Random Speckle Modulation Technique for Laser Interferometry

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In spite of its obvious advantages over conventional contact and immersion techniques, laser interferometry has not yet become a practical tool in ultrasonic nondestructive evaluation since its sensitivity is insufficient in most practical applications. Part of the problem is that the maximum signal-to-noise ratio often cited in scientific publications and manufacturers' specifications cannot be maintained on ordinary diffuse reflecting surfaces. Although these surfaces reflect a fair amount (5–50%) of the incident laser light, this energy is randomly distributed among a large number of bright speckles. Unless the detector happens to see one of these bright speckles, the interferometer's signal-to-noise ratio will be much lower than the optimum. This adverse effect is almost completely eliminated by the suggested random speckle modulation technique. The conventional interferometric technique was modified to assure random occurrence of a few very bright speckles and to move the whole speckle pattern around at an appropriate speed. Random but frequent bright flashes detected from the surface of the specimen resulted. The bright periods are 0.1 ms or longer, sufficient to trigger the ultrasonic pulser and detect the transmitted signals before the flash subsides. As much as 5–10 times improvement of the optical sensitivity was achieved by this novel approach and close to maximum signal-to-noise ratio was maintained everywhere on the surface of a diffuse object.

KEY WORDS: Ultrasonic remote sensors; laser interferometry.

INTRODUCTION

Ultrasonic methods have a very important role in nondestructive evaluation (NDE) of materials. Conventional ultrasonic techniques are based either on direct contact between the ultrasonic sensor (transducer) and the workpiece to be inspected or on liquid coupling when both the ultrasonic sensor and the workpiece are submerged in water. In many applications, especially in process monitoring, remote, noncontact ultrasonic sensors are desired. A promising noncontact method to couple waves without mechanical contact is a combination of pulsed laser generation and laser interferometric detection. The main advantage of optical remote sensing is the ability to work in high-temperature (or otherwise hostile) environments and on rough surfaces, awkward shapes, and moving objects. The schematic diagram of laser generation and detection of ultrasound is shown in Fig. 1. The focused light of a high-power pulsed infrared laser irradiates a small spot on the surface of the specimen. The absorption of this very short (but intense) optical pulse causes localized heating and subsequent thermal expansion of the surrounding material. At higher laser intensities, some material at the surface may be vaporized, producing recoil forces in the specimen. Both mechanisms contribute to the generation of diverging acoustical waves in the sample; the waves can be detected at another point on the surface by a laser interferometer.

Recent development of inexpensive, neodymium-
doped yttrium aluminum garnet (Nd:YAG) solid-state lasers allows easy generation of ultrasonic waves by pulsed infrared laser irradiation for most applications. Laser detection is more difficult in similar applications, primarily because of its inherent sensitivity to external mechanical vibrations and the difficulty in assuring sufficient optical reflection from rough or darkened surfaces. The first problem is satisfactorily solved by heterodyne interferometry (a recent review of the different versions can be found in Ref. 1).

According to the heterodyne principle, the two legs of the interferometer have slightly different frequencies, which produces a so-called “beat” signal as they combine on the photodiode. A Bragg cell acousto-optical modulator shifts the laser frequency in the reference leg by a very small amount of \( f_o = 40 \) MHz with respect to the \( \nu = 5 \times 10^8 \) MHz principal spectrum line of Helium–Neon laser. Weak surface vibration caused by an incident ultrasonic wave can be detected as a proportional phase modulation of the beat signal. Assuming that the object surface exhibits a harmonic vibration \( z(t) = a \sin(\Omega t) \) with amplitude \( a \) and angular frequency \( \Omega \), the instantaneous phase of the beat signal \( \phi \) oscillates around its mean value \( \phi_m \) at the same frequency.

\[
\phi = \phi_m + \Phi(t) \tag{1}
\]

and

\[
\Phi(t) = (4\pi a/\lambda) \sin(\Omega t) \tag{2}
\]

where \( \lambda \) denotes the wavelength of the laser light.

Due to adverse effects such as thermal expansion, mechanical vibrations, acoustical noise, etc., the mean phase \( \phi_m \) is somewhat random and slowly changes in time. The ultrasonic signal \( \Phi(t) \) can be easily separated from this low-frequency component by measuring the phase of the beat signal with respect to an appropriate reference signal rather than to the local oscillator driving the Bragg cell. This reference signal is produced from the beat signal itself by simple means such as a voltage-controlled oscillator, a narrow-band filter, or a delay line.\(^{(1)}\)

One of the main advantages of laser interferometric detection of ultrasonic vibrations is that the instrument can be easily calibrated for absolute measurements because of the exceptional stability of the optical wavelength. The absolute sensitivity of the interferometer, \( S \), can be defined as the ratio between the optical phase-modulation and the ultrasonic displacement

\[
S = \frac{\Phi(t)}{z(t)} = \frac{4\pi}{\lambda} \tag{3}
\]

i.e., two times the optical wavenumber. An even more important parameter of the laser interferometer is its noise-limited detection threshold, \( a_m \), which is the vibration amplitude producing a 0 dB signal-to-noise ratio at the output of the detector.\(^{(2)}\) The threshold sensitivity measures the ability of the interferometer to detect weak ultrasonic vibrations on the object’s surface, and depends greatly on the strength of the laser light reflected from the object. As opposed to the absolute sensitivity, the threshold sensitivity is a function of many system parameters which should be optimized to obtain the best performance.

An ideal optical detector would produce quantum (or shot) noise only which is proportional to the average detector current. In this case, the threshold sensitivity can be easily determined from the condition that the signal-to-noise ratio be unity:\(^{(1,2)}\)

\[
a_m = \left( \frac{\lambda}{4\pi} \right) (4\nu B / P_r \eta)^{1/2} K^{-1} \tag{4}
\]

where \( h \) is the Planck’s constant, \( \nu \) is the frequency of the laser light, \( B \) is the bandwidth of detection electronics, \( P_r \) is the total available laser power, \( \eta \) is the photodetector’s quantum efficiency, and \( K \) denotes the optical efficiency of the system:

\[
K = 2(PP_o / P_o + P_r)^{1/2} \tag{5}
\]

where \( P_o \) and \( P_r \) denote the detected optical powers from the object and reference legs of the interferometer.

Three principal factors can be separated in Eq. (4) corresponding to three major limitations on the threshold sensitivity. The first factor is the inverse of the absolute sensitivity. For example, it is approximately 50 nm for a Helium–Neon laser of 633 nm principal wavelength. The second factor is proportional to the square-root of the ultrasonic bandwidth \( B \) and inversely proportional to the square-root of the available laser power \( P_r \). This factor is approximately \( 7.1 \times 10^{-5} \) for \( P_r = 5 \) mW laser power, \( B = 10 \) MHz bandwidth, and \( \eta = 50\% \) quantum efficiency. The third factor is the inverse of the optical efficiency of the interferometer, \( K \). If the total energy is evenly divided between the two beams and there are no
optical losses \( P_o = P_r = 1/2 P_i \), \( K = 1 \) and the threshold sensitivity is approximately \( 3.6 \times 10^{-3} \) nm. Although this threshold sensitivity would be sufficient in most ultrasonic NDE applications, it should be considered a theoretical limit, and not practically attainable.

2. OPTICAL EFFICIENCY

The main problem of optical detection of ultrasonic signals in realistic NDE applications is that the optical efficiency, \( K \), is inevitably very low for unpolished, weakly reflecting objects. It is easy to show that in such cases the best results can be achieved by directing almost all (90–95%) of the available laser power to the object beam \( (P_o = P_i) \). Still, the returning object beam power \( (P_r) \) is usually negligible compared to the unattenuated reference beam power \( (P_i) \).

From Eq. (5),

\[
K = 2R^{1/2}
\]  

(6)

where \( R = P_o/P_o \) denotes the reflection coefficient of the object. The reflection coefficient is ultimately limited by the reflectivity \( R_o \) of the surface, but it also includes additional losses due to nonspecular reflection from a diffuse surface. Figure 2 demonstrates the basic concepts of specular and diffuse reflection. For specular reflection from a polished metal surface, the incident optical power \( P_o \) is almost entirely reflected back toward the detector and \( R \) can be as high as 90% or even higher. In comparison, the reflection coefficient of a real surface is usually much lower, partly because only a smaller fraction \( R_o = 0.05 \)–0.1 of the incident energy is reflected from darker surfaces and partly because the reflected field becomes diffuse and only a small fraction of the diverging reflected energy is picked up by the object lens and focused to the detector. The main problem is that this second effect cannot be reduced simply by increasing the numeric aperture of the lens to accumulate more scattered light from a larger viewing angle. This approach would work with incoherent light only when the light scattered in different directions can be added together by focusing all rays to a given spot. On the other hand, the image of the illuminated object when using coherent laser light exhibits a random interference modulation, or "speckle pattern." Phase cancellation caused by the random phase distribution of these speckles means that averaging more than one speckle over the detector's aperture does not increase the interferometric signal.

The effect can be easily demonstrated using a brief calculation assuming that the total detector area, \( A_t \), is covered by \( n = A/A_t \) small speckles of \( A_t \) area each. The beat current component \( i_b \) produced by a single speckle can be expressed as

\[
i_b = 2r(A/A_t)(P_o/A_t)^{1/2} (P_r/A)^{1/2},
\]

(7)

where \( r \) denotes the responsivity of the detector and \( P_o \) is the optical power conveyed by a single speckle. Since the individual phases of these elemental beat current components are randomly distributed, the output beat current of the diode

\[
i_b = n^{1/2} i_b = 2rP_o^{1/2}P_r^{1/2}/A
\]

(8)

In other words, the beat current is limited by the energy content of a single speckle and cannot be further increased by adding up many speckles.

The only feasible way of increasing the optical efficiency of the interferometer seems to be to increase \( P_o \), the energy of a single speckle. Because the total reflected power \( P_o = P_o R_o \) is distributed over a \( 2\pi \) solid angle containing 50% bright speckles and 50% dark spots,\(^3\)

\[
P_o = P_o A_t \Theta/\pi
\]

(9)

where \( \Theta \) denotes the average solid angle of a single speckle\(^6\):

\[
\Theta \approx 0.11 \lambda^2/d_o^2
\]

(10)

Here, \( d_o \) is the diameter of the illuminated spot, which should be reduced to the diffraction limit to obtain the largest possible speckles. In this case,\(^5\)

\[
d_o = 4\lambda F/\pi d
\]

(11)

where \( F \) is the focal length of the objective and \( d \) denotes the diameter of the laser beam. Substituting Eq. (11) into Eq. (10) and subsequently into Eq. (9) yields

\[
P_o/P_o \approx 0.022 R_o d^2/F^2
\]

(12)

Technically we can choose the aperture-to-focal-length...
ratio \( d/F \) as high as 0.5. In this case, the reflection coefficient \( R = 0.0055 \) \( R_o \), or slightly more than 0.5% of the reflectivity \( R_o \). The optical efficiency can be calculated from Eq. \( (6) \) as \( K = 0.046 \) for \( R_o = 0.1 \) and the threshold sensitivity is still fairly good at approximately 0.1 nm for a bandwidth of 10 MHz. Practically, the aperture-to-focal-length ratio, \( d/F \), is limited by the depth of focus to values much below the above-mentioned technical limit of approximately 50%. To demonstrate the relationship between the aperture-to-focal-length ratio and the depth of focus \( z \), Fig. 3 shows the caustics of two Gaussian laser beams focused by \( d/F = 0.2 \) and 0.04. Obviously, the depth of focus is greatly reduced with a smaller focal spot diameter.

The depth of focus, \( z \), can be defined as the distance between the points where the cross-section of the beam is doubled with respect to the focal plane. For a Gaussian beam,\(^5\)

\[
z = \frac{\pi d^2}{2\lambda} = \frac{8\lambda F^2}{\pi d^2} \tag{13}
\]

which yields a meager \( z = 0.04 \) mm for \( d/F = 0.2 \) and a more convenient \( z = 1 \) mm for \( d/F = 0.04 \). Comparing Eqs. \( (12) \) and \( (13) \) reveals that the reflection coefficient of the object increases with the \( d/F \) ratio is the same way as the depth of focus decreases and their product is basically beyond our control:

\[
R_z = 0.056 \lambda R_o \tag{14}
\]

where, again, \( \lambda \) is the wavelength of the laser and \( R_o \) is the reflectivity of the object. Our main purpose is to increase the interferometer's optical efficiency to optimize industrial uses. Reducing the depth of focus to a tenth of a millimeter offers gains in optical efficiency but also renders the instrument useless in most industrial applications. A more practical approach to improving the interferometer's threshold sensitivity would be to increase the laser power or use the available power more efficiently.

3. RANDOM SPECKLE MODULATION

Previous calculations showed that assuring a reasonable focal depth of approximately 1 mm requires that the \( d/F \) ratio not exceed 0.04 which, in turn, sets a limit on the threshold sensitivity of the interferometer around 1.4 nm for dark surfaces (5% reflectivity). The actual threshold is expected to be at least two or three times higher than the theoretical optimum, and would not be sufficient in many anticipated industrial applications.

Laser interferometry's threshold sensitivity is most improved by taking advantage of the pulsed nature of the ultrasonic signals to be detected. In passive applications, the ultrasonic signal is generated in the test piece as a result of external or internal changes, such as stress, temperature, radiation, chemical composition, metallurgical structure, etc. As for detection, these signals occur randomly, therefore the ultrasonic sensor must always be ready. On the other hand, in active applications, the ultrasonic signal is generated by the inspection system itself in a periodic way. The transmitter usually radiates a few hundred pulses per second into the sample, which are then picked up by the receiver after a propagation delay. The overwhelming majority of ultrasonic NDE applications are the active type. Acoustic emission is the lone exception which really requires continuous monitoring of the sample. In that case, specularly reflecting polished surfaces might be required to assure an acceptable detection threshold.\(^6\)

A sequential diagram of active ultrasonic inspection is shown in Fig. 4. The generated pulse (often called the "main bang") is followed by a series of directly trans-

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Fig. 3. Caustics of a Gaussian beam in the vicinity of the focal plane (\( \lambda = 633 \) nm).

Fig. 4. Sequential diagram of active ultrasonic inspection.
mitted or reflected echoes within a short period, depending on the propagation delay. Because the sound velocity in most solids of interest is higher than 2000 m/s and the total propagation path is usually less than 200 mm, at least in those applications where optical sensing is feasible, the propagation delay is seldom longer than 100 μs. The brief "windows," during which ultrasonic pulse arrivals can be expected, are separated by much longer silent periods where continuous specimen illumination is simply a waste of laser energy. Concentrating the available energy into relatively short, but sufficient windows can result in a substantial improvement of the optical sensitivity. Depending on the repetition frequency, which is usually as low as 10–20 Hz for laser generation, an increase of two orders of magnitude or more can be expected in the peak intensity of the object beam, for a given average laser power.

Apparently, the easiest way to take advantage of the higher optical efficiency of pulsed operation is to replace the customary low-power continuous-wave laser by a pulsed laser of similar or even higher average output. Of course, the ultrasonic transmitter has to be electronically synchronized to the laser pulses through an appropriate delay network to assure that the interferometer is operational by the time the ultrasonic signals to be received arrive to the point of detection. Unfortunately, because of rapid fluctuations and very short spikes and bursts inherently present in the output of pulse solid-state lasers of high gain, the principal source of noise is the amplitude variation of the strong reference beam rather than the much weaker shot noise (considered in our previous calculation). In the quantum-noise-limited case, the noise amplitude turns out to be proportional to the square-root of the laser power and some (although modest) improvement of the threshold sensitivity can be achieved by increasing the laser power. In the amplitude-noise-limited case, both signal and noise are proportional to the applied laser power, and the threshold sensitivity cannot be further improved. In conclusion, high-power pulsed lasers are inherently much noisier than the commonly used low-power continuous-wave lasers.

Although pulsed operation offers the most promising opportunity to improve the laser interferometry's threshold sensitivity from weakly reflecting surfaces, use of pulsed lasers is unsatisfactory considering the excessive cost, technical complications, and small improvement. An alternative solution is to use a continuous-wave laser in combination with an optical modulator. This is also very cost effective at less than $100 per mW output. Of course, there is no way of concentrating the continuous power into brighter flashes of short duration. On the other hand, the total energy reflected from a diffuse surface is inherently spatially concentrated into a random cluster of bright speckles. The technique of random speckle modulation transfers this highly uneven spatial distribution into a similarly uneven time distribution and operates the interferometer in a pulsed mode only during the brightest flashes (or speckles).

The detectable coherent optical reflection from a diffuse surface is limited by the total laser power contained in a single speckle. Even this limited sensitivity is quite difficult to realize in practice since it assumes that the photodiode is covered by a single bright speckle. Normally, the photodiode is only partially covered by a bright speckle and occasionally a completely dark speckle is encountered. When scanning the surface with a laser interferometer, the threshold sensitivity inherently fluctuates. Although the absolute sensitivity is the same everywhere, the detector's noise level greatly increases when darker speckles are encountered. At certain points, the reduction of the optical reflection may exceed the dynamic range of the electronic system and another nearby point must be chosen on the surface for detection. Such problems cannot be avoided by conventional laser interferometry since there is no way to eliminate the speckle effect.\(^3\)

If the speckle effect cannot be eliminated, perhaps it can be used to enhance the process. Keeping one bright speckle on the aperture of the photodiode all the time is nearly impossible. But, it is feasible to assure that a bright speckle falls on the photodiode for some of the time by simple moving the speckle pattern around at an appropriate speed. For example, if there is only a 1% chance of a very bright speckle covering a detector, we can still choose a modulation amplitude and frequency that assures that approximately 100 bright speckles hit the photodiode per second and that the duration of these flashes can be approximately 0.1 ms—sufficiently long to trigger the transmitter and detect the ultrasonic pulses before the speckle moves away.

The schematic diagram of the random speckle modulation technique is shown in Fig. 5. The interferometer uses a continuous-wave, Helium–Neon laser with 5 mW output power at 633 nm. An electromechanical vibrator scans the focal spot around the reference point on the specimen's surface. This motion is dominantly normal to the surface, but some lateral wobbling can also occur. The laser beam is very sharply focused to a diffraction limited spot by an objective lens of typically \(d/F = 0.2–0.5\) aperture-to-focal-length ratio. Although the depth of focus is as low as 0.1–0.2 mm, the actual measuring range is determined by the modulation depth, and it can be as high as 10 mm or even more. Relatively low modulation frequency of 20–200 Hz is used to assure a suf-
4. EXPERIMENTAL RESULTS

Figure 7 shows the geometrical arrangement of the experiment using a Polytec OFV2000 Laser Vibrometer. This small and rugged interferometer was originally designed for relatively low frequency (below 200 KHz) industrial applications. In order to extend its frequency range up to 20 MHz, we equipped this instrument with a home-made high-frequency phase-demodulator using the selective filtering technique. The interferometer uses a double-lens focusing system schematically shown before in Fig. 5. The first lens of small diameter and focal length \( d_1 = 5 \text{ mm} \) and \( F_1 = 8 \text{ mm} \) expands the 1-mm-diameter collimated beam of the Helium–Neon laser. The second lens of much larger dimensions \( d_2 = 28 \text{ mm} \) and \( F_2 = 50 \text{ mm} \), focuses the expanded beam on the object’s surface to a diffraction limited spot. The smaller first lens is mounted on a 50-mm-long spring cantilever which is vibrated by an electromagnet at its resonant frequency of approximately 200 Hz. The vibrational amplitude of the lens can be adjusted between 0.5–3 mm peak-to-peak.

Figure 8 shows the actual amplitude distribution of the beat signal at a given point on the object. This 40-MHz beat signal is proportional to the square-root of the coherently reflected power from the object. Due to the random nature of the speckle pattern, the amplitude changes in a wide range of approximately 60 dB. A simple electronic circuitry detects and holds the peak of the signal for about 10 ms. A comparator generates a trigger signal for the ultrasonic transmitter whenever the beat signal exceeds 90% of the previous peak. These trigger signals are not necessarily periodic. First, there might be more than one speckle of equally bright-ness generated at a given point. Second, due to the back-ward and forward motion of the vibrating lens, the brightest speckle occurs two times in each vibration cycle. This “aperiodic” behavior is clearly shown in Fig. 8. Finally, whenever the interferometer moves with respect to the test object, the speckle pattern can significantly...
change during one vibration cycle and the beat signal will never repeat itself. Nevertheless, the ultrasonic inspection is not affected in any way by this somewhat irregular triggering unless the average number of pulses per second drops below a minimum.

The average length of the bright flashes can be increased by reducing the modulation speed, i.e., by reducing the vibrational amplitude or frequency. In the first case, the effective focal depth becomes proportionally smaller, while in the second case, the repetition frequency of the trigger signal drops accordingly. The optimal adjustment can be found by considering all three requirements. For example, a repetition frequency of 200 Hz and a focal depth of 10 mm can be easily maintained for 200 μs flash duration, which is more than sufficient to run most ultrasonic experiments. Naturally, this extended focal length will not have an adverse effect on the threshold sensitivity of the interferometer, which is related to the instantaneous focal depth z of the focusing objective (see Eqs. 4, 6, and 14). Random speckle modulation does not increase the peak sensitivity of the interferometer, which is acceptable in many NDE applications, but it maintains this peak sensitivity everywhere on a diffusely reflecting surface, which is absolutely necessary in industrial applications.

This improvement is well demonstrated in Fig. 9 and 10 showing the two-dimensional amplitude distributions of the beat signal without and with random speckle modulation. These pictures were taken by the experimental system previously shown in Fig. 7. The amplitude of the beat signal (or speckle brightness) is plotted as a function of the relative position of the test object with respect to the interferometer. A computer-controlled X-Y table was used to move the object over a range of 10–2.5 mm in the axial and lateral directions, respectively. In the conventional mode of operation, i.e., without the random speckle modulation, the focal range was less than 1 mm which requires that the object be placed precisely at the focal distance and be kept there within a few tenth of a millimeter. Even then, the beat signal might be very weak whenever a dark speckle is encountered accidentally. At these points, the signal-to-
noise ratio might be so low that either the test object or the interferometer has to be moved a little to regain an acceptable signal. On the other hand, random speckle modulation completely eliminates these very dark speckles and extends the effective focal range to close to 10 mm.

A more quantitative comparison between these two distributions is presented in Figs. 11 and 12 showing the density distributions of the speckle patterns shown in Figs. 9 and 10. The suggested random speckle modulation technique increased the average level by more than 10 dB and, even more importantly, the lowest levels by almost 20 dB. The beneficial effect of this considerably higher and more even speckle brightness distribution is clearly visible in Figs. 13 and 14 showing the ultrasonic B-scans obtained by moving the object 0.5 mm laterally in the focal plane. Both B-scans represent a 10-μs-long portion of the detected signal. The center frequency of the contact transducer used to generate the ultrasonic pulse at the other end of the 2"-thick object was 2.25 MHz. The random speckle modulation technique greatly increased the average signal-to-noise ratio. Without it, the noise distribution was very uneven: some of the A-scans were very clean while others were completely lost in noise. As a result of the random speckle modulation, the signal-to-noise ratio is equally high everywhere in Fig. 14 and very close to the best lines of Fig. 13.

5. CONCLUSIONS

A novel data-acquisition and signal-processing technique was introduced to increase the average signal-
to-noise ratio and effective focal range of laser interferometry. The suggested technique, which is called random speckle modulation, requires only minor modifications in the commonly used and commercially available continuous-wave heterodyne interferometers. We have demonstrated that the effective focal range can be easily increased to 10 mm while not only maintaining but significantly improving the threshold sensitivity. This simple technique works very well on moving objects as well. These improvements can greatly increase the feasibility of laser interferometric detection in industrial NDE applications.

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