Pulse Compression Techniques for Laser Generated Ultrasound

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Abstract - Laser generated ultrasound for nondestructive evaluation has an optical power density limit due to rapid high heating that causes material damage. This damage threshold limits the generated ultrasound amplitude, which impacts nondestructive evaluation inspection capability. To increase ultrasound signal levels and improve the ultrasound signal-to-noise ratio without exceeding laser power limitations, it is possible to use pulse compression techniques. The approach illustrated here uses a 150mW laser-diode modulated with a pseudo-random sequence and signal correlation. Results demonstrate the successful generation of ultrasonic bulk waves in aluminum and graphite-epoxy composite materials using a modulated low-power laser diode and illustrate ultrasound bandwidth control.

INTRODUCTION

Laser-based ultrasound is an advanced nondestructive inspection technology that typically relies on a fast high power laser pulse to generate ultrasound in solid materials [1-2]. The power density of this laser pulse can be modest and induce thermoelastic expansion in the material (the thermoelastic regime of laser generated ultrasound), or can be high ($>10^6$ W/cm^2) and cause material melting or ablation. In either case, ultrasound is generated which propagates in the material. However, since material melting or ablation causes material damage, it is preferable to use the thermoelastic regime for nondestructive laser-based ultrasound generation. Restricting laser-based ultrasound to the thermoelastic regime limits the amplitude of the ultrasonic waves that can be obtained with a laser pulse. It also significantly limits the signal-to-noise achievable with laser generated ultrasound. Some methods for improving the effective signal-to-noise are based on modulating the laser source, either temporally or spatially, [3-9]. Previous reports on temporal modulations of a laser source to produce longitudinal waves produced narrow band ultrasonic waves having improved signal-to-noise but sacrificed temporal resolution, [7-9]. Those methods employed high power lasers and/or complicated optical-electronic systems. Recently, it was shown that it is possible to generate ultrasonic surface waves in a thin steel sample with a pseudo-random modulated laser-diode [10]. In this method the ultrasonic surface waves generated by the laser-diode were detected with an optical fiber interferometer attached to the sample surface. The received interferometer signal was cross-correlated with the drive signal to recover laser generated acoustic signatures. Conventional ultrasonic flaw detection systems have used this cross-correlation technique and demonstrated improved signal-to-noise within the power limitations of piezoelectric transducers, [11-16]. However, applications of ultrasonic cross-correlation systems have not seen wide commercial development and usage, in part, because simple classical systems provide adequate signal-to-noise ratios for most current inspection applications. In contrast, laser based ultrasound may be a more appropriate application of cross-correlation techniques due to the imposed limit to the thermoelastic regime, the desire for non-contact generation, and the high cost of high-power laser systems. In this paper we demonstrate that a pseudo-random modulated laser-diode can also generate longitudinal waves through the bulk of a thick material and be detected with a conventional piezoelectric transducer and that a swept frequency (chirp) modulation can be used to control the frequency bandwidth. This extends the usefulness of laser-diode-generated ultrasound to more conventional nondestructive evaluation applications.

EXPERIMENTAL SYSTEM AND MEASUREMENTS

The experimental setup employs a laser-diode with a power of 150 mW, wavelength of 809nm, and a modulation bandwidth of 1GHz. The laser beam is collimated with an aspheric lens to a 5mm diameter and then focused to a small spot on the sample using a 25.4mm diameter, 75mm focal length lens. Assuming the collimated beam has a Gaussian distribution, we calculate that the spot radius at the focus is approximately 8μm and the surface power density is of the order of 10^5W/cm^2, which is well below the ablation limit of 2x10^6W/cm^2 for aluminum [17]. Positioning the sample slightly off the focus of the 75mm focal length lens increased the spot size and reduced the power density far below material damage. The laser-diode was modulated using a pseudo-random sequence (m-sequence) of excitation pulses [18, 19]. This sequence turned the laser on and off a total of 4095 times. Laser pulse widths ranged from 800ns to 9600ns in duration and the complete pseudo-random sequence lasted 2.1ms. The generated ultrasonic waves were detected with a piezoelectric transducer coupled to the sample's back surface, opposite the laser beam that was incident on the sample front surface. A preamplifier was used to amplify the transducer signal with a gain of 60dB before digitization. One hundred waveforms were averaged and the resulting signal was stored for post processing. This signal averaging reduced the affect of low frequency signal modulations caused by small ground loops. A background signal, comprised of a signal with the laser beam blocked, was also obtained and stored. The stored signals were then correlated with a laser-diode drive signal and then the background was subtracted to remove radiated transmitter noise coming from the laser-diode driver.

A portion of the laser-diode drive signal and the received transducer signal are shown in figure 1. Figure 1a shows the laser-diode drive signal and figure 1b shows the received transducer signal after traveling through a 12.4mm thick aluminum sample. The receiving transducer had a center frequency of 0.5MHz and 12.7mm diameter. The received signal shows little resemblance to the input.

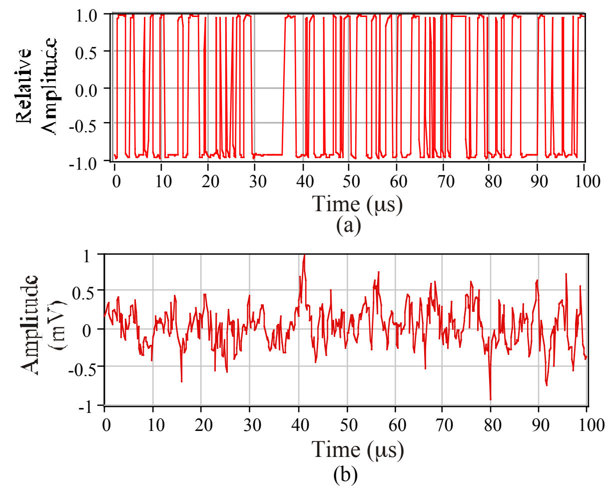

Figure 1. A portion of (a) the laser-diode driver output and (b) signal averaged transducer received signals are shown.

The result of correlating the drive signal with the received signal was compared with two other generation examples. In one comparison, a conventional transmitting transducer was coupled to the sample front surface opposite the receiving transducer. This front surface transducer had the same center frequency and bandwidth specifications as the receiving transducer. In a second comparison, a 20ns, 4mJ, Nd:YAG laser pulse was used to generate ultrasound.

Additional experiments were performed to demonstrate the capability of the laser-diode system. These included using the modulated laser-diode to generate ultrasonic waves in a thick-stitched graphite composite sample and using a swept frequency (chirp) to illustrate control over the bandwidth of the ultrasound generated.

RESULTS

The comparison measurements made with different generation systems performed on an aluminum sample 12.4mm thick are shown in figure 2. The top graph, figure 2a, shows a plot that is the result of using the 0.5MHz piezoelectric transmitter. The center graph, figure 2b, shows the result of using a Q-switched Nd:YAG to generate ultrasound. The bottom graph, figure 2c, demonstrates the result of using the modulated laser diode and correlation methods. In all measurements the receiving transducer used had a center frequency of 0.5MHz.

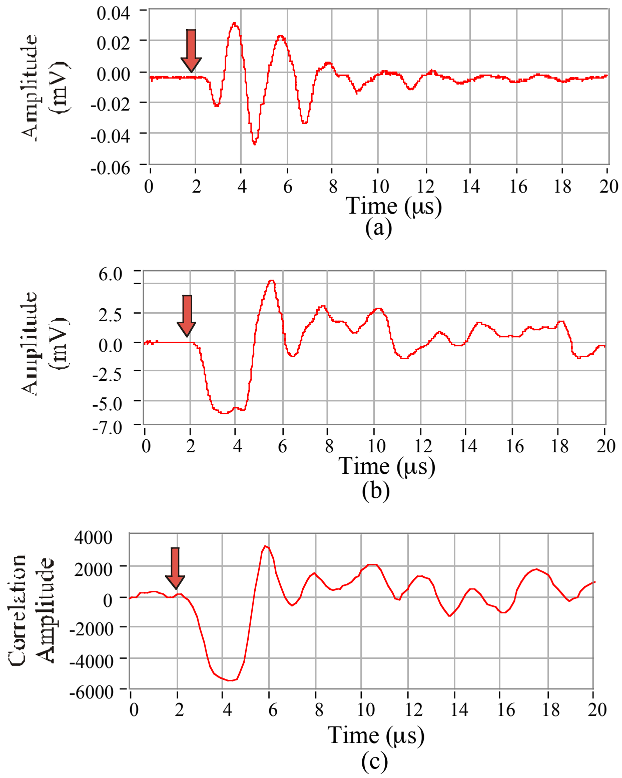

Figure 2. Comparison of the ultrasonic response on an aluminum sample with (a) piezoelectric transducer generation, (b) Q-switched laser generation, and (c) modulated laser-diode generation.

In all plots a large amplitude signal change can be seen initiating at about 2μs. The initial arrival time of a longitudinal wave traveling through this sample is calculated to be 1.97μs and, thus, corresponds to the initial arrival times shown in the plots. The piezoelectric generated longitudinal wave, figure 2a, has a typical ringing signal seen with mechanical generation while the laser-generated waves, figures 2b and 2c, are more characteristic of an impulse response convolved with a receiving transducer's response. Subsequent waves are the result of signal reverberation through the sample and in the case of figures 2b and 2c, the slower shear waves also reverberate in this sample.

It should be noted that the energy of the pulsed Nd:YAG laser was 4mJ/pulse whereas the energy of the modulated diode was ~0.16mJ/pulse sequence. Both laser generation methods show similar signal to noise ratios and wave functions at this frequency tested. Much of the pulsed Nd:YAG energy goes into high frequency generation while the pulse modulation method confines its energy more to the frequency being measured, resulting in the apparent increased in generation efficiency

A second set of measurements, using the modulated laser diode to generate ultrasound, was taken on a thick stitched graphite-epoxy composite sample with a series of flat bottom holes. Similar material had previously been examined with a laser-based ultrasound scanning system, [20]. Ultrasonic longitudinal wave velocity in this material was measured to be 3480m/s. A series of measurements are shown in figure 3 for four material thicknesses.

Figures 3a, 3b, 3c, and 3d correspond to material thickness of 4.3mm, 6.6mm, 8.6mm, and 13.7mm respectively. Calculated initial arrival times of longitudinal waves for each material thickness are 1.24μs, 1.90μs, 2.48μs, and 3.94μs, respectively. A large amplitude signal can be seen initiating approximately at these calculated initial arrival times

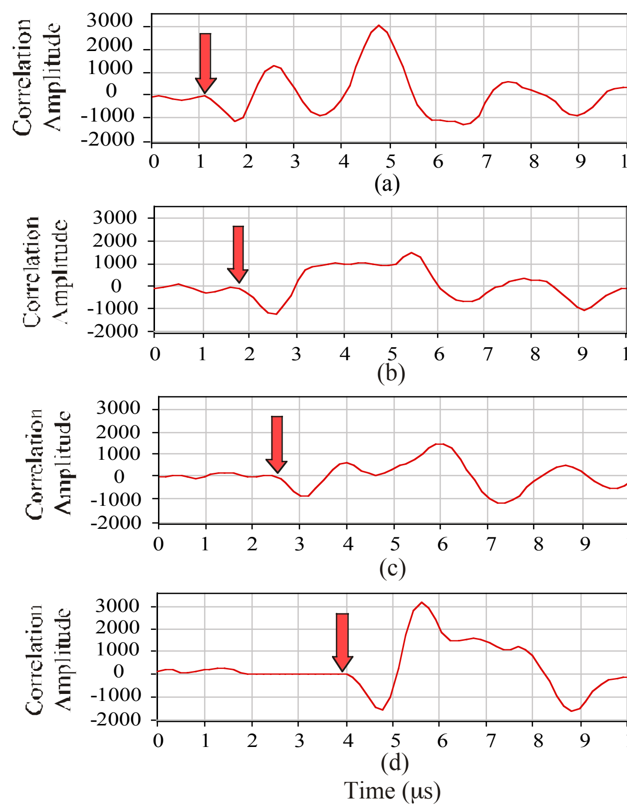

Figure 3. Correlation plots on a thick stitched composite sample. Material thickness are (a) 4.3mm, (b) 6.6mm, (c) 8.6mm, and (d) 13.7mm. The arrows indicate the calculated first arrival times for the longitudinal wave in each case.

for each of the respective figures. At subsequent times, reflected longitudinal and shear waves and other waves modes can be seen. Only at the thickest composite examples, 8.6mm and 13.7mm, figure 3c and 3d, are the ultrasonic waves beginning to resolve themselves at these frequencies.

A linear swept frequency of 1.0 to 3.5MHz, and a 2.25MHz transducer were used to generate and receive ultrasound in the same composite sample. For the material thickness of 13.7mm the ultrasonic signal is shown along with the frequency spectrum of the echo in figure 4.

In figure 4a, a large amplitude signal can be seen, over the background noise. This signal approximately appears at the calculated initial arrival time of the longitudinal wave, 3.94μs. The background level noise masks lower amplitude and subsequent signal reverberations. The frequency spectrum in figure 4b has a maximum at about the transducer center frequency of 2.25MHz and is slightly skewed toward the lower frequency range. This distortion could be due, in part, to the composite material attenuating higher ultrasonic frequencies.

Bandwidth control of the generated ultrasound is illustrated by using different bandwidth chirp signals

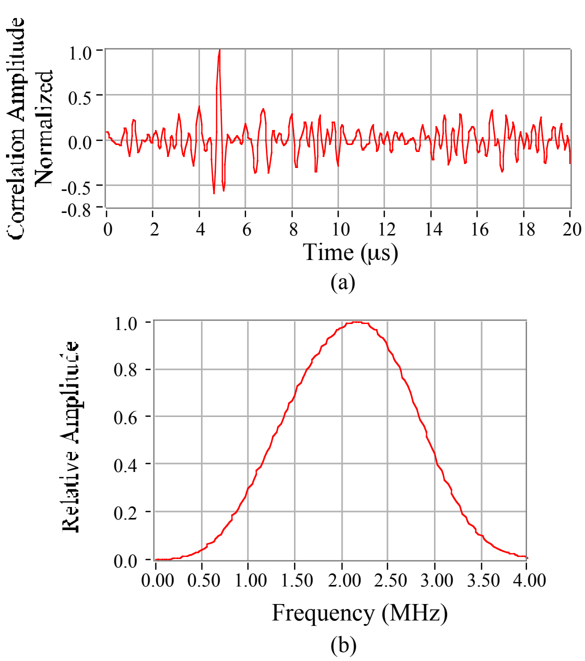

Figure 4. The (a) ultrasound signal and (b) frequency spectrum of the signal gated between 4 and 6 μs.

to modulate the laser-diode. Chirp start and stop frequencies were 0.1 to 1.0MHz, 0.25 to 1.25MHz, and 0.5 to 1.5MHz. These bandwidths covered 100%, 75% and 50%, respectively, of the 0.5MHz receiving transducer. Ultrasound bandwidth control results are shown in figure 5. These signals were generated in the same aluminum sample used above and thus have the same signal arrival time as the signals shown in figure 2. The signal in figure 5a, has the largest amplitude longitudinal wave while figures 5b and 5c show decreasing amplitude and loss of signal. The decreasing amplitude and loss of signal corresponds to the decreased overlap of the transducer and chirp signal bandwidths.

CONCLUSIONS

These results illustrate the successful generation of ultrasonic bulk waves in aluminum and composite samples using a modulated laser diode. In the examples shown here, we can correlate ultrasonic time-of-flight with the experimental waveforms. The power density is estimated to be a factor of more than

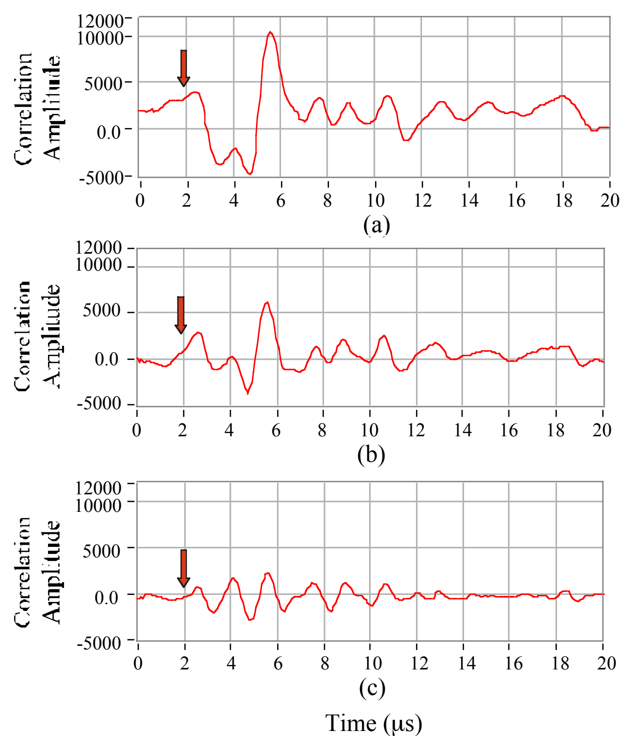

Figure 5. Illustration of generated ultrasound bandwidth control using a 0.5MHz transducer and a chirp bandwidth with (a) 100%, (b) 75%, and (c) 50% overlap. The arrow indicates the calculated first arrival for the longitudinal wave.

10^3 below any material damage threshold. The energy/pulse sequence is ~25 times less than the Q-switched laser pulse with no apparent degradation in signal-to-noise ratios. Q-switched laser generation of ultrasound and this new system of excitation produced comparable waveforms as detected by the 0.5 MHz receiving transducer. The required optics and electronics for the modulated laser-diode system is very simple and the laser diode generation package is extremely compact compared to a Q-switched laser system. Finally, the flexibility in controlling the modulation parameters of this system offers potential advantages of bandwidth control and signal to noise improvements at less peak energies than Q-switched lasers. This control is an extremely desirable feature for nondestructive evaluation applications, especially for a very small, compact, and non-contacting probe.

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