Abstract—A review of the various optical methods to detect ultrasound (bulk and surface waves) at the surface of opaque solids is presented. The most useful techniques are thoroughly analyzed. Their performance when nonideal conditions are encountered, such as vibrations, air turbulence, and rough light scattering surfaces is evaluated. This review includes a description of knife-edge techniques, optical heterodyning, differential interferometry, and velocity (time-delay) interferometry methods, plus a mention of various less-important techniques.

I. INTRODUCTION

EARLY EFFORTS to detect ultrasound by optical means were motivated by the need to visualize and image the ultrasonic field. Although this motivation is still present, as demonstrated by a survey of recent literature on the subject, the main thrust behind optical detection of ultrasound is now to fully exploit the potential of laser ultrasonic generation [1], [2] by coupling both techniques in order to make a powerful inspection tool for materials. Since in this case the sample could be located at a large distance (more than 1 m) from any optical element of the generating or receiving system, important applications are foreseen in the inspection of materials at high temperature (such as all metals and ceramics) for process and quality control. A technique based on laser generation and optical detection could be used, for example, to detect flaws as soon as they are created during processing, to measure production parameters (thickness, temperature . . .), and to determine microstructural properties on-line (grain size, porosity . . .). Ultrasonic inspection in hard to access areas (corners, edges) would also be greatly facilitated by this all-optical inspection system. These areas are often prone to the development of defects, during production or in service. Furthermore, the development of ultrasonic techniques for microstructural material characterization (grain size, magnetic domains, porosity . . .) may benefit greatly from the broadband nature of ultrasound generated by the laser pulse. Since the poor sensitivity of optical detection is the main reason that limits the practical evolution of this technology to full commercial application, particular attention will be given to this question throughout this review.

In this review, we will try to cover all the techniques known to have been used to detect ultrasound produced in opaque solids. The detection of ultrasound in transparent solids or liquids is well established [3], [4] and will not be part of this review. In this paper, newer techniques will be analyzed thoroughly, whereas well-established techniques will not be detailed and the reader will be referred to previous reviews such as that by Stegeman [5] for further information. This review deals primarily with the detection of ultrasound and not the detection of thermal waves, although in many cases the distinction is unclear, since a stress and a strain is induced at the same time as the thermal wave and the same apparatus could be used. For these reasons, the references to works in photoacoustics which have used a method also applicable to ultrasonic detection will be given.

The optical detection techniques for ultrasound will be classified into noninterferometric techniques and interferometric techniques. The former are well developed or of limited application, while the latter are more general and are presently the object of active developments.

II. NONINTERFEROMETRIC TECHNIQUES

The various optical techniques to detect ultrasound which are not based on interferometry and which have been either considered or implemented are the following:

- knife-edge technique
- surface-grating technique
- technique based on reflectivity
- technique based on a light filter.

A. Knife-Edge Technique

The principle of this technique is shown in Fig. 1. When an ultrasonic wave impinges on a surface or propagates along it, a ripple is produced causing the deflection of a laser beam sent onto the surface. The beam deviation is measured with either a detector with a knife edge in front of it or a position-sensitive detector. The beam size on the surface has to be smaller than the ripple spacing. Surface waves have been visualized using this technique [5]–[9] as well as bulk waves. When bulk waves are used, the technique permits characterization of the sample microstructure and detection of internal defects [10]. It has matured into a commercial inspection device, the SLAM [11] (scanning laser acoustic microscope). Evaluation of the sensitivity of the technique can be found in a review by Whitman and Korpel [12] and a paper appearing in this issue [13]. The detection limit has been reported to be about a few 10⁻¹⁰ Å for a polished nonabsorbing surface, a detection bandwidth of 1 MHz, and a laser power of 10
B. Surface-Grating Technique

Produced by the surfacewave gives two first-order diffracted beams, which after interfering with the specularly reflected zeroth-order beam, produce a moving intensity corrugation at certain distances from the surface. The signal is detected through a Ronchi grid of suitable periodic spacing. This technique is mostly limited to continuous excitation on a clean polished surface and has been reviewed by Whitman and Korpel [12] and Stegeman [5].

C. Reflectivity Technique

The ultrasonic stress produces a small change of the sample refractive index which in turn causes a change of the specularly and diffuse reflectivity of the sample. The change of reflectivity is small and of the order of the ultrasonic strain. This technique has, however, been applied successfully to detect the ultrasonic echoes in a thin film produced by laser generation with picosecond time resolution [18]. We should also note that a similar technique is used in photothermal detection [19], but the change of reflectivity being in this case caused by the temperature or carrier concentration changes.

D. Use of a Light Filter Based on Absorption

This technique is based on the frequency demodulation of frequency shifted by ultrasound scattered light (Doppler effect, see below) by the absorption band of an optical medium (solid, liquid, gas), the laser frequency being tuned to the slope of the band [20]. In practice, the absorption bands found in solids, liquids, and gases are too broad for normally used ultrasonic frequencies (<100 MHz) to give a sensitive device. However, in the case of liquids and gases the absorbing medium can be given easily a large cross-section and can be made long if necessary. Since the filtering action depends only on the path-length through the medium, this technique is rather insensitive to the direction of incoming rays. This is combined with a large cross-section and enables a large gathering efficiency of scattered light (see below for gathering efficiency or étendue), which may make such a simple technique attractive in spite of the generally poor discrimination sensitivity mentioned above, but its use has not been reported so far. Light filtering action can be also easily obtained by interferometry and this is described below.

It is also possible to narrow the Doppler limited linewidth obtained in a gas cell by using saturated absorption [21]. A powerful laser beam burns a narrow hole through the atoms or molecules Maxwellian velocity distribution, which can be used to frequency demodulate the weaker beam received from the surface [22]. The sensitivity of such a technique depends on the chosen gas, the laser power, the interaction length, and the angular distribution of received scattered light that broadens the resonance feature by the residual Doppler effect. No experimentation to apply this technique to the detection of ultrasound is known at this time.

Finally, it should be noted that all these techniques give a filtering bandwidth that is fixed and determined by the medium, unlike interferometry, which enables easily to chose the most suitable bandwidth (see below).

III. INTERFEROMETRIC DETECTION: BACKGROUND

In this section, we will present some background information which will be useful to understand the merits and limitations of the various interferometric detection techniques presented below. These techniques will be classified into the following three types, which can be identified by reference to Fig. 2.

1) Optical Heterodyning: This technique consists of beating the wave scattered by the surface, which can have a very complicated and distorted wavefront, with a reference wave.

2) Differential Interferometry: This technique consists of producing the interference of two waves issued from different points on the surface or from one single point illuminated by two distinct beams.

3) Velocity or Time-Delay Interferometry: This technique uses only one wave issued from the surface and generates a signal by beating it with itself delayed by a certain time.

If the pathlengths have been compensated the first two techniques can use a broadband source and do not require a single frequency laser. By opposition, the third technique, which involves necessarily a time delay, requires a narrow optical bandwidth source, in practice a single frequency laser, or to encode the spectrum of a broader band source (spectral modulation technique, see below).
A. Effects of Ultrasound in the Time Domain and Frequency Domain

Let us assume that the surface moves by $\delta(t)$ at a location where a light field $E_0 \cos \omega t$ is incident, $\omega = 2\pi\nu$, where $\nu$ is the optical frequency. In the backscattered direction, the light field is then proportional to $\cos[\omega t - 4\pi\delta(t)/\lambda] = \cos[\omega t - 2\omega\delta(t)/c]$, where $\lambda$ is the optical wavelength. This phase factor can also be written $\int_0^t \omega(1 - 2\omega(t)/c) dt$, where $\omega(t) = \delta(t)/t$ is the surface velocity. This shows the well-known Doppler effect: the instantaneous frequency is $\nu(1 - 2\omega(t)/c)$.

If we assume, for simplicity, that $\delta(t) = U \cos(2\pi f_u t + \psi)$, where $f_u$ is the ultrasonic frequency, $U$ is the amplitude of the displacement ($U$ is much less than $\lambda$), and $\psi$ a phase constant (this is valid for continuous ultrasonic excitation), but pulse excitation can be readily handled by Fourier analysis), the back scattered light field can then be written as proportional to

$$\cos[\omega t - 4\pi U \cos(2\pi f_u t + \psi)/\lambda]$$

$$= \cos \omega t + 4\pi\delta(t) \sin \omega t/\lambda$$

$$= \cos(2\pi\nu t) + 2\pi U [\sin(2\pi(\nu + f_u) t + \psi)$$

$$+ \sin[2\pi(\nu - f_u) t - \psi]]/\lambda.$$
A bidimensional random walk problem is encountered. The detection are satisfied and that the performance is not limited. This could imply the use of a detector with internal gain. The signal-to-noise ratio is then determined by taking $i_s/i_{N} = 1$ and using the expression of $I_s$ as a function of $U$ or $\delta$.

IV. OPTICAL HETERODYNING

As mentioned before, this technique consists in beating the wave reflected by the surface with a reference wave. The experimental configuration generally used is sketched in Fig. 5 and constitutes what is called a Michelson interferometer. Other configurations based on the other two-wave interferometers (Mach-Zehnder, Fiseau, ...) can be used as well. All of them have the common characteristic that the surface acts as one mirror of the interferometer. Without the frequency shifter, these probes are called homodyne and with it in either interferometer arm, these are called heterodyne (sometimes super-heterodyne).

A. Homodyne Interferometers

Without the frequency shifter in either arm (homodyne interferometer), the light intensity received by the detector can be written as follows:

$$I_D = I_L \{ R + S + 2\sqrt{R} \sqrt{S} \cos \{ 4 \pi \delta(t)/\lambda - \Phi(t) \} \}

(4)$$

where $I_L$ is the laser power, $R$ is the effective transmission coefficient in intensity for the beam in the reference arm, and $S$ is that for the beam reflected off the surface ($S$ is much less than unity for practical unpolished surfaces), $\Phi(t)$ is a phase factor that depends upon the interferometer path difference and is affected by vibrations. In practice, the reference mirror is mounted on a piezoelectric pusher, which enables to adjust the path difference in such a way that $\Phi = \pm \pi/2 + 2n\pi$ (n is an integer). It then follows that the signal is proportional to the displacement. In practice, electronic stabilization circuitry should be used to keep this adjustment in spite of ambient vibrations.

D. Signal-to-Noise Considerations

We will assume that the conditions for quantum limited detection are satisfied and that the performance is not limited by amplifier noise. In the case of low light levels, this could imply the use of a detector with internal gain such as a photomultiplier or an avalanche photodiode. A short discussion of noise problems can be found in another article of this journal [13].

The light intensity $I_D$ received by the detector comprises two terms. The first one, noted $I_s$, to which the photocurrent signal $i_s$ corresponds, is associated to the ultrasonic motion of the surface and vanishes when the ultrasonic displacement is zero. The second one, associated to the photocurrent $i_0$, is the residual part of the received intensity. In most cases encountered in practice, the ultrasonic displacements are much less than an optical wavelength, so $I_s$ is small compared to $I_0$. The amplitude of the photocurrent signal $i_s$ is given by

$$i_s = G\eta e I_s/h\nu$$

(1)

where $\eta$ is the quantum efficiency of the detector, $e$ is the electron charge, $h\nu$ is the energy of a quantum of light of frequency $\nu$, and $G$ is the internal gain of the detector. The $i_0$ is expressed by an equation similar to (1) with $I_0$ substituting $I_s$. The photocurrent noise (RMS) value is then given by (we assume that the amplification process does not introduce additional noise):

$$i_{N} = \sqrt{2 GeB I_{0}}$$

(2)

where $B$ is the detection bandwidth. The resulting signal-to-noise ratio is then

$$i_s/i_{N} = I_s\sqrt{\eta/(2Bh\nu I_0)}.$$
which have amplitudes much larger than the ultrasonic displacements to be detected [26]-[34]. Faster compensation can be obtained with an electrooptic phase shifter [35]. The error signal for stabilization can be obtained by detecting the second harmonic of a dithering voltage applied to the piezoelectric pusher and using a lock-in amplifier tuned to the second harmonic (the zero of the second derivative of the signal corresponds to \( \phi = \pm \pi / 2 + 2n\pi \) condition above). Another simpler stabilization scheme is based on the comparison of the dc output of the detector to that corresponding to the fringe midpoint (\( \Phi = \pm \pi / 2 + 2n\pi \), condition above).

These homodyne stabilized interferometers do not work well in presence of strong vibrations and often require for best operation to be located on a vibration-free table (except possibly the wider bandwidth compensation system of [35]).

Calibration is generally obtained in these systems by opening the stabilization loop and making the piezoelectric pusher to vibrate with an amplitude larger than \( \lambda / 2 \). If the fringe pattern is not very stable, calibration should be performed frequently. This situation occurs with most surfaces (except mirrors) which scatter light and produce a speckle effect, except if a very stable setup is provided. A solution that has been experimented, but with additional complexity, is to dither constantly the piezoelectric pusher at a frequency above the response bandwidth of the stabilization loop [34]. It is also possible to obtain calibration without opening the stabilization loop by measuring the error voltage of the stabilization network [35]. This only requires to know the proportionality factor between displacement and observed voltage and vibrations amplitudes larger than \( \lambda / 2 \).

Another method to eliminate the problem of vibrations is to vibrate continuously the reference mirror and to take a measurement at the proper time [37], but this is hardly applicable to short pulse ultrasound. It is also possible to have a system insensitive to vibrations by generating inside the Michelson interferometer two collinear optical beams in quadrature, which are detected by two separate detectors. As can be readily deduced by expanding (4) for small \( \delta(t) \), two signals proportional to \( \delta(t) \cos \Phi(t) \) and \( \delta(t) \sin \Phi(t) \) are obtained by filtering out low frequencies. The \( \delta(t) \) can be deduced by squaring the two signals [31], [38]. This system has a drawback to require critical detector adjustments (the detectors should see the same fringe pattern) and squaring at high frequency. Alternatively, it is possible to digitize the two signals and then, to compute the ultrasonic displacement [39].

In order to maximize the signal for a rough surface, the beam should be first focused to a diffraction limited spot on the surface. This gives a speckle spot size of the order of the incident beam diameter. Secondly, the reference mirror should be adjusted so that the reference wavefront is parallel to the average wavefront reflected by the surface. The first requirement can be understood as follows. When the surface is not at focus several speckles (let us say \( N \)) interfere with the reference beam. We have seen above that they add incoherently, so the response corresponds approximately at most to \( \sqrt{N} \) times that of one speckle. Since in this case, the intensity of each speckle is on average \( 1 / N \) that of the incident beam, the signal is smaller than at focus when \( N = 1 \).

We would like to mention that a solution to avoid the speckle problem would be to use a phase conjugate mirror [40] in association with a displacement interferometer such as described above. The phase conjugate mirror would receive part of the scattered light and send it back in such a way that light retraces its path and produces a uniform wave to interfere with the reference wave. No system using such a scheme is known to exist presently.

Finally, it should be noted that the detection bandwidth of such a detection scheme is given by the optical detector and extends from \( \approx 50 \) KHz (displacements at lower frequencies are compensated by the stabilization loop) to 100 MHz and more. From the point of view of practical use, we note that the flexibility can be greatly enhanced by using a single-mode optical fiber in the probing arm [41].

B. Heterodyne Interferometers

If the detection is performed about a higher frequency by shifting the optical frequency in either arm (heterodyne interferometer), the signal from the detector (\( -2\pi f_B t \) is added to the phase in (4)) includes a carrier at the shifting frequency \( f_B \) and two sidebands (as shown in Fig. 3, except that the spectrum is now centered on \( f_B \)). Calibration can readily be performed by comparing the sidebands amplitude with that of the carrier.

Many systems based on a Michelson heterodyne interferometer have been described in the literature and differ either by their optical configuration or electronic processing technique. They generally use a Bragg cell (acoustooptic cell excited at frequency \( f_B \)) to shift the optical frequency. The cell can be single pass, which gives a shift of \( f_B \) [42]-[49] or double pass (used as beam splitter and beam mixer), which gives a shift of \( 2f_B \) [50]-[54] (see Fig. 6).

By sending the two incident beams at proper angles, it is also possible to generate two angularly separated beams, one down-shifted and the other up-shifted [55]. Two Bragg cells can also be used: one is located in the reference arm and the other one is in the arm of the beam sent to the surface [56].

The simplest way to process the phase modulated signal at \( f_B \), is to use a commercial spectrum analyzer [56] or a
VHF receiver tuned to one of the sidebands followed by square law detection [44], [47]. In this case, the phase of the ultrasonic displacement is lost. Another way is to use standard FM demodulation [52], [53], (slope discrimination followed by diode detection and low-pass filtering) which gives a signal proportional to the surface velocity. The frequency response of such a detection scheme is limited approximately to the linear region of the discriminator. For higher frequencies, the response for constant displacement amplitude is not linear and levels off. A response proportional to surface velocity can be also obtained by a frequency-tracking technique [43], [57] described in Fig. 7. The frequency response of such a scheme is limited by the tuning capability of the voltage-controlled oscillator and the response time of the feedback loop. It appears for this reason mostly applicable to low ultrasonic frequencies and has been used for detecting vibrations [43].

It should be noted that the two modes of signal processing described above, which give an output proportional to the velocity, ensure in practice immunity to ambient vibrations since those occur only at low frequencies.

It is also possible with a frequency tracker to obtain a response proportional to the surface displacement [48], using the circuit described in Fig. 8. The operation of this mode of signal processing can be explained by expanding for small $\delta$ the equation for the heterodyne interferometer corresponding to (4):

$$I_D = I_L \{R + S + 2\sqrt{R}\sqrt{S}\cos[2\pi f_B t + \Phi(t)] + 4\pi\delta(t)/\lambda \sin[2\pi f_B t + \Phi(t)]\}$$

The voltage-controlled oscillator will lock to give zero dc signal at the output of the mixer, i.e., its output has to be proportional to $\sin[2\pi f_B t + \Phi(t)]$. Then the output bandpass filter (cuts low frequencies and frequencies around $2f_B$) gives a signal proportional to $\delta(t)$.

Another scheme to obtain a displacement signal for narrowband ultrasonic excitation [50], [55] consists of isolating the signal at $f_B$ and one of the sidebands with filters and then mixing them. Since the vibrations have the same effect on the phase of the central frequency at $f_B$ and the phase of the sidebands, a signal independent of the vibrations is obtained. It is also possible to use a commercial lock-in amplifier and to drive it with a reference signal derived from mixing the ultrasonic frequency with the central $f_B$ frequency filtered out from the detector output [46]. If a signal derived from the Bragg cell generator at $f_B$ is used instead of one derived from the detector, the output is observed to fluctuate constantly with vibrations.

It is also possible to detect both sidebands at the same time for broadband pulsed ultrasound with the scheme shown in Fig. 9 [58]. This scheme divides the detector signal into two in-phase components. The central peak at $f_B$ is filtered out from one of them and then mixed to the other one after being given a phase shift of $90^\circ$. By reference to (5), it can be seen that, after eliminating with a filter high frequencies of the order of $2f_B$, a signal pro-
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The amplitude signal is obtained from the detector output to have a response independent of the fringe signal amplitude and proper operation of the RF mixer, a constant amplification and hard clipping or automatic gain control. Finally, for all the schemes mentioned above, in order to have a response independent of the fringe signal amplitude and proper operation of the RF mixer, a constant amplification and hard clipping or automatic gain control.

An example of a heterodyne interferometer which maximizes the intensity sent to the surface for best signal-to-noise ratio:

\[ S = (1 - A) (\alpha/2D)^2. \]  

Equations (7) and (9) give for the preceding parameters with \( a = 4 \text{ mm}, D = 15 \text{ cm} \) a detection limit \( \text{cf} = 1 \text{ A}. \) In practice a surface rarely scatters isotropically and a speckle brighter than average can be found, so a lower limit can be expected. This limit can be lowered by using higher laser power (the detection limit scales as \( 1/\sqrt{I_L} \) or a closer working distance \( D \) (the detection limit scales as \( 1/D) \), but closer focusing produces a smaller spot size and a shorter depth of focus.

These results are consistent with the antenna theorem for heterodyne detection [59], [60] which states that the effective étendue of the receiving system is \( \lambda^2 \) at most. For an illuminated spot radius \( w \) on an isotropically scattering surface the brilliance is \( I_L(1 - A)\pi w^2. \) This expression multiplied by the étendue \( \lambda^2 \) gives the effective received power for detection according to the antenna theorem. We see that the power is maximized for \( w = w_0, \) where \( w_0 \) is the diffraction limited spot radius. In this case, one speckle spot beats with the reference beam. Since \( w_0 - 2 \lambda / \pi a \) we retrieve (9). It is useful for further comparison to rewrite (7) (in the limit \( R \gg S) \) using the étendue parameter \( E: \)

\[ i_k/\eta = (4\delta/\lambda) \sqrt{2\pi I_L(1 - A) E \eta (BhvS_i)} \]  

where \( S_i \) is the illuminated spot area on the surface. Equation (10) can also be expressed with the solid angle subtended by the receiving aperture as seen from the surface. This solid angle \( \Omega \) is equal to \( E/S_i. \) The detection limit calculated previously for a nonabsorbing isotropically scattering surface corresponds approximately to a limit of \( 10^{-6} \text{ A} (\text{W sr Hz})^{1/2}. \)

When a heterodyne interferometer is used a slightly reduced signal-to-noise is encountered. This originates mostly from the detection scheme (Fig. 8 or Fig. 9), which uses only half of the power produced by the mixing process by eliminating frequencies components around \( f_B. \) It can be shown that the proper equation for the signal-to-noise ratio is (7) with \( \sqrt{RS/(R + S)} \) replaced by \( \sqrt{RS/2(\sqrt{R} + \sqrt{S})}, \) which reduces to \( \sqrt{S/2} \) for \( R \gg S. \) When a single sideband is detected [46], this expression should be further halved. A detection limit identical to the one found above for the homodyne interferometer...
is obtained for a mirror-like nonabsorbing surface and 50-
percent reflecting-transmitting beam splitter. For the non-
absorbing isotropically scattering surface, the value found
above should be multiplied by \( \sqrt{2} \).

Finally, we want to mention that the limits of detection
calculated in this section can be obtained in practice and
they have been roughly verified [61], [62], [46]. When
discrepancies have been reported [50], [55], it is sus-
pected that the theoretical assumptions were not verified
by the experiment system.

D. Other Interferometric Methods

The laser itself is made of an interferometer and can be
used to detect ultrasonic motion by feedback upon it. A
simple He–Ne laser can demonstrate easily the effect [63],
which should exist with any laser, e.g., laser diodes [64].
It seems, however, difficult to make very quantitative
measurements because of the complexity of the problem
which involves three coupled cavities and a nonlinear me-
dium (the laser).

Instead of using two-wave interference, a multiple-wave
interference phenomenon can be used as well by making
the surface one of the mirrors of a Fabry–Pérot interfer-
ometer [65]. Very large sensitivity can be obtained, but
the surface has to be nicely polished and the alignment is
critical.

V. DIFFERENTIAL INTERFEROMETRY

As mentioned previously, two wavefronts are made to
interfere: they could be issued from one single point on
the surface illuminated by two distinct beams (differential
interferometry for in-plane measurement) or two distinct
points (differential displacement interferometry).

A. Differential Interferometry for In-Plane
Measurement

This technique is similar to differential Doppler ane-
mometry [66] and is illustrated in Fig. 11. As seen in Fig.
11, the probe is made by having two beams, issued from
the same laser and separated by an angle \( 2\theta \), focused at
the same location on the surface. A grating is then pro-
duced on the surface, and part of the speckle field scat-
tered from the surface is received by a detector. The grating
is fixed when the frequency of the two beams is the
same (homodyne probe) and moving when it is hetero-
dyne. If \( N \) speckles of mean intensity \( I_{sp} \) are seen by the
detector, the detected intensity in the case of the hetero-
dyne probe can be written (the speckles add up incoher-
ently):

\[
I_D = \sqrt{NI_{sp}} \cos [2\pi f_B t + (\vec{k}_1 - \vec{k}_2) \cdot \vec{\delta}(t) + \phi(t)]
\]

where \( f_B \) is the shifting frequency \( (f_B = 0 \) homodyne
probe); \( \vec{k}_1 \) and \( \vec{k}_2 \) are the wavevectors of the two beams;
and

\[
(\vec{k}_1 - \vec{k}_2) \cdot \vec{\delta} = 4\pi \sin \theta (\sin \alpha \delta x + \cos \alpha \delta z)/\lambda
\]

where \( \alpha \) is the angle between \( \vec{k}_1 - \vec{k}_2 \) and normal-to-the-
surface, and \( \delta x \) and \( \delta z \) are, respectively, the in-plane and
out-of-plane displacements. As seen previously, when the
frequency is shifted, this expression gives a carrier signal
at \( f_B \) and two sidebands, which enables easy calibration.
In-plane and out-of-plane displacements can be detected,
but this probe is particularly useful to detect displace-
ments parallel to the surface (in this case \( \vec{k}_1 - \vec{k}_2 \) is per-
pendicular to the surface and \( \alpha = \pi/2 \)).

When both sidebands are detected, (or in the case of a
homodyne probe) the detected signal intensity \( I_s \), as pre-
viously defined, is given by

\[
I_s = \sqrt{NI_{sp}} (\vec{k}_1 - \vec{k}_2) \cdot \vec{\delta}.
\]

Since \( I_0 = NI_{sp} \) and using (3), a signal-to-noise ratio
approximately independent of number of speckles is ob-
tained:

\[
i_s/i_N = (\vec{k}_1 - \vec{k}_2) \cdot \vec{\delta} \sqrt{\eta I_{sp}/(2Bhv)}.
\]

Equation (13), also shows that, in order to improve the
signal-to-noise ratio, \( I_{sp} \) should be maximized, which
means that the speckle size should be of the order of the
detection aperture and consequently that this aperture
should be large enough to collect a large part of the scat-
tered light. Accordingly, this means very sharp focusing.
When typical numerical values are used, a detection limit
of the same order as the one found in Section IV is ob-
tained. However, if we want the system not to be too
bulky, \( \theta \) should be small which could reduce the sensi-
tivity.

It is possible to construct a probe which, by a simple
change, could detect the normal displacement (as in Sec-
tion IV) and the in-plane displacement (differential con-
figuration) at the same point [56], [67]. A broadband
probe with such a capability has been recently used to
compare the normal and in-plane displacements of a Ray-
leigh surface wave, giving results in agreement with the-
ory [68].

B. Differential Displacement Interferometry

This technique consists of focusing at two distinct lo-
cations on the surface, then to produce an interference
pattern from the two point sources and to detect it through
a Ronchi grid (see Fig. 12) [69], [70].
This technique is very insensitive to ambient disturbances, but detects only the differential normal displacement between the two illuminated points. Its detection bandwidth in the case of the detection of surface waves is a function of the spacing between the two points.

VI. VELOCITY OR TIME-DELAY INTERFEROMETRY

We have seen in Section IV-B that a signal proportional to surface velocity could be obtained by using a frequency discriminator, which could be a RF filter used on its slope, to demodulate the heterodyne signal. The same operation could be done directly at optical frequencies by using an optical filter. As mentioned in Section II-D, filters that are based on absorption of light do not generally have a sufficiently steep slope to be useful (except if saturated absorption is used). Steep slopes and high discrimination sensitivity can be obtained by optical interferometry. The basic setup is shown in Fig. 13.

As mentioned in the background section, the basis of the technique consists of making the waves scattered by the surface interfere with itself after some time delay. In practice, the delayed wavefront does not match exactly the initial wavefront and limitations on the size of the useful area of the wave and on its divergence are encountered. These limitations are related to the concept of étendue of the interferometer and a sensitive system will be such that they have been minimized to give a large light-gathering capability.

The interferometers which can be used can be classified into two types: 1) two-wave interferometers, e.g., Michelson and Mach–Zehnder and 2) multiple-wave interferometers, e.g., Fabry–Perot. For all these devices, since the signal is (in the first approximation) proportional to velocity, there is excellent immunity to ambient vibrations.

A. Velocity Interferometry with a Two-Wave Interferometer

A typical setup is sketched in Fig. 14. We note the main difference between this setup and the one of Fig. 5: here the interferometer does not make use of the surface as a mirror, but views the light scattered by it. This type of system has been used in shock-wave research [71] and has also been considered for the detection of ultrasound [72].

The received intensity for a given direction $\theta$ of an incident ray is

$$I_D = A_1 + A_2 \cos (2\pi \nu / \Delta \nu_{FS} + \phi)$$

(14)

where $A_1$, $A_2$, and $\phi$ are constant, the free spectral range $\Delta \nu_{FS} = 1/\tau = c/2\Delta d(\theta)$, $\tau$ is the delay time, and $\Delta d(\theta)$ is the difference of arm lengths for the incident ray inclined by $\theta$. As sketched in the insert of Fig. 14, which plots the spectral response given by (14), frequency discrimination is obtained when the laser frequency (a single frequency laser source is necessary) is tuned to a zero crossing:

$$2\pi \nu / \Delta \nu_{FS} + \phi = \pm \pi/2 + 2m\pi$$

where $m$ is an integer.

The surface being rough and irregular acts as an incoherent source, so the fringes are only observed at infinity [73] or at the focus of a lens. It can be readily shown that $\Delta d(\theta) = \Delta d \cos \theta$, where $\Delta d$ is the path difference for the ray perpendicular to the mirrors. The fringes are then concentric rings, and in practice the central fringe is selected by using a circular hole at the lens focus (at the expense of a much higher complexity a mask pattern matching the fringes can be used). Taking a maximum path difference of $\lambda/4$, it follows a limit angle $\theta_M = \sqrt{\lambda/4\Delta}$. In order to be able to detect ultrasound in the range 1–10 MHz, the free spectral range $\Delta \nu_{FS}$ (the bandwidth $\Delta \nu$ is defined as $\Delta \nu_{FS}/2$) should not be too large: taking $\Delta \nu_{FS} = 25$ MHz yields $\Delta d = 6$ m (even if folding mirrors are used, the system will be large and bulky) and $\theta_M = 2 \times 10^{-4}$ rd, for $\lambda = 1.06 \mu$m. Using an entrance aperture of 10 cm in diameter (and mirrors of this size), the system has an
étiendue of ≈ 10^{-3} \text{mm}^2 \text{sr}^{-2}. This is much larger than the optical heterodyne systems described in Section IV, but not sufficient in many cases. A spot 4 mm in diameter viewed through a six-inch lens at 1.5 m requires an étiendue of 0.1 \text{mm}^2 \text{sr}. Fortunately, there is a known way to increase the étiendue, and it will be presented below after a discussion of the time and frequency response.

The time response of this interferometer can be understood by considering that the pathlength from the laser source is changed by \( \delta(t) \) for one arm and by \( \delta(t - \tau) \) for the other [74]. Then, when the laser frequency is properly adjusted to the zero crossing, the detected signal intensity \( I_s \) is given by (\( \delta \ll \lambda \)):

\[
I_s = A_4A_5 \pi (\delta(t) - \delta(t - \tau))/\lambda.
\]  
\((15)\)

After substitution of \( \delta(t) = U \cos (2\pi f_u t + \psi) \), this expression shows that the frequency response of this probe to ultrasonic frequencies is proportional to \( S(f_u) = 2 \sin \pi f_u/2\Delta \nu = 2 \sin \pi f_u \tau \) (sketched in Fig. 15). The response is therefore only linear at low frequencies when \( f_u \ll \Delta \nu \). In this case, it can readily be shown that the detected signal is proportional to the surface velocity and to the Doppler shift and that it can simply be obtained by differentiating (14). It should also be noted that the interferometer which produces the maximum response for a given ultrasonic frequency \( f_u \) has a bandwidth \( \Delta \nu \) equal to \( f_u \) (i.e., a delay time equal to half the ultrasonic period). Identical results can also be obtained by an analysis in the frequency domain, where the interferometer is considered as a linear filter with \( 1 + \exp (-i2\pi \nu \tau) \) as transfer function and where the laser frequency plus the two sidebands are applied at the input. Other two-wave interferometers such as the Mach–Zehnder [75]-[77] can be analyzed in the same way and give similar results.

The étiendue of the Michelson interferometer can be greatly enhanced by having in the longest arm a slab of index \( n \) (glass, liquid) in such a way that the two mirrors are imaged from each other through the beam splitter and the slab [78], [79]. In this case, the two emerging rays originating from the same incident ray are superimposed in first approximation (see Fig. 16). The path difference \( \Delta \) is then equal to \( 2h(n - 1/n) \), where \( h \) is the slab thickness. The maximum ray inclination to the axis is limited by the third order spherical aberration of the slab (wavefront deformation = \( \theta^2 \Delta /8n^2 \)). This gives a maximum inclination \( \theta_m = (2n^2 \lambda/\Delta)^{1/4} \). Using the same numerical values as before (\( \Delta_{PS} = c/\Delta \)) and \( n = 1.5 \), it follows \( h = 7.2 \text{m} \) and \( \theta_m = 1.5^\circ \). If the mirrors have a size sufficient to accommodate this maximum inclination, it then results in a very large étiendue (\( \gg 1 \text{mm}^2 \text{sr} \)). If the viewed area is a \( \frac{1}{4} \) inch in diameter at 2 m, this étiendue will then require in order to be totally used, a front lens too large to be feasible. Therefore, it can be calculated that the étiendue will be limited by the viewed area and the front optics size (\( \approx 0.06 \text{mm}^2 \text{sr} \) for the example chosen), and that there is no need to increase further that of the interferometer (as explained in [80]). Such wide-angle Michelson interferometers (WAMI) have been used in shock-wave research [81] and anemometry [82].

The sensitivity of a two-wave velocity interferometer is now evaluated. We assume a beam splitter with 50-percent reflection and transmission and neglect any other reflection losses in the interferometer. The average intensity received \( I_0 \), for stabilization at half maximum, is given by

\[
I_0 = A_1 = A_2 = LE/2
\]  
\((16)\)

where \( L \) is the radiance (luminance) of the viewed area and \( E \) is the étiendue. We find

\[
L = I_0(1 - A)/\pi S_f
\]  
\((17)\)

with the same notations as before. We have assumed isotropic scattering and that all the light from the illuminated spot passing through the input lens aperture is received by the detector. We assume further a surface displacement \( \delta = U \cos (2\pi f_u t + \psi) \). The detected signal intensity at frequency \( f_u \) is

\[
I_s = I_0 S(f_u) (4\pi U/\lambda)
\]  
\((18)\)

where, in this case, from (15), \( S(f_u) = 2 \sin (\pi f_u/2\Delta \nu) \). It then follows using (3) a signal-to-noise ratio:

\[
i_s/I_0 = 4 \sin (\pi f_u/2\Delta \nu) (U/\lambda) \sqrt{nI_s(1 - A)} E\eta/(\hbar BS_f).
\]  
\((19)\)

As noted previously, the sensitivity is best when \( f_u = \Delta \nu \). For this value, we note that (19) is approximately the same as (9) of the heterodyne technique. By comparing those two equations, we can deduce that, for a given illuminated area \( S_f \), the Michelson velocity technique is better since the étiendue is not limited to \( \lambda^2 \). It is however possible to obtain about the same signal-to-noise ratio with the heterodyne technique if the incoming beam has the same size as the receiving aperture of the velocity interferometer and is focused onto the surface to a diffraction limited spot (i.e., the speckle size is of the order of the
receiving aperture and $E/S_I = \Omega$, where $\Omega$ is the solid angle and is the same in both cases). It should be noted that, in this case, the heterodyne signal will be very sensitive to the position of the target surface and if it is moving, the signal will fluctuate constantly. Also because of the sharp focusing, the depth of field will be small. The velocity interferometric technique does not have these limitations since many speckles are collected and therefore should be preferred for industrial applications. Taking the same $\Omega$ as before (e.g., aperture $40$ mm in diameter, distance $= 1.5$ m) and the same intensity ($5$ mW at $6328 \text{ A}$), we find the same limit of $= 1$ A, which corresponds to $10^{-5} \text{ W sr/Hz}^{1/2}$. For a mirror-like surface, the appropriate expression for the signal-to-noise is (19) multiplied by $\sqrt{\pi/\Omega}$. A detection limit approximately the same as the one found for heterodyne detection is also obtained.

This detection limit assumed a very stable single-frequency laser source, both in amplitude and frequency. In practice, the laser should be stabilized with respect to the interferometer. For a source which has good stability, simple piezoelectric control of the laser cavity length or the interferometer path difference is appropriate. For more unstable lasers, the fluctuations of amplitude and frequency could be compensated by dividing or subtracting electronically the signal coming from the sample with a signal representative of these fluctuations [83].

Other velocity two-wave interferometers, which could be used in principle for the detection of ultrasound have been reported in the literature: one is based on optical polarization interference in birefringent crystals [84] and the other on spectral coding or spectral modulation [85].

This technique consists of using a broad band source to illuminate an interferometer. The spectrum of the light emerging from the interferometer is modulated with a period $\Delta f_p$ equal to $1/\tau$, where $\tau$ is the delay time of the interferometer. This light is reflected by the target surface into the same interferometer and then detected. When the target moves, the spectrum of the reflected light is shifted by the Doppler effect, and a signal indicative of the target velocity is detected. As might be expected, since the same signal should be obtained independently of the sign of the velocity, the response is quadratic for small velocities and practical delay times, which result in poor sensitivity.

Such a concept has been recently put into a useful device by using fiber optics technology [86], [87], which enables long delay times (see Fig. 17). By using either a phase modulator on a fiber arm or using nonreciprocal effects of fiber birefringence, a linear signal is obtained. The amplitude of the signal depends greatly upon the surface reflectivity into the fiber. This problem is solved by dividing the signal by the one at the modulator frequency [88] (or twice the modulator frequency). Being sensitive to velocity this device is immune from ambient disturbances. Single-mode fibers should be used and since their core diameter is less than $10 \mu$m, the étendue is $\approx$ or less than $10^{-4} \text{ mm}^2 \text{ sr}$, which is more than given by optical heterodyning techniques but orders of magnitude less than provided by bulk étendue-widened Michelson or Mach-Zehnder interferometers (or confocal Fabry-Pérot, as follows).

B. VELOCITY INTERFEROMETRY WITH MULTIPLE-WAVE INTERFEROMETERS (FABRY-PÉROT)

We have seen that in order to obtain adequate sensitivity at low ultrasonic frequencies with a two-wave velocity interferometer long path length differences are required (a bandwidth of $1 \text{ MHz}$ requires a difference of $75 \text{ m}$). A solution is to use multiple-beam interference, i.e., a Fabry-Pérot interferometer. In this case, the interferometer bandwidth can be decreased nearly at will by choosing suitable mirror reflectivity (the higher the reflectivity, the narrower the bandwidth).

Fabry-Pérot velocity interferometers have been used previously in anemometry [89]-[91] and in shock-wave research [92]. For the narrow bandwiths of interest for the detection of ultrasound, a confocal Fabry-Pérot should be preferred to a planar one since it has a much larger étendue [93], [94]. Contrary to what has been stated (20), a planar Fabry-Pérot has approximately the same light gathering efficiency as a simple Michelson interferometer (not étendue-widened) for the same bandwidth. Large étendue is obtained by having the two mirrors confocal: as seen in Fig. 18, all the emerging rays overlap after two round trips (in the paraxial approximation). A large circular fringe is observed at the output, whose size is determined by the third order spherical aberration of the system.

Fig. 17. Schematic of the All-Fiber Optic Sensor (adapted from [86] and [87]).

Fig. 18. (a) Schematic showing the principle of the confocal Fabry-Pérot. Only the two rays emerging first are represented for clarity. (b) Response to optical frequency.
In the confocal Fabry–Pérot, the bandwidth and the étendue are interrelated [93], [94]: \( \Delta \nu = \frac{2 \pi^2 R^2}{E} \), where \( R \) is the radius of the mirrors. Therefore, adequate light gathering capability may require an interferometer sufficiently long. Setting \( \Delta \nu = 10 \text{ MHz}, R = 50 \text{ cm}, \lambda = 0.6328 \mu \text{m} \) gives \( E = 0.1 \text{ mm}^2 \text{ sr}^{-1} \), which enables to receive all the light through a lens 6 inches (15 cm) in diameter coming from a spot = 4 mm in diameter located on a target at 1.5 m from the lens. A confocal Fabry–Pérot system with these parameters has been realized [95] and is sketched in Fig. 19. In this system, real-time calibration is obtained by passing the incident beam through an electrooptic phase shifter, so the signal observed is independent of the target orientation and reflectivity.

The frequency response of the Fabry–Pérot velocity interferometer is not as simple to calculate as that of a two-wave interferometer. It has been calculated [96], [97] and is plotted for the parameters given above in Fig. 20, together with experiment verification data.

The sensitivity of such a receiver is now evaluated. When the laser frequency is stabilized at half height of a peak and when the two output beams are collected by the detector, the average received intensity is \( I_0 = LE/4 \) (this assumes a mirror reflectivity close to 1 and that all the light from the illuminated spot passing through the input lens aperture is received by the detector). The detected signal intensity at \( f_1 \) is given by \( \langle S(f_1) \rangle \), where \( S(f_1) \) is equal to \( 2f_1 \Delta \nu \) for \( f_1 \ll \Delta \nu \). The signal-to-noise ratio is then given by

\[
i/f_N = S(f_1) \langle U/\lambda \rangle \sqrt{2\pi I_0(1 - A) E_\gamma/(h\nu B_S)}.
\]

Since the maximum of \( S \) is \( = 1 \), (20) gives a signal-to-noise ratio \( \approx 1/2.8 \) of that given by the two-wave interferometer (19), i.e., for the same \( B \) as before (aperture 40 mm in diameter at a distance of 1.5 m) and the same intensity (5 mW at 6328 Å) the detection limit is \( = 3 \text{ Å} \) for an isotropically scattering nonabsorbing target. This value corresponds to \( 3 \times 10^{-5} \text{ Å} (\text{W sr Hz})^{-1/2} \). We should note that, when the two emerging beams are made to interfere constructively the signal is doubled and the detection limit is reduced by \( \sqrt{2} \). As mentioned above, in practice, many surfaces have a more directional scattering distribution, so the detection limit is smaller. For comparison, for a mirror-like nonabsorbing surface, this limit will be multiplied by \( \sqrt{(1 - A) \Omega/\pi} \), which is \( 1/2 \) for the example given.

**VII. Applications**

Although the purpose of this review was not to describe all the applications of ultrasonic optical detection, but rather to focus on the detection techniques, several applications which have been described in the literature are mentioned below. It is expected that these techniques will be of wider use in the future owing to the development of more powerful, more stable, and higher repetition rate lasers.

Besides being at the basis of the operation of the SLAM [10], [11] mentioned earlier, optical detection of ultrasound has been used for the characterization of SAW devices [6]–[9], [12], [47], [50], [65], [87], the characterization of ultrasonic transducers [31], [35], [45], the study of the interaction of ultrasound with defects [52], [98], [99], the detection of acoustic emission [28], [30], and ultrasonic field mapping [12], [37], [58]. In association with laser generation, it has been used in the laboratory for nondestructive evaluation of materials, such as the measurement of elastic constants of composites [100], anisotropy and acoustoelectric coupling constant of piezoelectric materials [101] and for flaw detection [61], [102]–[105]. We note also the use of similar techniques in photothermal detection [15], [16], [106]. The application of ultrasonic optical detection in industrial environments where the surfaces are rough and absorbing, where vibration and turbulence levels are high, has not been so far reported, but appears possible if a detecting device with proper sensitivity and immunity to environmental disturbances is used with a laser source of adequate stability and sufficient power.

**VII. Conclusion**

Following this review of various optical techniques to detect ultrasound, the main conclusion is that all the techniques (knife-edge, optical heterodyning, differential interferometry for in-plane measurement, velocity interferometry, and other less important techniques having not been analyzed in depth) have approximately the same sen-
sitivity. The detection limit amounts to about $10^{-6}$ Å (W/Hz)$^{1/2}$ for a mirror-like surface and about $10^{-6}$ Å (W/sr/Hz)$^{1/2}$ for an isotropically scattering surface (except knife-edge). These figures apply for a nonabsorbing surface illuminated by visible light ($\lambda = 6328$ Å). When another wavelength $\lambda$ is used, they are multiplied by $\lambda/6328$. When the surface absorbs the fraction $A$ of incident light, they are multiplied by $1/\sqrt{1-A}$. These figures also assume that all the techniques are used properly at their optimum capability for the intended use.

The choice of a particular technique for a given application is not therefore a matter of sensitivity. However, the various techniques we have described are not equivalent and some are better than others according to the intended use:

**Laboratory Applications on Polished Surfaces:** In this case, the knife-edge technique comes ahead, because of its simplicity, its insensitivity to vibrations, and its broad detection bandwidth. **Laboratory Applications on Scattering Surfaces:** Optical heterodyning should be preferred because of its broad detection bandwidth. As we have seen, it is possible to build a system which permits the detection of normal and in-plane displacements at the same location on the surface, which may be necessary for some applications. Compensation for vibrations is better accomplished with a heterodyne probe (super-heterodyne technique) than with a stabilized homodyne one.

**Industrial Applications:** The requirements of good immunity from vibrations and air turbulence, and the requirement of insensitivity to precise alignment and system setting indicate that velocity interferometry which enables to receive many speckles, should be preferred. The system based on a confocal Fabry–Pérot has the advantage to enable to tailor easily the reception bandwidth to the ultrasonic frequencies to be detected. The systems based on two-wave interferometers which are very bulky for optimum detection in the MHz range are suitable for high frequency applications (>100 MHz).

**REFERENCES**


[32] The author acknowledges the contribution of one referee of this paper for pointing out this possibility.


Acoustic displacement amplitudes on an object with a retro-reflective...


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