LONG CAVITY LASER EXCITATION AND DIGITAL FILTERING OF NARROWBAND ULTRASOUND FOR ENHANCED SIGNAL-TO-NOISE RATIO

J.B. Deaton, Jr. *, J.B. Spicer **, and J.W. Wagner

Center for Nondestructive Evaluation
Johns Hopkins University
Baltimore, MD 21218

Current Address: * NASA LaRC, Hampton, VA 23665
** NIST, Gaithersburg, MD 20899

INTRODUCTION

In recent years numerous efforts have addressed the substitution of laser-based ultrasonic testing techniques for conventional piezoelectric transducers in demanding applications where contact with the specimen surface is impractical [1]. Ultrasonic signals are typically generated by pulsed laser irradiation of the sample surface [2] and detected by some sort of heterodyne, Fabry-Perot, or path-stabilized Michelson interferometer [3]. While optical methods for generation and detection of ultrasound have performed quite satisfactorily under controlled laboratory conditions, similar success in more demanding industrial environments has proven elusive because the optical techniques suffer limitations with regard to generation efficiency and detection sensitivity. For laser ultrasonics to play a greater role in industrial NDE and on-line process control, substantial improvement in overall system sensitivity must be realized.

BACKGROUND

The signal-to-noise ratio (SNR) of a shot noise limited optical detection system is functionally dependent on the optical power, \( P \), delivered to the detector, the bandwidth, \( B \), of the detection electronics, and the surface displacement, \( \delta \), associated with the acoustic disturbance [4]:

\[
SNR \propto \frac{\delta^2 P}{B}
\]
Equation 1 summarizes the three options available for increasing the SNR of the optical detection system. The most obvious remedies involve the use of more powerful lasers for generation and detection of the ultrasound. On the generation end, raising the energy in the source laser pulse will generate larger surface displacements which will be easier to resolve. One must be aware, however, that the laser power density will eventually exceed the threshold for ablation of the target material, and the resulting surface damage is not acceptable for many practical applications in nondestructive testing. On the opposite end of the picture, a more powerful cw laser might be used in the interferometer system to increase the power delivered to the photodetector, yielding a commensurate increase in the SNR. However, there are some significant disadvantages associated with these 'brute-force' solutions, most notably the additional expense, size, and complexity of the larger laser systems.

The remaining option for enhancing the SNR is to reduce the electronic bandwidth of the optical detection system. However, to realize any benefit from narrowband detection, the spectral content of the laser generated acoustic event must closely match the passband of the interferometer. This requirement can not be satisfied for an acoustic signal launched by a single Q-switched laser pulse, the most common laser acoustic source. A single 10-20 nsec laser pulse generates a broadband ultrasonic pulse characterized by a continuous frequency spectrum spanning several tens of megahertz. It is therefore necessary to develop an alternate laser source capable of generating ultrasound of a much narrower spectral content to permit narrowband operation of the interferometer with maximum sensitivity.

In contrast to a broadband single pulse signal, substantial bandwidth reduction has been obtained for multiple pulse signals generated with temporal modulation of a Nd:YAG laser source, either by repetitive Q switching [5] or mode locking [6]. Alternatively, various schemes for the spatial modulation of the laser source have been explored for the generation of multiple pulse ‘toneburst’ ultrasound. McKie et al. demonstrated a narrowing of the bandwidth of bulk longitudinal waves generated by projecting an array of closely spaced line sources on the surface of an aluminum target with a lenticular array [7]. Also, Nakano and Nagai exploited the interference of angularly separated laser beams to create similar multi-line source geometries for the excitation of ‘toneburst’ Lamb waves in thin plates [8].

This paper reviews recent progress in the mode-locked laser generation of multiple pulse ultrasound. In particular, it is shown that digital filtering provides a satisfactory means for rejecting much of the noise in the waveforms while still maintaining the temporal fidelity.
EXPERIMENTAL DESCRIPTION

Multiple pulse acoustic signals with a pulse repetition frequency (PRF) ranging between 1 MHz and 20 MHz are potentially useful for many applications in ultrasonic NDE. For commercially available laser systems, typical mode-locked PRF's are around 100 MHz. The PRF of a mode-locked laser is inversely proportional to the spacing between the two end mirrors that form the resonant cavity, so to reach the useful frequency range requires a laser cavity length in excess of 10 m, which would be impractical for a standard two-mirror cavity design.

In the laser used in this study, long cavity lengths were made possible by inserting a three-mirror White cell [9,10] within the resonant cavity. By adjusting the White cell mirrors, it was possible to vary the total laser cavity length from 11 m to 59 m, with a corresponding variation in the laser PRF from 2.5 MHz to 13 MHz. Additional details regarding the specific configuration of the long-cavity mode-locked Nd:YAG laser have been described previously [11].

Successful mode locking was achieved on only 50-80% of the flashlamp pulses; however, this was to be expected, since passive mode locking with a saturable absorber is an inherently unreliable process. When fully developed mode locking did occur, the laser output was emitted as a train of as many as 50 mode locked pulses with individual pulse energies estimated to be as high as 0.5 - 1 mJ per pulse. The instrumentation available to measure the temporal signature of the mode-locked output was bandwidth-limited to a resolution of about 1 nsec. Exact measurement of the mode-locked pulsewidth was not made, however, it was apparent that the pulsewidth was much narrower than that for a conventional Q-switched pulse.

EXPERIMENTAL RESULTS

For this study, the mode-locked laser was adjusted for a PRF of 5 MHz (a cavity length of 30 m). The laser beam was focused with a plano-convex lens (200 mm focal length) to a spot diameter of ~2 mm on the front surface of an aluminum disc (1.2 cm thick, 5 cm in diameter). The generation surface was constrained by a thin transparent film of light oil. This surface constraint acted to enhance the amplitude of the longitudinal wave generated on epicenter [12]. Ultrasonic waveforms were detected on epicenter on the opposite face of the sample with a path-stabilized Michelson interferometer. The detection surface was polished to a mirror-like finish to return the maximum possible optical power to the photodetectors.
Fig. 1. (A) A multiple pulse longitudinal waveform generated at a mode-locked PRF of 5 MHz. (B) Frequency spectrum of the multiple pulse longitudinal waveform shown in Part A (solid line) compared with that of a single pulse from that waveform (dashed line).
Figure 1-A shows a typical mode-locked laser generated multiple pulse longitudinal signal with a repetition rate of 5 MHz, in agreement with the mode-locked PRF of the laser. The frequency spectrum of this waveform is shown in Fig. 1-B, revealing that considerable acoustic energy is concentrated at the fundamental and subsequent harmonics of the 5 MHz pulse repetition rate. Such a comb-like frequency spectrum would be expected for a pulse train of this sort [13]. For comparison, the spectrum of a single mode-locked laser generated pulse is shown by the dashed line in Fig. 1-B. The single pulse spectrum outlines the envelope of the multiple pulse spectrum, with the acoustic energy distributed over a wide bandwidth.

Having demonstrated that the long-cavity mode-locked laser was capable of generating the desired multiple pulse acoustic signals, the next challenge was to integrate a similar comb-like frequency response in the detection stage of the laser ultrasonics system. As previously reported [11], simple bandpass filtering to select the fundamental frequency component proved to be unsatisfactory. To maintain sufficient temporal fidelity of the filtered signal, it was necessary to retain all (or at least the majority) of the signal harmonics which are equally separated by the laser PRF in the frequency domain. Construction of a suitable multiple-bandpass electronic filter appeared to be an expensive and difficult (if not impossible) task, so efforts were focused instead on a digital filtering solution.

The Wiener filter [14] was selected for this application, because, working in the frequency domain, it was a straightforward process to separate the signal information from the noise background for the multiple pulse signals. In terms of the noise-free signal of interest, \( S(f) \), and the noise, \( N(f) \), the Wiener filter function, \( \Phi_w(f) \), may be expressed as the ratio of the power spectral density of the signal alone over the sum of the power spectral densities of the signal and noise components, as follows [15]:

\[
\Phi_w(f) = \frac{|S(f)|^2}{|S(f)|^2 + |N(f)|^2}.
\]  

In practice, this filter function was evaluated using a single representative waveform detected by the broadband interferometer. First, the multiple pulse signal alone was extracted from the raw waveform and processed with a Fast Fourier Transform (FFT) algorithm to produce the numerator in Eq. (2). A separate FFT on the raw waveform (containing both signal and noise) then yielded the power spectrum in the denominator in Eq. (2).

Once the filter function was calculated from a particular waveform at a given PRF, the same filter could be
applied to any other multiple pulse waveform at that PRF. The first step in the Wiener filtering of a multiple pulse waveform was to generate the real and imaginary components of the Fourier transform with the FFT. The real and imaginary components were then separately multiplied by the filter function, and these ‘filtered’ real and imaginary components were used as the inputs for an inverse FFT algorithm. The inverse FFT yielded the filtered version of the original temporal waveform. For this study, the Wiener filtering was implemented after the data had been recorded in the computer memory; however, it is anticipated that this filtering process could be conducted in near-real-time using either a powerful desktop computer or actual on-chip hardware processing.

Figure 2 shows unfiltered (upper trace) and Wiener filtered (lower trace) versions of the waveform from Fig. 1 on an expanded time scale. It is apparent that the SNR has been enhanced by the Wiener filtering. In particular, notice that in the lower trace it is possible to resolve both the initial arrival (P) of the multiple-pulse longitudinal wave as well as the first echo (3P) of this signal after three passes through the sample. The first longitudinal echo was completely buried in the noise in the
raw waveform. It was calculated that the Wiener filter reduced the noise power in the original signal by about 10 dB.

CONCLUSIONS

The long-cavity mode-locked laser in concert with digital Wiener filtering permits the optical generation and detection of narrowband multiple pulse ultrasound. In comparison with conventional single pulse methods, this strategy offers several advantages for applications in remote noncontacting NDE. Most importantly, reducing the detection bandwidth, which is made possible by the commensurate reduction in the spectral extent of the laser generated signal, enhances the sensitivity of the overall system. Also, laser excitation of multiple pulse signals allows unprecedented control over the spectral signature of the ultrasound by simply adjusting the PRF of the pulsed laser source. Therefore, the ultrasonic frequency can be selected to suit a particular application. Finally, with a multiple pulse laser source, it is possible to deliver a greater total amount of optical energy to the sample without exceeding the threshold for destructive ablation of the target material. This is particularly important for the NDE of sensitive components.

One must also conclude that the long-cavity mode-locked laser has significant limitations, including rather low output pulse energy and poor reliability, which handicap its utility for practical industrial applications. Accordingly, efforts are continuing in the development of alternative laser sources with much greater output energies and high reliability.

ACKNOWLEDGEMENTS

One of the authors (JBD) is grateful to the Newport Corporation for generously supporting this work with a Research Award for Graduate Study.

REFERENCES