DIRECTIONAL LASER GENERATION AND DETECTION OF ULTRASOUND WITH ARRAYS OF OPTICAL FIBERS

Yves H. Berthelot and Jacek Jarzynski

School of Mechanical Engineering
Georgia Institute of Technology
Atlanta, Georgia 30332-0405

The generation and detection of ultrasound with laser beams has become a viable technique in nondestructive testing of materials [1,2]. The main advantage of the technique is its intrinsic non-contact nature. Its main limitation seems to be its fairly low efficiency as compared with that of other standard NDE techniques. An interesting recent development [3-5] consists in using optical fibers to guide the laser light and illuminate the sample under investigation in virtually any desired source configuration. Another inherent advantage of the use of optical fibers is that the optical bench is completely decoupled from the sample under investigation, thus rendering the technique practical for in-situ measurements. The objective of the present study is (1) to present some preliminary experimental results complementary of those of Vogel [4] on the generation of ultrasound with an array of optical fibers; (2) to discuss the possibility of generating directional surface waves in a very narrow frequency band, thus increasing the signal-to-noise ratio; and (3), to discuss the feasibility of the directional detection of ultrasound by using an array of optical fibers as a receiver, also with the goal of increasing the signal-to-noise ratio.

GENERATION OF DIRECTIONAL ULTRASOUND

Optical fibers can be used to guide laser light from a remote optical bench to a sample under investigation. Positioning the fibers over the surface of the sample can be quite accurate and virtually any heating configuration can be achieved on the specimen. Of particular interest is the array configuration which can provide substantial directivity in the thermoelastic generation process. [It is assumed that the laser power density on the surface is such that the thermoelastic mechanism of sound generation is the dominant one]. A block diagram of the experiment is shown in Fig. 1. It is desired to produce ultrasound at an angle of 60^o below the surface of a $45 \times 50 \times 71$ mm block of aluminum. For simplicity, the array effect is tested with only two fibers. The laser source is a 1 watt CW argon-ion laser whose intensity is modulated with an acousto-optic (AO) Bragg cell such that the ultrasound generated is a tone burst of 5 periods of a 1 MHz signal. (The details of the modulation process can be found in ref. [5]). The key element in achieving the desired directionality is to use the fibers not only as light waveguides but also as time-delays so that a phased array of thermoelastic sources is produced on the surface of the sample. Proper phasing is achieved when the generation of ultrasound at point B (facing the end of the second fiber) is delayed by an amount equal to the time taken by the tone burst generated at point A (facing the end of the first fiber) to travel the extra distance

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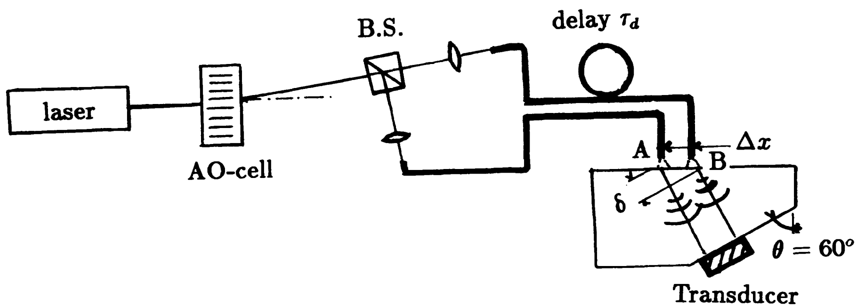

Fig. 1. Laser generation of directional ultrasound.

δ it has to cover before reaching the receiving transducer at the desired angle (60^o) below the surface. In other words, if one can delay the light output by the second fiber by an amount δ/c_L, where c_L is the longitudinal wave speed in the sample, the tone bursts emanating from both fibers will be received in phase at the transducer.

The delay in the second fiber is produced by having a second fiber longer by an amont Δl than the first fiber so that the phase relationship between the two tone bursts is

$$\phi = \omega\left(\frac{\delta}{c_L} - \frac{\Delta l}{c_{light}}\right)$$

where ω is the angular frequency of the ultrasound being generated and c_{light} is the speed of light in the optical fibers. In our experiment, the following values of the parameters were used: $\omega = 2\pi \times 10^6$ rd/s, $\delta = \Delta x \cos 60^o$ (where Δx is the distance separating the two fibers on the surface of the sample), $\Delta l = 50$ m, and $c_{light} = 2 \times 10^8$ m/s (multimode fiber with index of refraction of 1.496). Fig. 2 shows the recorded waveforms at the receiver, a 1 inch 1 MHz NDT transducer. Fig. 2(a) represents the acoustic signature recorded when the two fibers are illuminating the same spot, i.e., when $\Delta x = 0$ mm and the signals received from the two fibers are 90^o out of phase. In such a case the rms-voltage over the pulse duration (5 μs) is 2.27 mv-rms. A similar acoustic signature is shown in Fig. 2(b) for the case when $\Delta x = 3$ mm, so that the acoustic signals generated by each fiber are received simultaneously at the receiver ($\phi = 0$). Fig. 2(b) does indicate that a stronger signal is present (as compared with that of Fig. 2(a)) thus validating the principle discussed in the previous section. The rms voltage computed over the pulse duration is 2.86 mv-rms. The minimum amplitude of the laser generated ultrasound is recorded when the two fibers are separated by a distance $\Delta x \approx 8$ mm. The measured waveform is shown in Fig. 2(c) The rms voltage is then reduced to 1.21 mv-rms. The signals shown in Fig. 2 have been averaged over 64 samples in order to increase the signal to noise ratio. It should also be kept in mind that the size of the receiving transducer (1 inch diameter) tends to modify the phasing array effect by averaging over its surface. The gain due to the array effect is expected to be proportional to the square root of the number of fibers being used. In the above experiment, the gain is thus expected to be 1.41 which is in reasonable agreement with the measured gain of 1.26 in the rms value of the signals.

The system shown in Fig. 1 uses an AO-modulator to obtain short bursts of light for the generation of ultrasound. The method requires that the laser either operates continuously or produces relatively long (several microseconds duration) pulses of light. The light power level is then limited to, typically, the kilowatt range. For the generation of ultrasound, lasers are

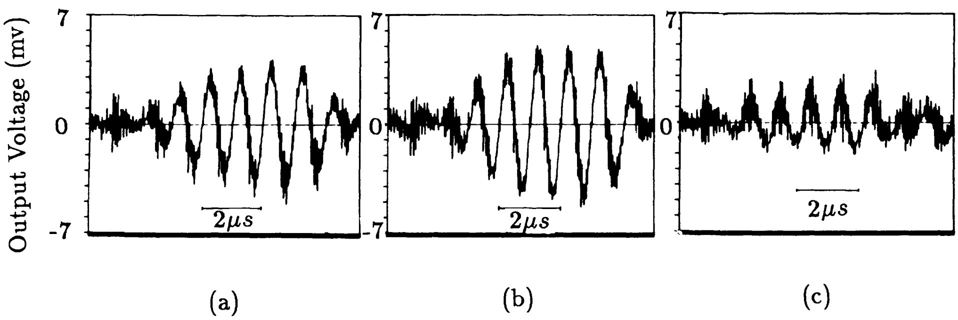

Fig. 2. Array effect in the laser generation of ultrasound with proper time delays through optical fibers. (a): $\Delta x = 0$ mm; (b): $\Delta x = 3$ mm; (c): $\Delta x = 8$ mm.

often operated in the Q-switch mode, producing very short (nanoseconds duration) high power (megawatts) light pulses. Optical fiber arrays can also be used with lasers operating in the Q-switch mode. In this case, light is coupled directly from the laser to the array using a star coupler (as demonstrated in ref. [4]) or by using a lens system to directly focus the light into the array. Multimode fibers can carry light pulses at power levels in the megawatt range. In summary, one can enhance the laser generation of ultrasound in a sample by producing a phased array with optical fibers of different lengths. The proof-of-concept experiment with only two fibers and a CW modulated laser needs to be extended to multiple-fiber arrays and possibly to two-dimensional shaded arrays. New developments in laser-to-fiber coupling and multi-fiber coupling could render the technique very useful for in-situ NDE applications.

LASER GENERATION OF NARROWBAND SIGNALS

In an effort to improve the detectability of laser-generated signals, several authors [6-8] have proposed to reduce the bandwidth of the signals, thus increasing the signal-to-noise ratio by reducing the noise present in the signal. Only the noise present in the narrow bandwidth of analysis affects the signal detection. Let a laser beam (an unmodulated CW laser or a long laser pulse) be scanned with an AO-cell in such a manner that a fiber is illuminated periodically every T_0. The question is then to find a "good" value of T_0 such that ultrasound is produced in a narrow bandwidth centered around $1/T_0$. A diagram of the proposed setup is shown in Fig. 3. As in Section I, several fibers are used to produce a directional phased array. However, the time delay between the illumination of the fibers is not produced by lengthening the fibers but rather by scanning the laser beam at a finite angular velocity $\Omega = d\alpha/dt$ over the fibers. The scan is achieved by an AO-cell driven by an FM-ramp signal of periodicity T_0. The deflection angle α of the first-order Bragg beam is, for small angles, directly proportional to the input frequency to the Bragg cell according to $2\alpha = k_{ac}\lambda_{opt,AO}$, where k_{ac} is the acoustic wavenumber in the cell and $\lambda_{opt,AO}$ is the optical wavelength in the cell. This type of periodic scan over the array of fibers allows to use unmodulated laser light. (In effect, the time modulation is replaced by a spatial modulation which makes full use of the array of fibers).

The basic idea behind the experimental setup shown in Fig. 3 is that the repetitive scan over the fibers tends to narrow the bandwidth of the thermoelastic signal. This is particularly true if the signal generated by a single fiber is bipolar in nature, since a series of bipolar pulses repeated at the proper rate could resemble a somewhat single frequency signal. It is well known [9] that surface waves generated at a free surface with a laser source (in the thermoelastic regime) do produce bipolar transients. The analysis below is thus restricted to the laser generation of surface waves.

The first step in finding a "good" value for the scan period T_0 is to find the time scale associated with a laser generated transient. The following analysis, although very simplified, gives valuable insight into the time scale of the problem. In the thermoelastic regime, the laser acts as a heat source (i.e., a monopole) of strength proportional to $q(t)I(\vec{r})$, where $q(t)$ represents the time waveform of the laser pulse, and where $I(\vec{r})$ represents the spatial laser intensity distribution. Let the laser excitation be Gaussian in space and let it be an ideal impulse in time ($q(t) \rightarrow \delta(t)$, the Dirac delta function). The thermoelastic wave displacement is thus directly proportional to the impulse response of the medium (i.e., to the Green's function of the problem). For a Gaussian laser beam of effective radius a , the impulse response is

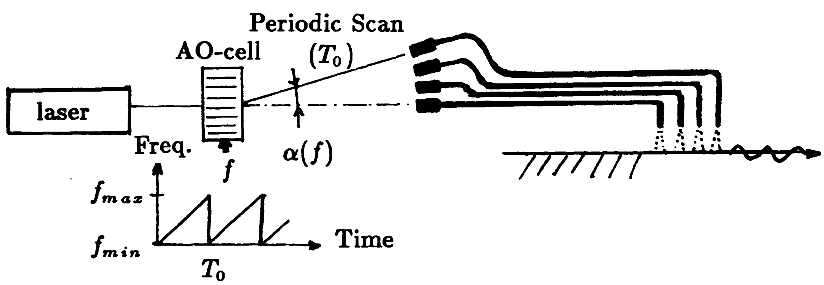

Fig. 3. Laser generation of directional narrowband ultrasound.

proportional to $\exp(-\xi^2)$, where $\xi = (r - c_R t)/a$ is a measure of the normalized retarded time. (c_R is the propagation speed of Rayleigh waves on the surface of the sample). It is implicitely assumed that the medium is isotropic, that the heat source is localized to a skin depth very small compared with the laser beam radius, and that the receiver is several beam diameters away from the source. For a laser beam illuminating a free surface, the effect of the boundary is to produce an image source such that the direct and image sources behave in fact like a dipole. The dipole effect can be thought as a spatial derivative, so that the final expression for the displacement u is

$$u \propto \frac{\partial}{\partial \xi}\left(e^{-\xi^2}\right) \propto \xi\, e^{-\xi^2}$$

The above simple analysis predicts that the expected waveform is bipolar in nature, with a time $\delta T = \sqrt{2}(a/c_R)$ between the two peaks. Table 1 shows a comparison with experimental data taken by Scala and Doyle [9] where the quantity $1/2\delta T$ is measured as a function of laser beam radius a. Except for the two smallest values of a (for which the authors warned that ablation was probably dominant over the thermoelastic regime), the data seem to support the time scale analysis described above.

The second step is then to find the relationship between the frequency spectra of the signal generated by a single laser pulse and that generated by a periodic sequence of N_p laser pulses

Table 1. Comparison of predicted time scales δT for laser generated ultrasonic transients with the data of Scala and Doyle [9] as a function of beam radius a.

Beam	radius a (mm)	0.44	0.56	0.75	1.0	1.2	1.37	1.62	1.94
$1/2\delta T$	measured(MHz)	1.9	1.8	1.2	0.9	0.8	0.7	0.6	0.5
$1/2\delta T$	predicted(MHz)	2.4	1.9	1.4	1.1	0.9	0.8	0.6	0.5

with the same total energy. Let $u_b(t)$ and $u_n(t)$ be the broadband (single pulse) and narrowband (periodic pulses) displacement waveforms, respectively. Let their Fourier transforms be denoted by $\hat{u}_b(\omega)$ and $\hat{u}_n(\omega)$, respectively. It can be shown that they are related by

$$\left|\hat{u}_n(\omega)\right| = \left|\hat{u}_b(\omega)\right|\left|\frac{\sin(N_p\omega T_0/2}{N_p\sin(\omega T_0/2)}\right|$$

where T_0 is the repetition period. The function $|\sin N_p\chi/N_p\sin\chi|$ peaks at unity whenever χ is a multiple of π. Therefore $|\hat{u}_n(\omega)|$ contains peaks around $1/T_0$ (fundamental), $2/T_0$ (second harmonic), and higher harmonics. An arbitrary criterion that can be used to define a "good" value for T_0 is that the second harmonic be 10 dB below the fundamental. This criterion ensures that the signal $u_n(t)$ is narrowband and centered around $f_0 = 1/T_0$. Since $\hat{u}_b(\omega) \propto \hat{\omega}\exp[-(\hat{\omega}/2)^2]$, where $\hat{\omega} = \omega(a/c_R)$, it can be shown that the value of T_0 which satisfies the above criterion for narrow bandwidth is $T_0 \approx 4(a/c_R)$. Fig. 4 shows the magnitudes of the Fourier spectra $\hat{u}_b(f)$ (broadband) and $\hat{u}_n(f)$ (narrowband) for $a = 1$ mm, $c_R = 3$ km/s, and for $N_p = 25$. The repetition period is thus $T_0 = 1.33\mu$s corresponding to an ultrasonic frequency of 0.75 MHz. The value of N_p is chosen to illustrate the side lobe structure associated with the repetition scheme.

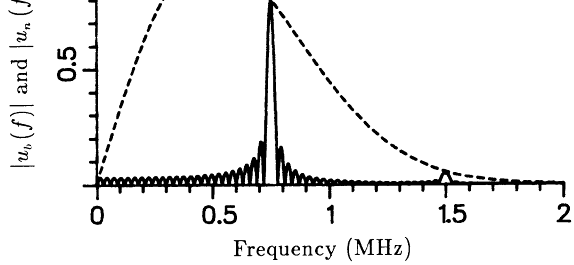

Fig. 4. Broadband and narrowband normalized Fourier transforms $|\hat{u}_b(f)|$ (dashed line) and $|\hat{u}_n(f)|$ (solid line) for $N_p = 25$, $a = 1$ mm, and $c_R = 3$ km/s.

The side lobes amplitude decreases as N_p increases and the peak at the fundamental becomes oven more narrowband. For a long laser pulse (large N_p) or a CW laser ($N_p \rightarrow \infty$), the laser generated ultrasound becomes extremely narrowband, thus increasing its detectability. In fact, the bandwidth Δf_n of the peak around $f_0 = 1/T_0$ in the narrowband spectrum $\hat{u}_n(f)$ is $\Delta f_n = 2/(N_p T_0) = c_R/(2aN_p)$. [The bandwidth is defined here as the frequency interval between the first zeroes in $\hat{u}_n(f)$ around $f = 1/T_0$.] As an example, let $a = 1$ mm, $c_R = 3$ km/s, and $N_p = 1000$ (which corresponds to a long laser pulse duration of 1. 33 ms). One finds that the ultrasonic signal is mostly concentrated around 0.75 MHz in a bandwidth Δf_n of only 1,500 Hz. In order to estimate the gain achieved with the method, let us assume that a typical bandwidth of detection of broadband ultrasonic signals is $\Delta f_b = 5$ MHz. The gain in signal-to-noise ratio being given by $[\Delta f_b/\Delta f_n]^{1/2}$, one finds a gain of about 35 dB in the example discussed above.

In summary, periodic scanning of the laser beam over an array of optical fibers with a Bragg cell allows to generate directional ultrasound in a narrow bandwidth, with unmodulated CW or long laser pulses. The gain can be in principle quite substantial.

DIRECTIONAL DETECTION OF ULTRASOUND

The non-contact detection of ultrasound with laser beams has been demonstrated for instance by Monchalin [10]. A standard detection method is the so-called laser heterodyne Doppler interferometry, the detail of which can be found in ref. [11]. In this section, it is proposed to probe the surface of the sample with several laser beams positionned in an array configuration so that detection in a preferential direction can be achieved. Again, optical fibers can be used very conveniently as waveguides of laser light. They can be accurately positionned above the sample and quite remote from the optical bench. A possible configuration is shown in Fig. 5. A CW helium neon laser can be used as the light source. A beam splitter separates the beam into the reference arm and the probing arm. The reference arm passes then through an acousto-optic Bragg cell before being coupled, for instance via a microscope objective, to an optical fiber. The purpose of the Bragg cell, which is driven at a frequency f_B, is to produce, when recombined at the photodiode with the laser beam from the probing arm, a signal at a conveniently detectable frequency. The laser light in the probing arm is coupled to an optical fiber which is split into several fibers acting as the element of the detecting array. For clarity, only two elements are shown in Fig. 5. The light output at the end of the fibers is collimated by a GRIN (gradient index of refraction) lens. Upon reflection on the surface of the sample, light is scattered by the local surface roughness. For each element of the array, (i.e., for each beam illuminating the surface of the specimen), the scattered light is collected and transmitted to a receiving fiber (through another GRIN lens). Then it is recombined with the reference beam. When the surface is vibrating at a frequency f_a under the action of an ultrasonic wave, the combination of the probing beam with the reference beam produces a detectable beat signal mainly at $f_B \pm f_a$. The key element in the proposed directional detection scheme is the proper phasing between each receiving element of the array of optical fibers. The time τ_d taken for ultrasound to propagate across the sample between a receiving fiber and the next must be equal to the time delay between the illumination of two succesive fibers in the array. In other words, it is necessary to lengthen the fiber going to the second element of the array by an amount $c_{light}\tau_d$, where c_{light} is the speed of light in the fiber. The spacing Δx between two consecutive elements of the array is related to the time delay τ_d by

$$\tau_d = \frac{\Delta x \cos\theta}{c_{ac}} = \frac{\Delta l}{c_{light}}$$

where θ is the angle of incidence of the ultrasonic wave below the surface of the specimen, and where c_{ac} is the acoustic velocity at which the wave propagates in the sample. When the detected signals are recombined with the reference beam and detected with a single photodiode, it is essential to add them in phase. It is therefore necessary to add a delay τ_d not only in the

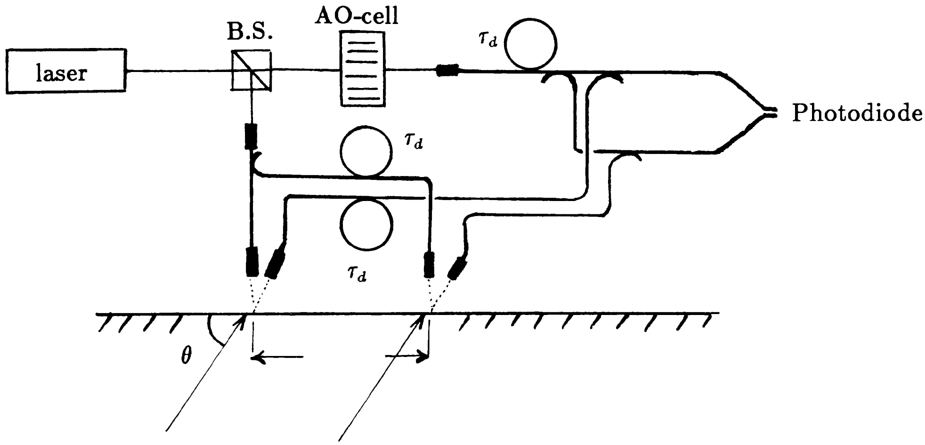

Fig. 5. Laser detection of ultrasound with an array of optical fibers. (Single photodiode setup).

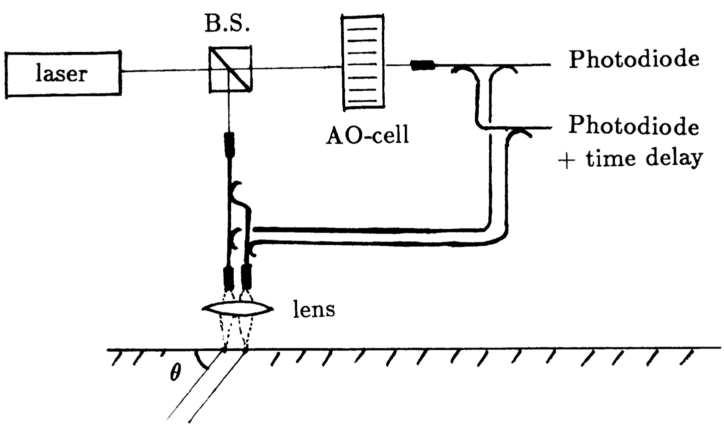

Fig. 6. Laser detection of ultrasound with an array of optical fibers. (Multiple photodiode setup).

reference arm of the interferometer but also in the signal detected with the first element of the array. These time delays are conveniently achieved by lengthening the corresponding fibers by an amount Δl.

An alternative setup is shown in Fig. 6. The principle of the directional detection is quite similar to that discussed above, except that here, the time delays necessary to take advantage of the array of detectors are performed after the detection by the photodiode. The advantage of the setup shown in Fig. 6 is twofold. First, it is much simpler to implement for large number of fibers; and second, it minimizes alignment problems since, for each element of the array, the fiber delivering the light is also collecting it. The main disadvantage of the method is that it requires N_f photodiodes, where N_f is the number of fibers in the array. As in the case of the generation with an array of optical fibers, the directivity of the discrete array is expected to be $D(\theta) = \sin N_f \chi / N_f \sin \chi$, where $\chi = 1/2\, kd \cos\theta$. The array is therefore more sensitive to sound incoming at an angle $\theta_0 = \cos^{-1}(\lambda/\Delta x)$, where λ is the wavelength of the sound in the sample and Δx is the spacing between the receiving fibers. One can therefore varies the angle θ_0 by changing the distance Δx. It can be shown that the larger the number of receivers, the narrower the beamwidth around θ_0. For instance, let $\Delta x = 2\lambda$ such that $\theta_0 = 60^o$, then for $N_f = 2, 4$, and 8, one finds that the corresponding beamwidths are about $37^o, 17^o$, and 8^o, respectively. The directional detection of sound might therefore be used to discriminate against unwanted echoes and reflections which would come at angles other than desired. If the techniques mentionned above (the directional detection and generation of narrowband ultrasound) were to be combined in a single operational system, one could anticipate such a laser ultrasonic probe to be very useful for in-situ nondestructive noncontact material inspection.

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References

1. G. Birnbaum and G. S. White, "Laser techniques in NDE," in *Research Techniques in NDT*, Vol. VII, Chapt. 8, 259-365, (1984).
2. D. A. Hutchins and A. C. Tam, IEEE Trans. UFFC, UFFC-33, 429-449, (1986).
3. E. Primbsch and W. Bickel, U.S. Patent 4,379,409 (1983).
4. J. A. Vogel, A. J. A. Bruinsma, and A. J. Berkhout, *Proceedings of Ultrasonics International '87*, (Butterworth, 1987), pp 141-152.
5. J. Jarzynski and Y. H. Berthelot, *J. Acoust. Soc. Am.* **85** (1), 158-162 (1989).
6. Addison, Graham, Linebarger, Tittman, QNDE **7**, 575.
7. Y. H. Berthelot, *J. Acoust. Soc. Am.* **85**(3), 1173-1181 (1989).
8. A. D. W. Mckie, J. W. Wagner, J. B. Spicer, and C. M. Penney, to be published in *Ultrasonics*, (1989).
9. C. M. Scala and P. A. Doyle, *J. Acoust. Soc. Am.* **85** (4), 1569-1576 (1989).
10. J.-P. Monchalin, *Rev. Sci. Instrum.* **56** (4) , 543-546 (1985).
11. L. E. Drain, *The Laser Doppler Technique*, (John Wiley and Sons, New York, 1980).