' t = 1$. At this time,

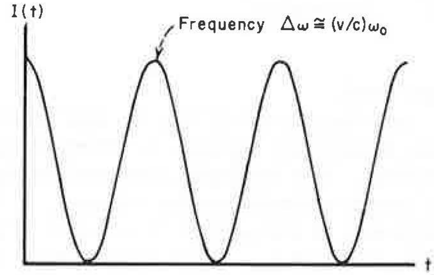


Figure 1. Time-varying interferometer signal for a surface moving with a constant velocity along the line of sight toward or away from the interferometer.

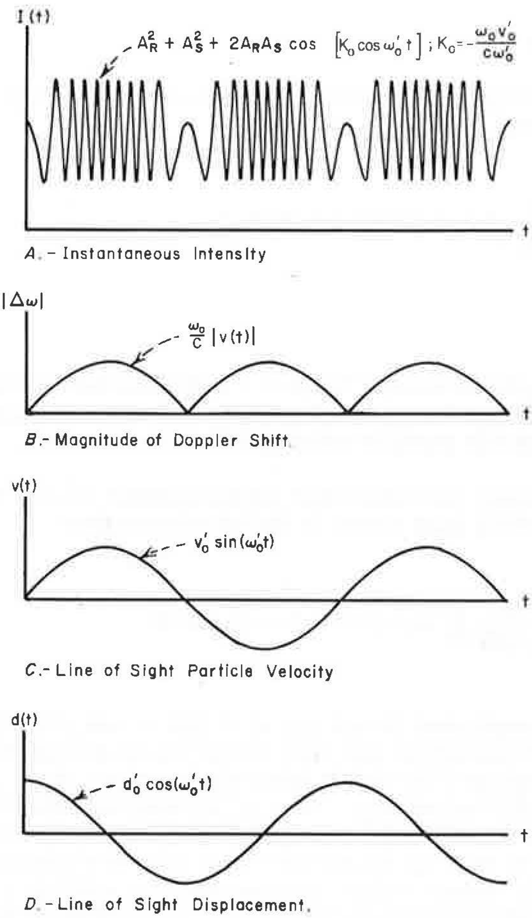


Figure 2. Characteristics of sinusoidally oscillating surface.

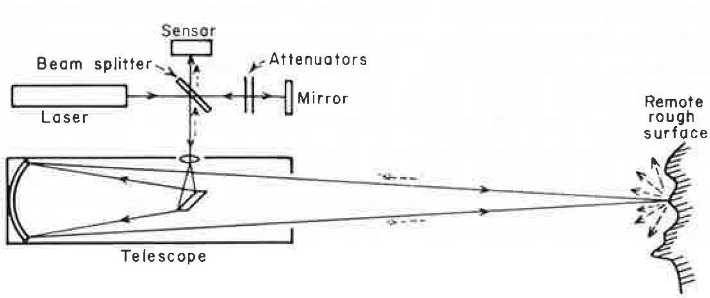


Figure 3. Schematic design of experimental apparatus.

$$|\Delta\omega| = (\omega_o/c)v_o' = (\omega_o/c)d_o'\omega_o' \tag{15}$$

where d_o' = peak displacement.

By measuring $|\Delta\omega|$ and the period of I(t), we can determine all relevant parameters of the sinusoidal motion, namely v_o', d_o', and ω_o'. There are alternate ways to analyze I(t) to get the same information. For example, because the interference fringes occur at intervals of $\lambda_o/2$ of the surface displacement where λ_o = optical wavelength, a simple count of the fringes contained in one period of I(t) will be enough to determine the peak surface displacement d_o'. If there are N fringes in one period of I, there are N - 1 fringe spaces corresponding to a total distance $2d_o' = [(N - 1)/2]\ \lambda_o$.

General Motion

In the most general case, the line-of-sight surface motion may be characterized as a Fourier synthesis

$$v(t) = \frac{1}{\sqrt{2\pi}}\int A_v(\omega_o')\exp(-i\omega_o't)\,d\omega_o' \tag{16}$$

where

ω_o' = a given circular frequency of the surface motion, and

$A_v(\omega_o')$ = an amplitude (velocity amplitude) at the frequency ω_o' chosen in such a way that the particle velocity v(t) is always real.

Following the same procedure that led to equation 13, one finds the phase difference $\Delta\theta(t)$ between the 2 light waves in the interferometer

$$\Delta\theta(t) = \frac{\omega_o}{c\sqrt{2\pi}}\iint A_v(\omega_o')\exp(-i\omega_o't)\,d\omega_o'\,dt \tag{17}$$

where the corresponding fringe signal is just $\sim \cos[\Delta\theta(t)]$.

Note that, if $\cos[\Delta\theta(t)]$ has been recorded, $\Delta\theta(t)$ can be extracted up to a constant phase factor such as $2N\pi$ with N integral; therefore, $d/dt\,[\Delta\theta(t)]$ can be calculated. Because $d/dt\,[\Delta\theta(t)]$ is just $\Delta\omega = [2v(t)\omega_o]/c$, one can extract the particle motion [velocity v(t)] by calculation of the fringe signal $\cos[\Delta\theta(t)]$. If desired, one can Fourier analyze this, integrate to find the displacement, or take derivatives to find the acceleration. The point we wish to stress is that, in principle, any arbitrary interferometer fringe signal I(t) can be completely analyzed to determine all relevant factors corresponding to an arbitrary line-of-sight motion of an optically sampled surface. As far as line-of-sight motions are concerned, the interferometer is fully as useful as a contact transducer. However, unlike ordinary contact transducers that have finite bandwidth response, the optical fringe signal has unlimited bandwidth in that $\Delta\omega$ can be 0 to $\sim 10^{14}$ Hz. A very large $|\Delta\omega|$ cannot be recorded or examined by electronic devices; therefore, a practical, but hardly deleterious, upper limit on $\Delta\omega$ does exist.

That the forgoing method of detecting surface motions is noninterfering should be clear. No acoustic-impedance-matching problems commonly encountered in the use of contact transducers and no mechanical-response problems exist.

INITIAL DESIGN CONSIDERATIONS

To realize a practical system based on the forgoing theoretical ideas, a sufficiently intense return beam must be possible. Surface parameters such as reflectivity and roughness may not be altered for a remote system measurement; therefore, we have at our disposal 3 variables: detector sensitivity, light-gathering aperture, and laser intensity.

By increasing the size of the light-gathering aperture, increasing the laser power, and using a detector of sufficient sensitivity, one can enhance the signal-to-noise ratio of the returned signal. Other more subtle things can be done to improve the system. However, by optimizing these parameters for any system, one will optimize the quality and usefulness of the returned signal.

EXPERIMENTAL RESULTS

In this section, laboratory experiments are described that illustrate both the feasibility of making interferometric measurements of dynamic displacements on remote unprepared surfaces and the feasibility of performing various field tests.

Experimental Apparatus

Figures 3 and 4 show the schematic design and the actual system of the experimental apparatus. Further details of the experimental design may be found elsewhere (3). Basically, the system consists of a simple Newtonian reflecting telescope with a 6-in.-diameter (15.24-cm-diameter) f/4 parabolic mirror, 4-mw helium-neon (He-Ne) laser, and Michelson interferometer. The telescope both sends and receives the laser light, and the Michelson interferometer analyzes the scattered light. Various sensors including photomultipliers were used, but, for the experiments reported here, a simple solid-state detector was employed.

An examination of equation 5 or equation 14 shows that a large value of A_0 will make the amplitude of the cross term that includes the desired signal large. The ability of the solid-state devices to safely operate in the presence of intense reference beams is one important advantage of the solid-state detectors over photomultipliers. For many of the applications envisioned for the interferometer, the ambient light levels may be too high to safely employ photomultiplier detectors.

Tests

Figure 5 shows interferometer output (upper trace) for a scotchlite target oscillating at 1 kHz (lower trace) 6 m from the interferometer. The qualitative similarity of the upper trace with the corresponding theoretical predictions shown in Figures 2a and 2d is evident. There are roughly 11 fringes for each period of the upper trace in Figure 5; therefore, the peak-to-peak displacement is about 5λ or about 3 μm. Evidently shorter optical wavelengths would improve this measurement.

The test shown in Figure 6 was performed to determine whether a signal could be obtained from a rough, unprepared surface moving in some complex way. The upper trace of Figure 6 represents the interferometer ouput from the rough unprepared surface of a struck limestone block 1 m in length located 6 m from the interferometer. The lower trace represents the simultaneous piezoelectric detector output at about 3 kHz resulting from a hammer blow signal propagating through the block. The piezoelectric crystal was located at a point several centimeters from the focus of the laser beam.

Because piezoelectric transducers tend to respond primarily to accelerations and because they have poor frequency response compared to the interferometer, a detailed comparison of the traces is not feasible. In making such tests, the block occasionally

suffered a small translation that was not recovered. The interferometer output is sensitive to this translation, but the peizoelectric transducer is unaffected by uniform translation. Nevertheless, from the basic success of such tests, noncontact velocity measurements that use the interferometer to detect first motion are certainly feasible, and, if no net translation is suffered by a surface, a complete analysis of the line-of-sight motion is possible.

The last test, which is shown in Figure 7, was performed by using very poor optical surfaces as targets to demonstrate the ability of the system to operate over large distances. The upper trace illustrates the interferometer output from an anthracite coal sample being driven sinusoidally at 30 Hz with a peak-to-peak line-of-sight displacement of about 15λ (9 μm) and located 100 m from the interferometer. The lower trace represents system noise with the laser beam blocked. The apparent amplitude modulation of the interferometer signal is due to variations in surface reflectivity as the coal sample moves.

It is clear from the foregoing results that truly remote measurements of surface vibration are feasible. However, certain limitations of the technique must be considered.

LIMITATIONS OF METHOD

In the forgoing sections, we deferred consideration of certain constraints and limitations imposed on the technique of interferometrically measuring surface displacements. In this section, we address these important points.

Effective Coherence

The generalized partial coherence factor (4) for 2 complex wave amplitudes A_1 and A_2 may be written as

$$\gamma = \frac{\langle A_1 A_2^* \rangle}{\langle A_1 A_1^* \rangle^{1/2} \langle A_2 A_2^* \rangle^{1/2}} \tag{18}$$

where

$$\text{averaging operation } \langle\,\rangle = \text{time average } \langle \times \rangle = \frac{1}{2T}\int_{-T}^{+T} \times \, dt, \text{ and}$$

$$T = \text{an arbitrary time.}$$

By writing the complex amplitudes at some fixed point as

$$A_1 = A_1^\circ \exp(-i\omega_1 t) \tag{19}$$

and

$$A_2 = A_2^\circ \exp(-i\omega_2 t) \tag{20}$$

where A_1° and A_2° are real numbers, one can show that, when ω_1 and ω_2 are constants, equation 18 reduces to

Figure 4. Experimental apparatus showing fringe system on oscilloscope.

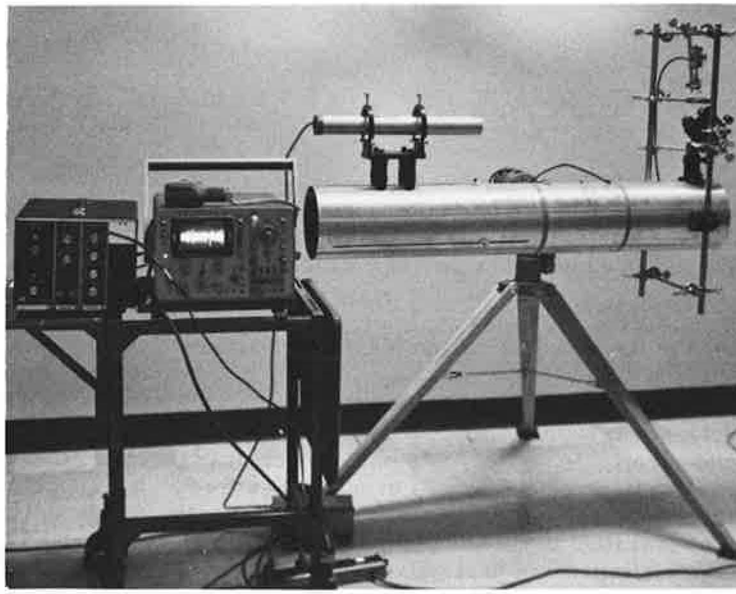


Figure 5. Interferometer output for a scotchlite target.

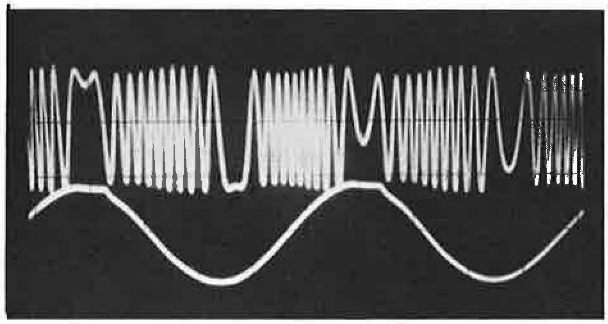


Figure 6. Interferometer output for a struck limestone block.

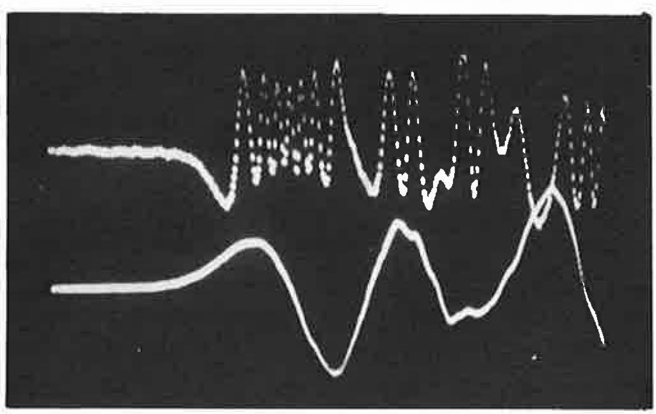
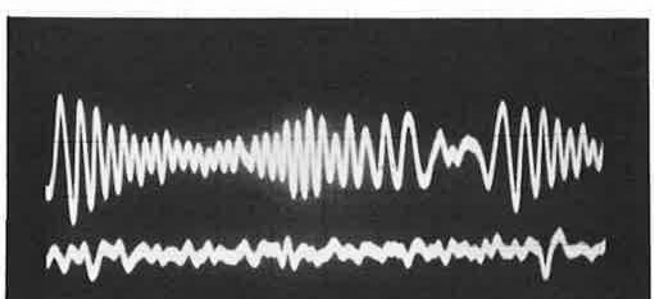


Figure 7. Interferometer output for anthracite coal sample.



$$\gamma = \frac{\sin(\omega_2 - \omega_1)T}{(\omega_2 - \omega_1)T} \tag{21}$$

The magnitude of the partial coherence factor, or $|\gamma|$, is a measure of the coherence of the 2 light beams whatever their origin. Thus we can compare 2 separate beams, parts of the same beam, or Doppler-shifted beams relative to stationary sources.

Detector Response Time and Maximum Particle Velocity

By using $|\gamma|$, we can determine the effect on coherence, or fringe visibility, as a function of response time. If all other sources of coherence degradation have been found acceptable and $|\gamma|$ is some number near unity, then an increase in T, the integration time in equation 21, will eventually cause $|\gamma|$ to reduce to a low value so that no fringes would be observed. If T is physically the response time of a given detector to the optical field being sampled, T must be as small as possible in order to have good fringe visibility. In particular, the argument of equation 21 must be small or $(\omega_2 - \omega_1) T < 1$. If $\omega_2 - \omega_1$ is the Doppler shift, then we evidently must have for a detector of given response time T

$$\Delta\omega(t) < 1/T \tag{22}$$

A typical photomultiplier may have an effective response time of about 10^{-6} sec; hence, measuring Doppler shifts $\omega_2 - \omega_1$ equal to about 1 MHz would be possible in principle. As a practical measure, in most of the measurements we performed, we employed solid-state detectors and amplifiers having considerably larger overall (combined) effective response times of about 10^{-5} sec. If a He-Ne laser is employed, this would mean that particle velocities as high as 3 cm/s could be detected.

Our principal reason for using solid-state detectors was that the cross terms in equations 5 or 14 could be enhanced by making A_o, the reference beam amplitude, very large. Such a procedure is possible by using solid-state detectors, but it cannot generally be used with a photomultiplier because of possible danger to the tube. In any case, the solid-state detectors and amplifiers that we used limited our peak particle velocities to about 3 cm/s. In the future, if the response times of these devices (plus amplifiers) are reduced, this peak particle velocity could be considerably increased.

Any other response time limitations imposed by any other piece of apparatus such as amplifiers, filters, and the like will have the same effect on the effect coherence or fringe visibility as a detector with poor response time will have.

Surface Properties

We do not intend to consider in detail the full range of surface properties to be encountered in actual situations; however, some simple general observations can be made that will tend to constrain what one can expect in any given situation.

Consider a perfectly diffuse surface. In such a case, the incident light flux F_o is scattered uniformly through a solid angle 2π. If the telescope aperture A is located at a distance R from this surface, the returned and collected light flux F_{ob} will be roughly

$$F_{ob} \approx \frac{A^2 r}{8R^2} F_o \tag{23}$$

where r = a surface reflectivity coefficient.

This simple formula shows clearly that the observed flux varies inversely as $1/R^2$ and directly with A^2, r, and F_o. One may compensate for low surface reflectivity by making F_o and A larger. However, a formula of this type is only valid when the particle size δ doing the scattering is less than S where S is the size of the focused spot

$$S \sim \frac{1.22\lambda R}{A} \tag{24}$$

In this case, because the diffraction-limited telescope of aperture A is used to both send and receive, S is limited by A. For very short observing distances, $A \sim R$ and $S \sim \lambda$, and the particular structure will not be resolvable when $\delta > \lambda$. Even if $\delta > \lambda$ but where $S > \delta$, we can still expect the surface to be diffuse. Whenever we have diffuse surfaces, the observed signal would be expected to drop as $1/R^2$. Such situations represent the poorest that could be encountered.

Note, however, that, for materials such as granites or other crystalline substances where crystal faces are frequently encountered, a drop-off considerably less than $1/R^2$ is to be expected under certain conditions. For example, consider a situation in which the diffraction limited spot size $S \lesssim \delta$, where δ represents the size of a highly reflective crystal face oriented perpendicularly to the axis of the incident light cone. In this special case, the observed flux could be much larger than that predicted by equation 22. It could be a large fraction of F_o. Materials of this type would not show the $1/R^2$ drop-off at least over distance ranges where $S \lesssim \delta$. It is interesting that behavior of just this sort has been observed in the laboratory for materials such as granite or hard coal where specular surfaces are frequently encountered. Anything that would be expected to enhance the specular characteristics of a surface (even an ordinarily diffuse one) thus would improve the returned signal. For example, one would expect that an improved signal would be possible in situations where surfaces are wet.

In actual experiments performed in our laboratory, we often found it necessary to search out the best point on a given surface. By moving the point of focus very slightly, one can always find these specular regions on most of the materials that we have examined. This thereby increases the signal-to-noise ratio dramatically. A more detailed account of tests on materials varying from scotchlite to soot and including various types of rocks is available elsewhere (3).

Insensitivity To Small Displacements

That piezoelectric devices are extremely sensitive to small relative displacements is well known. Typically, a particle displacement of 1 A° (0.1 nm), which is roughly the spacing in a crystal lattice, results in large signals. By comparison, the laser interferometer is a relatively insensitive device. To see this, we note that the He-Ne laser line has a wavelength of λ = 6328 A° (λ = 632.8 nm). For a system of the type discussed in this paper, measuring displacements much smaller than about 1 percent of a fringe spacing is unreasonable. Thus we cannot easily detect displacements of less than about $\delta \sim 0.01\ (\lambda/2) \sim 32$ A° [$\delta \sim 0.01\ (\lambda/2) \sim 3.2$ nm] even at low frequencies. This rough calculation makes it clear that the interferometer as currently envisioned will not compete in sensitivity with peizoelectric devices. However, when appropriate compensating sources such as small explosives are used, the lack of sensitivity of the interferometer need not pose a problem.

Miscellaneous

Many further minor difficulties stand in the way of obtaining good quality measurements having a simple interpretation. First, we note that problems of vibration, in some cases, may be serious because we are detecting relative line-of-sight motion.

If both the source and the interferometer are moving and the interferometer motion is unknown, inferring the source motion from the interferometer signal alone is not possible. In most cases dampening instrument motion considerably should be possible. We also note that observing times are typically short (in the millisecond range), and, unless the disturbance agitating the interferometer has a frequency in the kilocycle range, no vibration problems should occur. However, very low frequency measurements would not be immune to this problem. Nevertheless, in extremely noisy environments, some independent record of the acceleration of the interferometer could be kept, say, by the use of a piezoelectric transducer or another laser interferometric measurement by using the same laser. The interferometer motion could then be subtracted from the relative motion to get the true line-of-sight source motion. Finally, we reiterate that all motion detected by the interferometer is line-of-sight motion and anything that changes the line-of-sight distance contributes. Thus lateral motion makes a contribution. The fringes observed in this case are more characteristic of the surface roughness than they are of surface motion itself. Note also that such things as shear waves and pressure waves cannot be distinguished by their displacements alone.

Although limitations such as these are not to be dismissed lightly, they are not particularly significant for many problems in which one is primarily interested in scalar properties (not dependent on direction) of the surface motion. For example, if one is interested in measuring the scalar frequency amplitudes corresponding to any displacement source, the fact that both P and S waves are present is not particularly relevant because they have essentially the same time variation if they originate from the same source.

In situations where one is measuring the time of arrival of the signal, the onset of any motion whether line-of-sight, lateral, or P or S is all that is required. A wide variety of other scalar measurements, such as Q-values, relative stiffness, attenuation coefficients, and response characteristics, are essentially unaffected by the line-of-sight constraint. Therefore, even though this does place severe limits on problems in which highly directional vector properties, such as the direction of first motion, are desired, there remains a large class of practical problems that can be handled by this technique.

POSSIBLE APPLICATIONS

In this section, we outline several additional applications not already mentioned. Although, in most cases, only laboratory simulations of the experiments discussed here have been performed, we can draw some definite conclusions about the applicability of these techniques to various practical problems.

Although it has not been specifically discussed, the laser interferometer can easily be made portable because the laser and associated electronics may be operated on batteries. This situation ensures that field applications are realizable.

Mining Geophysics

Perhaps the first use in mining or tunneling situations of the techniques developed here would be in hazard detection. The roof fall and rock burst are 2 of the most frequent causes of mine fatalities. Either of them is usually preceded by distinct changes in the elastic properties of the rock that is ultimately to fail. Such changes can take the form of a change in the effective stiffness of a given structural member or a part of this member. For example, just before rock bursts in mine pillars, measured P-wave velocities through the pillar invariably are observed to increase from some anomalously low value to a more normal value (5). Behavior of this type can be monitored by doing a conventional P-wave survey with geophones or by using the laser interferometer. In certain situations in which time is critical, the simplicity and ease of operation of the interferometer could make it a convenient means of measuring such transient

phenomena before a disastrous failure.

The laser interferometer also could be used to detect loose slabs of rock by taking advantage of their reduced stiffness. A loose slab can easily be made to move through a larger displacement for a given applied force compared with nearby competent rock. Such increased displacements would appear as an increased fringe frequency.

The character of rock is often specified in terms of its Q-value, which, put simply, is inversely proportional to the energy loss per cycle that such a rock exhibits for a given acoustic input. Rock with a low Q-value is highly attenuating and generally has a low E-value. If rock of this type is struck by some impulsive source, it generally sounds dull because the high frequencies are more rapidly attenuated than the low frequencies are. On the other hand, rocks with high Q-values sound metallic when struck (even with nonmetallic objects or sources), and they tend to "ring" for a much longer time than the low-Q-value rocks. Rocks of this type have generally high E-values as well.

The laser interferometer could be used to rapidly obtain qualitative information on the Q-value of rock at or near the sampling point by merely ascertaining how long the rock or rock structure rings after being subjected to a given impulse. Roof rock in large rooms or rock in tunnel faces could be examined remotely by striking the near vicinity of the optically sampled point with a projectile and examining the response. A line of such measurements across the roof span or across an excavation face could then be used in principle to detect bad rock areas or zones. Such areas would be distinguished by having low Q-values or short ringing times compared with adjacent higher Q-value rock, which should have a higher Young's modulus and be more competent.

Apart from mining or tunneling applications of this type, there are situations in which techniques such as seismic holography are to be employed to image certain discontinuities on rock. Several techniques (including holographic techniques) that would, for example, attempt to look ahead of the working face in a tunneling operation have been contemplated by various investigators. The laser interferometer provides a simple remote means of rapidly obtaining the necessary arrival time data or other seismic data for such procedures provided sufficiently energetic impulsive seismic sources such as an explosive are employed.

Civil Engineering Applications

Perhaps the most interesting application that comes to mind in this area is the use of such a system in vibration analyses or modal studies of various structures. Information on the natural modes of vibration of existing buildings and bridges is essential if the integrity of structures in earthquakes or violent wind storms is to be ascertained. Such studies can be, and have been, performed by using contact transducers and the wind as a driving force; however, the laser interferometer would greatly simplify such measurements and, at the same time, give the experimenter great flexibility in his or her choice of measuring points.

Hostile Environments

Like holographic interferometry, the interferometric technique described in this paper could be applied to the examination of moving surfaces (or changes in indexes of refraction) in environments inaccessible to ordinary instruments because of high pressures or temperatures. The advantages of simple point measurement are that no holograms are required and that problems of interpretation of fringe data due to the problem of nonlocalized fringes do not occur. However, the holographic interferogram has the distinct advantage of covering an entire scene rather than a single point.

CONCLUSIONS

The experimental study presented indicates that a modified laser interferometer may

be employed to detect line-of-sight motion on unprepared rock surfaces at distances from the interferometer of at least 100 m. With further technical improvements in the system, improved signal-to-noise ratios and greater distances of operation are possible.

The demonstrated feasibility of the system for performing remote measurement of displacements on an unprepared nonspecular surface should provide considerable encouragement to those interested in improving and applying this technology to their own particular needs; in particular, there is reason to expect that such techniques might be used in tunneling and underground excavation in general for evaluating the integrity and safety of rock structures.

After this paper was prepared, the interferometer shown in Figure 4 was made portable (battery operated) and taken to a mine for tests. The tests are still in progress; however, results to date generally confirm the predicted usefulness of the interferometer in hazard-detection applications and rock-structure analysis in general. We have also recently begun construction of a folded beam design that uses high-quality, commercially available optics. This improvement promises to reduce significantly the size and weight of the system.

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