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Horizontal Shear Wave Imaging of Large Optics

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HORIZONTAL SHEAR WAVE IMAGING OF LARGE OPTICS

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ABSTRACT. When complete the National Ignition Facility (NIF) will be the world's largest and most energetic laser and will be capable of achieving for the first time fusion ignition in the laboratory. Detecting optics features within the laser beamlines and sizing them at diameters of 0.1 mm to 10 mm allows timely decisions concerning refurbishment and will help with the routine operation of the system. Horizontally polarized shear waves at 10 MHz were shown to accurately detect, locate, and size features created by laser operations from 0.5 mm to 8 mm by placing sensors at the edge of the optic. The shear wave technique utilizes highly directed beams. The outer edge of an optic can be covered with shear wave transducers on four sides. Each transducer sends a pulse into the optic and any damage reflects the pulse back to the transmitter. The transducers are multiplexed, and the collected time waveforms are enveloped and replicated across the width of the element. Multiplying the data sets from four directions produces a map of reflected amplitude to the fourth power, which images the surface of the optic. Surface area can be measured directly from the image, and maximum depth was shown to be correlated to maximum amplitude of the reflected waveform.

Keywords: Structural Health Monitoring, Horizontal Shear Waves, Laser Damage

INTRODUCTION

NIF will be the world's largest laser (1.8 MJ) and consist of 192 high energy laser beams focused onto a 1 mm sized fuel pellet target of deuterium and tritium to study inertial confinement fusion. The target sits in the center of a 10 m diameter Al vacuum chamber with fused silica windows. High energy fluences of the laser can create damage on the vacuum side of the window [1]. Routine operation of the system requires an in-situ method for detecting, locating, and sizing any damage sites, so that optics can be timely refurbished or replaced. The windows are large optics made of fused silica and measuring 430 mm by 430 mm and 43 mm thick. A photograph of a window with some laser damage is shown in Fig. 1. A close-up picture of a damage site is shown in Fig. 2. Sensors are restricted to the edges of the window to prevent from interfering with the beamline of the laser. The full surface area of the vacuum side of each window must be inspected. Previous work used 5 MHz longitudinal waves to successfully detect and locate the damage, but suffered from mode conversions and multiple echoes from defects as well as inaccurate sizing [2]. Another approach utilized 1 MHz point-like sources and tomographic reconstruction algorithms, but showed poor resolution, poor signal-to-noise, and inaccurate sizing [3].

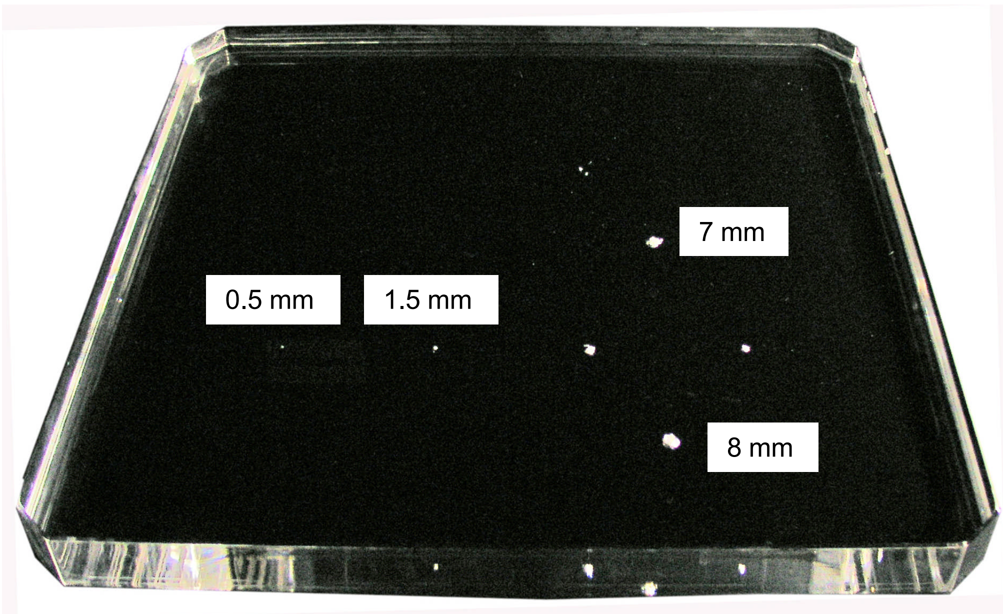

FIGURE 1. Photograph of a fused silica target chamber vacuum window show multiple damage sites.

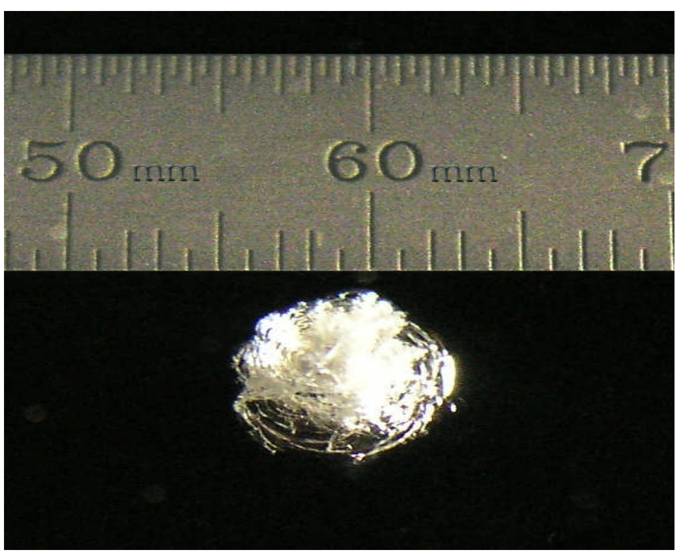

FIGURE 2. A 7 mm laser damage site is shown.

METHOD

The goal of the technique is to detect, locate, and size damage sites of 0.1 mm and larger with good signal-to-noise. Longitudinal and shear waves were investigated on the optic shown in Fig. 1. Sensors were placed along the sides of the optic near the vacuum surface as shown in Fig. 3. Longitudinal modes were found to have problems with multiple reflections. Mode conversions from the defect and from reflections at the top and bottom surface of the optic created multiple reflections from any damage sites as well as the back surface.

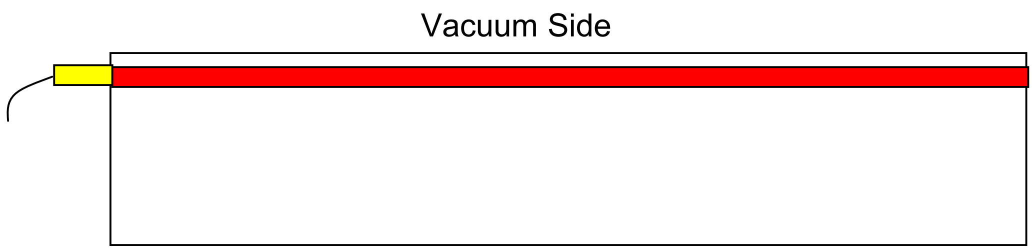

FIGURE 3. Sensors were placed at the side of the optic as close to the vacuum side (where laser damage occurs) as possible.

Directivity of the transducer had a large effect on the presence and amplitude of any multiple reflections. Frequencies of 5 to 20 MHz were tested for longitudinal modes. As the frequency increased multiple reflections decreased in amplitude but were still present. The higher directivity at higher frequencies lessened any echoes bouncing off the bottom side of the optic. A sample RF waveform using 5 MHz longitudinal waves with reflections from a 4 mm defect is shown in Fig. 4. Note the many multiple reflections.

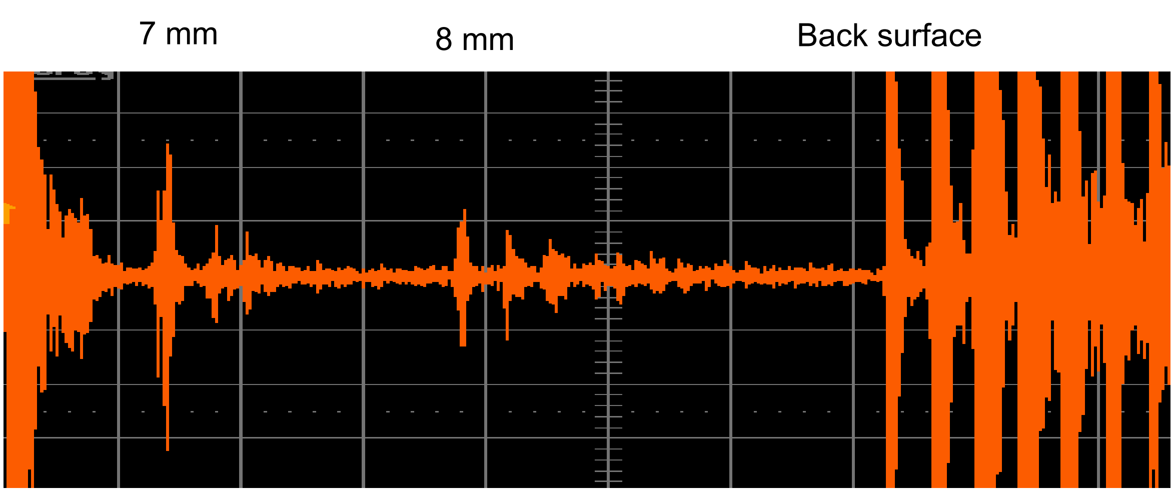

FIGURE 4. A 5 MHz longitudinal wave detects 7 mm and 8 mm damage sites, but many multiple echoes exist from the damage sites and from the back surface.

Shear waves were also tested at 5 and 10 MHz. The sensors were polarized horizontally, so that the displacement was parallel to the vacuum surface. Horizontal polarization reduced the effect of the mode conversions because it is decoupled from the longitudinal and shear vertical modes. A sample waveform is showing the detection of 8 mm and 7 mm damage sites is shown in Fig. 5. Comparing Fig. 4 and Fig. 5 shows drastic improvement in signal-to-noise for the 10 MHz horizontal shear over the 5 MHz longitudinal mode. The multiple reflections are virtually eliminated. The smaller wavelength also generates better resolution.

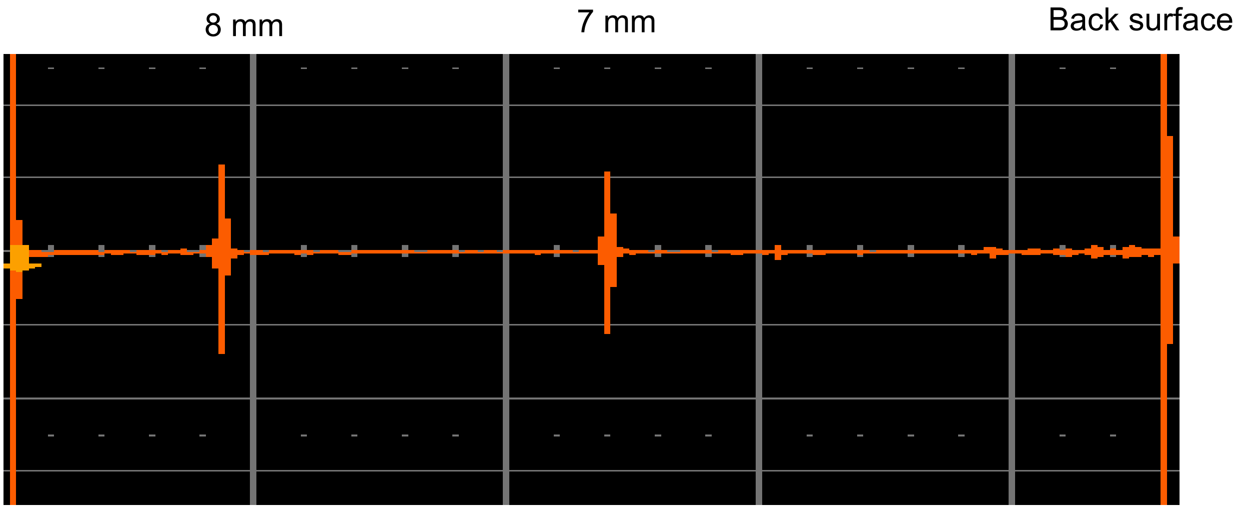

FIGURE 5. A sample waveform shows the detection of 8 mm and 7 mm damage sites on a fused silica optic with excellent signal-to-noise and virtually no mode conversions.

10 MHz horizontal shear wave data was taken by covering the sides of the optic shown in Fig. 1. Data was obtained by multiplexing 32 elements 12.7 mm diameter placed tangent to one another. A sampling rate of 100 MS/s was used. This setup produces a resolution of 0.037 mm along the axis of propagation, but a resolution of only 6.35 mm transverse to the axis of propagation. A schematic of the setup is shown in Fig. 6. For data on two adjacent sides, one data set has high resolution in the x-direction and low in the y-direction, while the adjacent side has low resolution in the x-direction and high in the y-direction.

To make the data sets symmetrical each waveform for a transducer was replicated over the length of the aperture of the transducer. The signal is replicated every 0.037 mm across the 12.7 mm width of the transducer. The result is four 11,600 by 11,600 data sets. The Hilbert transform of each waveform is also taken to obtain the envelope. These four sets are combined into a single image by taking the product of the data sets. The result is a two-dimensional image of the surface of the optic. Measuring across the image yields the surface dimensions of the damage. It should be noted that the amplitude on the surface image does not represent the depth of the surface damage, since the ultrasound is primarily interacting with the boundary of the damage, and the reflections will have phase changes.

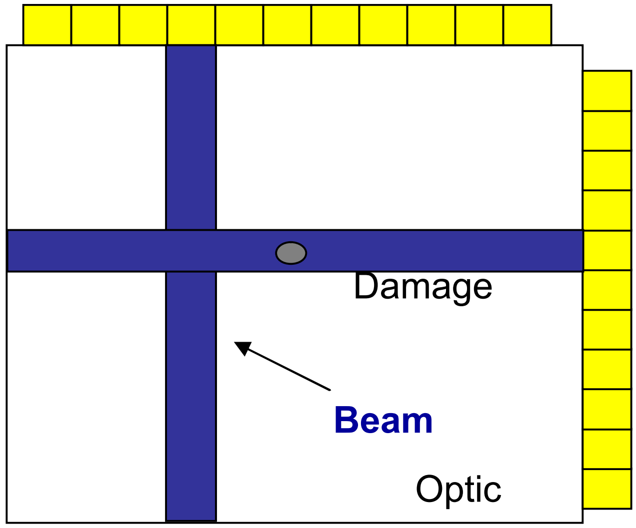

FIGURE 6. A schematic of the setup of transducers on an optic is shown.

RESULTS

Images were produced with 10 MHz horizontally polarized shear wave sensors using data taken on the optic shown in Fig. 1. Damage is generally hemispherical in shape; each site has a very complex rough surface often consisting of a “crush” zone and other areas with a combination of radial and circumferential cracking. Damage sites ranged in size from 0.5 mm to 8 mm in diameter. Each damage site was successfully imaged.

Fig. 7 shows the surface images obtained using the imaging method discussed in this paper for a few of the damage sites. The images are zoomed and show an area of 25.4 mm by 25.4 mm around the damage site. The extent of the surface damage can be directly measured from the two-dimensional image. All of the damage sites were easily detected with excellent signal-to-noise. The damage sites were accurately located as well. The images gave accurate measurements compared to physical measurements with a ruler (see Fig. 2). In the 0.5 mm and 1.5 mm the damage appears to have a “shadow” in each direction. This is an artifact that is created by the replication of the waveform that is done in the processing. This does not inhibit the technique from detecting, locating, or sizing the damage. Also, the amplitude on the surface image does not correspond to actual damage depth.

Depth information can not be directly obtained from the surface image. The relationship with maximum depth of the damage and maximum amplitude of the detecting waveform was studied to determine viability of obtaining depth information from the ultrasonic data. The longitudinal wave data did not have monotonically increasing amplitude for increasing depth. The horizontal shear wave data yielded a monotonically increasing relationship as shown in Fig. 8. The result shows that an approximate maximum depth can be obtained from the shear wave technique.

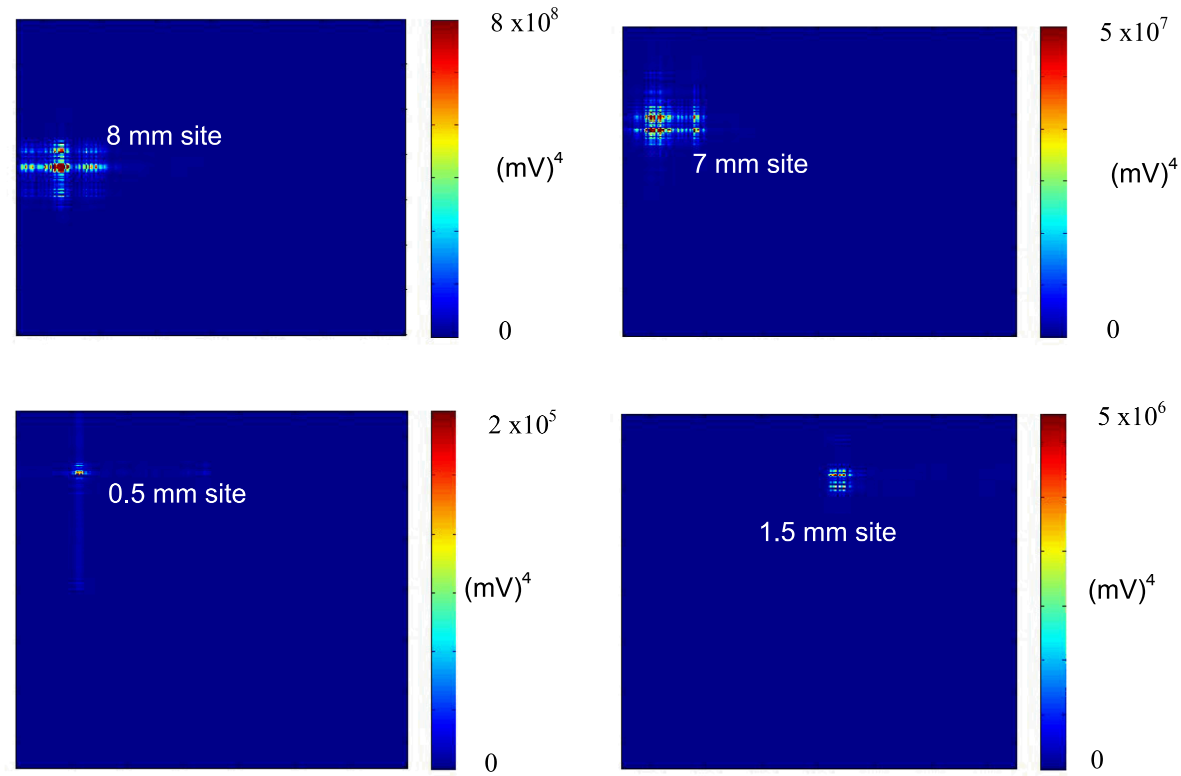

FIGURE 7. Horizontal shear wave images (25.4 mm x 25.4 mm) of the surface around 8-, 7-, 0.5-, and 1.5-mm damage sites show excellent signal-to-noise for detection.

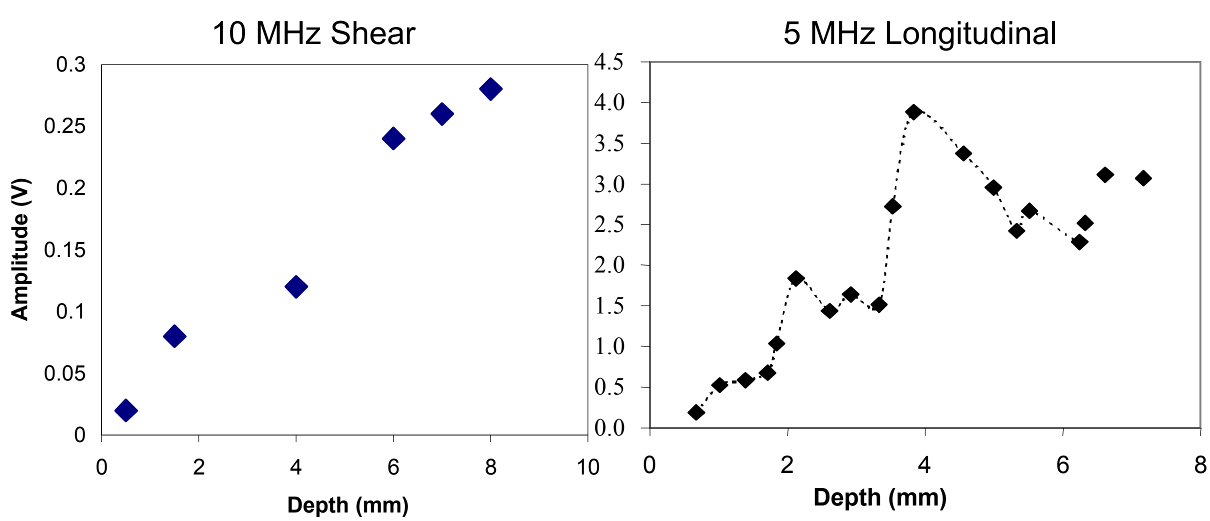

FIGURE 8. 10-MHz shear-wave yields a monotonic relationship with maximum laser damage depth, while the 5-MHz longitudinal-wave data has a non-monotonic relationship. Data is from sample shown in Figure 1.

CONCLUDING REMARKS

An ultrasonic technique for the structural health monitoring of large optics was developed. 10 MHz shear waves produced the best signal-to-noise ratios with minimal influence from mode conversions. Horizontal polarization reduced the mode conversions because this mode does not couple with the longitudinal and shear vertical. Higher frequency improved the signal-to-noise by improving the directivity of the transducer. An imaging method combining waveforms from each side of the optic was used to simplify data interpretation. The method produces a 2-D image of the surface that can be used to measure the extent of the surface damage. Maximum depth of the damage was shown to be obtainable through correlation with the maximum amplitude of the detecting waveform. Damage sites from 0.5 mm to 8 mm were shown to be successfully detected, located, and size with excellent signal-to-noise ratios. Signal-to-noise was high enough to believe sites as small as 0.05 mm could be detected.

ACKNOWLEDGMENTS

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