SOURCE EFFICIENCY AND SENSOR DETECTABILITY FACTORS IN LASER ULTRASONICS

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INTRODUCTION

Perhaps the greatest fundamental deterrent to the application of current laser ultrasonic technology has been the fact that the detection sensitivity or detectability of laser receiver systems, compared with their piezoelectric counterparts, is rather poor. That is to say that in general, and especially on a dollar-for-dollar basis, piezoelectric transducers are able to detect much smaller surface displacements than can easily be detected by laser methods. As will be discussed shortly, there are several strategies which may be used to overcome these detectability shortcomings. Indeed, several of these strategies have been investigated at the laboratory level and some implemented in full-scale systems which have been demonstrated to perform reliably and with good detectability even in an industrial or field inspection application [1]. In this latter case, however, the successful strategy pursued to improve laser ultrasonic detectability limits has not been inexpensive in terms of the cost of laser equipment necessary to reach satisfactory performance levels. Nevertheless, there are several inspection and process control applications where critical structural and materials property information can only be obtained by remote noncontact ultrasonic inspection, thus justifying the expense of such a sensor system.

DETECTABILITY

In order that a common vocabulary might be employed in discussing the limits and potential improvement of detectability of laser ultrasonic systems, consider the definitions illustrated graphically in Figure 1. Such a plot could be applied in general to a large number of transducers in which some sensed parameter, in this case surface displacement or velocity, causes a corresponding change in the transducer output. The rate of change of output as a function of the input parameter is called sensitivity and is the slope of the transducer response curve. As the amount of surface displacement being transduced becomes smaller and smaller, the output decreases as well, but only to the point where noise inherent either in the detection process or in the amplifying and processing electronics exceeds the level of the expected output signal. The point at which the measurable output falls below the noise floor for that particular transducer is referred to as the detection limit or the system's detectability. Detectability, therefore, can be improved by reducing the noise floor, increasing the sensitivity, or amplifying the output signal without amplifying the noise. In any of those cases, however, the ratio of signal-to-noise must be improved in order to enhance the detectability.

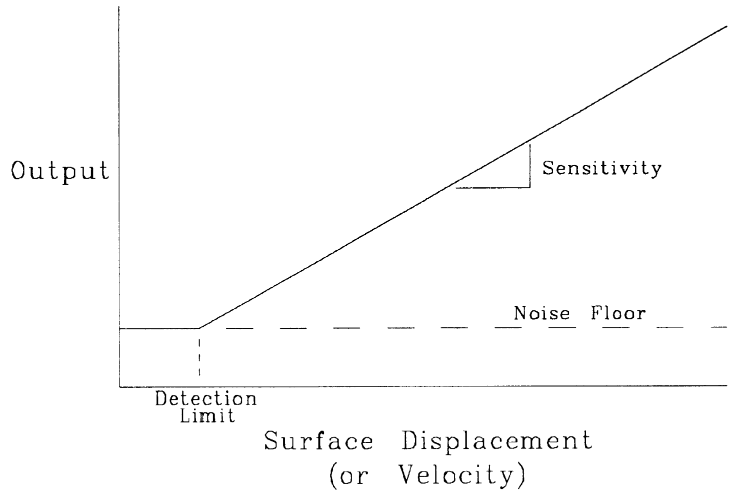

Fig. 1. Generalized transducer response curve.

While it is often the case in practice that other noise sources are encountered, such as thermal noise, ambient vibration, and fluctuations in laser amplitude or frequency, these can, in principle, be controlled whereas shot noise represents a fundamental base line for noise over which the system developer has no control [2]. In fact, so-called shot noise limited performance of laser interferometer detection systems is not difficult to achieve, especially in a laboratory setting. For this reason, one can consider that the fundamental signal-to-noise ratio which must be improved to enhance laser ultrasonic detectability is that ratio between the surface displacement or velocity signal and the shot noise from the detector within the interferometer system. For virtually all interferometer designs, the proportionality shown below for the signal-to-noise ratio applies [3].

Only the three parameters δ, P, and B are shown since these represent factors over which a laser ultrasonics system's designer or developer may exercise control. In order that this expression might take on some numerical significance, note that one can solve for the minimum displacement, that is, the detectability

$$SNR \propto \delta^2 \frac{P}{B}$$

$$\begin{aligned}&\textit{where}:\\&\quad \delta \text{ - surface displacement}\\&\quad P \text{ - optical power}\\&\quad B \text{ - system bandwidth.}\end{aligned} \quad (1)$$

limit, δ_{min}, at the point where the signal-to-noise ratio equals 1, such that:

$$\delta_{min} \propto \sqrt{\frac{B}{P}}. \quad (2)$$

For laser interferometer systems, investigators report a detectability limit on the order of 10^{-5} angstroms, $(Watt/Hz)^{1/2}$. Note that the units of $(Watt/Hz)^{1/2}$ indicate that for an interferometer system capable of capturing and processing one watt of optical power and operating only with a 1Hz bandwidth, could indeed see displacements as small as 10^{-5} angstroms. In practice, however, most laboratory systems collect only a few milliwatts of reflected laser light and may operate at bandwidths of 5MHz to 10MHz (though much higher bandwidths are possible). In that case, the absolute detectability limit is on the order of 0.5 angstroms of surface displacement. While this number sounds impressively small, bear in mind that piezoelectric transducers are able to provide even greater detectability.

From Equation 1 then, it is clear that enhancements to signal-to-noise ratio which will be necessary to broaden the applicability of laser ultrasonic systems depend on the possibilities either for improving δ, the surface displacement, or P, the received reflected optical power, or upon reducing B, the overall system bandwidth. What remains then, is to consider schemes by which each of these parameters might be appropriately modified to enhance signal-to-noise ratio and thus improve the effective detectability.

MAXIMIZING SURFACE DISPLACEMENT, δ

To determine how one might increase the amplitude of an ultrasonic disturbance produced by laser excitation of the surface, it will be important to recall how the surface of a material acts as a transducer to convert impinging optical energy into acoustic energy. From a macroscopic perspective, there are surface thermoelastic, constrained (or buried) thermoelastic, and surface ablative (or plasma) source mechanisms. These depend on the laser source power density and materials properties.

Modifying Laser Source Parameters

Understanding now that the efficiency with which the surface of a material can transduce laser light into ultrasonic energy is a function of material absorption and laser power density, one can consider now the potential for improving δ, the surface displacement, by proper selection of the source laser. The first parameter of the laser which might be controlled, although not necessarily the easiest, is the wavelength of the laser source. In general for metals and alloys, the shorter the wavelength of the source laser, the greater is the absorption efficiency. In polymers and composite materials, longer wavelengths may be strongly absorbed depending on the prevalent chemical bonds in the polymer or polymer matrix of a composite [4]. Unfortunately, the decision to change significantly the laser wavelength in order to improve absorption efficiency for one material relative to another often requires the purchase of an entirely different laser or laser system.

As discussed previously, laser power density can have a profound effect on the amplitude of the laser generated acoustic signal including altering significantly the mechanism by which sound is produced. In the thermoelastic regime, one observes a linear increase in the amplitude of both bulk, shear, and longitudinal waves as well as surface waves with increasing laser energy deposition [5]. Beyond the point at which the incident laser power density exceeds the ablation threshold for the material being inspected, a phenomenon which appears to be a shielding of the surface by the plasma generated on ablation reduces initially the amplitude of the shear wave generated [5]. The longitudinal wave, however, appears to continue to increase in amplitude with increased laser energy deposition up to a point where, once again, an apparent shielding by the plasma becomes so severe that the longitudinal wave generation efficiency itself decreases. Still, all of this discussion of the ablative mechanism for generation of laser ultrasound is appropriate only for those applications where the small amount of surface damage produced by laser ablation can be tolerated. In many cases, therefore, the limits to the value of δ (surface displacement) which can be produced by a laser generation mechanism are imposed by the threshold value at which surface damage begins to take place. This limit is imposed based upon the wavelength of the laser source and the absorption and thermal conductivity properties of the surface. In many instances the maximum laser ultrasonic signal which can be produced safely may be well below that which could have been generated without damage by a contact piezoelectric transducer.

Laser Arrays

Several investigators have considered distributing the laser energy over the surface and delivering sub-damage threshold levels of laser energy in such a manner that enhanced signal strengths can be generated without the risk of surface damage [7-11]. Single-point time-modulated arrays have been shown to produce an enhancement of the ultrasonic signal energy at a single frequency to which the receiving system can then be tuned [12,13]. Distributed arrays of laser energy have also been shown to produce enhancement. In these cases, by controlling the array spacing and/or timing of array excitation so that the weaker signals generated by each array element can be superimposed to produce a single large amplitude ultrasonic displacement [7-10,14].

INCREASING REFLECTED LIGHT POWER, P

Referring back to Equation 1, notice that improvement in the signal-to-noise ratio can be made by increasing the value of the parameter P, the optical power captured and processed by the interferometer system. The laser ultrasonic system developer may have the freedom to alter several parameters which might increase the value of P. These parameters include the reflectivity and surface finish of the specimen being inspected, the design of the optical receiver, and the laser power used in the receiving system.

Material Finish

Since the signal-to-noise ratio is directly related to the light power which can be collected and processed by an interferometer system, it may be obvious that the ability of the surface of a particular material being inspected to reflect light can have a critical effect on the detectability of the laser system. Metallic materials which can be polished in the laboratory can be made to provide near-mirror quality specular reflection of a laser beam back into an interferometer system to achieve sufficiently high values of P to obtain good signal detectability. Metalized tapes and retro-reflective coatings have also been applied to polymeric and ceramic specimens in particular which can not be polished locally. Unfortunately, it is more likely the case in a field or industrial application of laser ultrasonics that the ability to polish or otherwise modify the surface of a specimen being inspected is a degree of freedom which will not be afforded to the inspector. One must, therefore, consider other mechanisms by which to increase the collected light power P.

Receiver Design

While a myriad of interferometric systems has been proposed and demonstrated to be effective for the detection of small ultrasonic disturbances [15], they can be classified to fall into one of two general optical categories. The first of these categories includes those interferometer systems in which a single beam (the equivalent of a single ray of light) is reflected from the surface and processed and detected by the interferometer. Such interferometer systems require that the surface being inspected be specularly reflective, at least over the region where the optical beam is reflected from the surface. As mentioned above, it is often possible in the laboratory to polish the surface of an object to be studied using laser ultrasonic systems and, thereby, meet the requirement of this particular category of interferometer systems. Even as-machined surfaces can be inspected with these systems provided the light from the interferometer is focused down to a very fine point of a few microns across so that the region over which the object must reflect specularly is dramatically reduced. Alternatively, light can be collected as scattered from a rough surface, but then light only from a single or very few number of optical speckles corresponding to reflections from portions of the rough surface which reflect light directly along the axis of the interferometer can be processed. Since the total amount of light processed from a rough scattering surface is only a small fraction of that reflected by the surface, the effective value for P is dramatically reduced when a single beam interferometer system is used to test objects with rough surfaces.

A second category of interferometers are those which are able to process and interfere entire speckle fields which may be collected over a broad area from reflection of light at a relatively small point from the scattering surface of a rough specimen. Interferometers in this category include time-delay systems and Fabry-Perot interferometers [16]. Since even scattered light can be processed effectively by interferometers of this category, constraints on surface finish, as well as the orientation of the surface normal relative to the interferometer system, are greatly relaxed.

Receiver Laser Power

It was pointed out in the earlier discussion on options for enhancing laser generation of sound that increasing the intensity of the laser generating beam could also increase the amplitude of a signal generated. It turns out that increasing the intensity of the receiving laser can also cause a corresponding improvement in detectability. While most laboratory systems incorporate detecting lasers producing only a few milliwatts of laser power, they are used most often to perform laser ultrasonic studies on specimens whose surfaces can be polished or otherwise prepared to insure a high degree of reflectivity. On an optically rough or strongly absorbing surface where one cannot exercise any option to modify the surface properties, however, an increase in reflected light can be achieved by simply increasing the intensity of the laser receiver beam incident on the surface at the point of detection. This technique has been used very effectively, although at consider cost, in systems which have been demonstrated industrially [1]. In lieu of small continuous wave helium neon lasers providing several milliwatts of outputs, frequency stabilized and smooth pulsed Nd:YAG lasers with pulse durations in excess of 10's of microseconds have been used in laser receiver systems. Usable signal detection levels have been demonstrated even on black graphite epoxy panels in excess of 1/2" thick. As laser technology improves, it may be that this approach of using very large receiving laser powers may become more economical for a broader range of field applications.

DECREASING BANDWIDTH, B

The total noise power introduced into a detection system will be proportional to the area under the noise curves bounded by the upper and lower frequency cutoffs of the detection system. In other words, by decreasing the bandwidth of the interferometer detection system and its processing electronics, one can reduce the amount of noise processed by the system. However, the energy within the signal whose detection is desired may also have a broad frequency distribution. Therefore, in limiting the bandwidth in order to reduce noise, one may soon reach the point where bandwidth limits are also excluding useful signal energy. For this reason, an arbitrary reduction in signal bandwidth may not achieve an overall enhancement signal-to-noise ratio. Rather, it will be necessary to insure that the bandwidth of the interferometer system, while reduced to eliminate noise, is still sufficient to admit the desired signal energy.

Ultrasonic signals generated by a pulsed laser tend to mimic the temporal characteristics of the laser pulse used to generate the sound. Therefore, for short laser pulse excitation, correspondingly short acoustic pulses are generated. Thus, these short time-domain pulses give rise to a very broad bandwidth distribution of energy in the frequency domain. Since a broad bandwidth receiving system must be used to detect the short laser generated acoustic signal, it will also admit shot noise over a broad bandwidth. To help overcome this conflict and to improve signal-to-noise ratio by the reduction of overall system bandwidth, it has been possible to time modulate and spatially modulate the laser source to produce narrowband ultrasonic signals. Using interference patterns [9], lenslet arrays [14], and diffraction graitings [10], the output beam of a source laser has been broken into a pattern of lines or spots, each of which serves as a local source of laser generated ultrasound. Depending upon the location of the detection point, either on the front or back

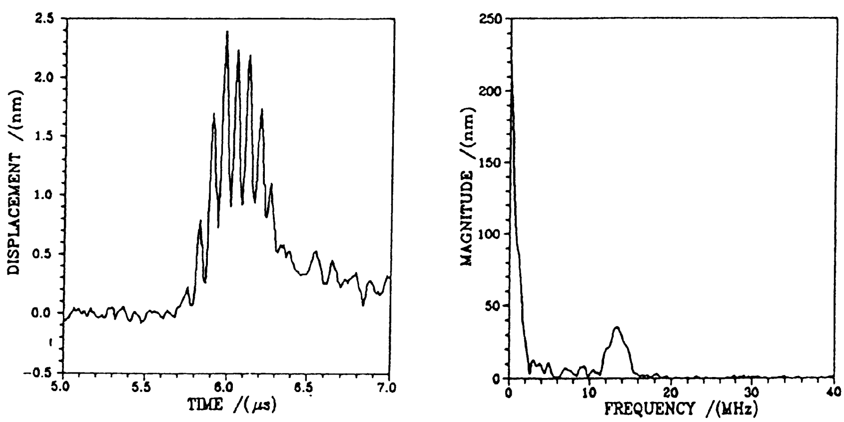

Fig. 2. Narrowbanding of acoustic signals using an array of laser line sources.

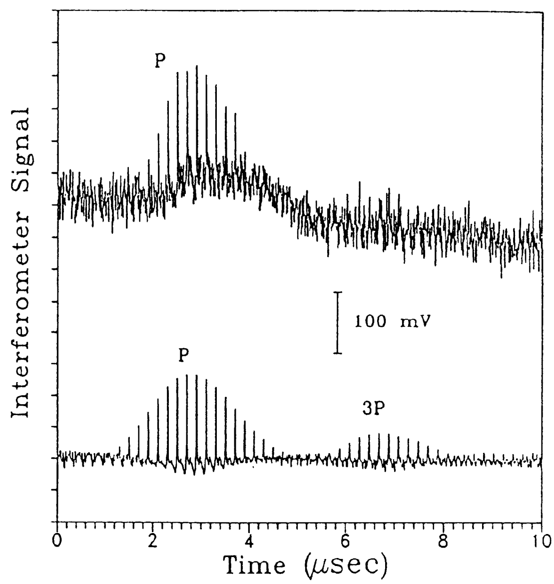

Fig. 3. Effect of narrowband (Weiner) filtering of a laser-generated ultrasonic signal produced by multiple pulsing at a single point.

surface of the specimen, energy from these array points arise in sequence depending upon the point separation. This effect is illustrated in the data presented in Figure 2 in which a series of eight cyclindrical lenslets were used to focus a laser beam into eight narrow lines on the front surface of a 1" thick aluminum specimen. Signals are shown as detected from the epicenter and from 60° off-epicenter on the back surface of the specimen. Strong enhancement of the signal content at 13 MHz is evident.

An alternative technique to using simultaneous excitation of multiple array elements is to perform time modulation of the laser beam at a single point. Several schemes have been used including Q-switching [12], long-cavity mode locking [13], and most recently, external cavity delay line system. Figure 3 shows a clear enhancement in signal-to-noise ratio when a time-modulated single-point excitation technique is employed. In the upper part of the figure, the broadband signal is plotted while below, the same data appear after having been processed using the filter whose bandwidth characteristics match those of the signal generated. Since only noise has been rejected by this processing method, the signal appears with much greater clarity and even the 3P multiply reflected signal arrival is now observed where it was previously obscured by the noise.

CONCLUSIONS

Laser ultrasonic systems continue to possess as yet unrealized potential for industrial and field applications where noncontact, remote, and high fidelity ultrasonic testing may be used to great advantage. Unfortunately, detectability limits impose difficult restrictions on the use of laser ultrasonic systems. On the other hand, design options do exist which should help insure that needed detectability can be obtained for a given application. This points up, however, the characteristic that successful design and use of laser ultrasonic systems will be application-specific to a degree far greater than conventional contact ultrasonic inspection systems. Still, with the great potential of laser ultrasonic technology, there must be continued research and development directed at existing and new schemes to improve detectability economically for broader application of laser ultrasonic technology.

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