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Laser Generation of Narrowband Lamb Waves for In-situ Inspection of Additively Manufactured Metal Components

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Abstract. Recent developments in metal additive manufacturing (AM) has created a lot of interest in sectors including automotive, aerospace and biomedical engineering. It is imperative that the components manufactured additively be inspected for flaws, mechanical properties and dimensional accuracy. Several non-destructive testing (NDT) techniques such as X-ray computed tomography and conventional ultrasonic testing have been implemented to evaluate the quality of these components. Recently, research has been focused on techniques that can perform non-contact testing and carry out an online inspection layer by layer while the component is being fabricated. Laser based ultrasonic technique has been found to be a promising method owing to its non-contact nature and ability to operate in harsh environments. In our study, narrow band lamb waves were generated using a pulsed Nd-YAG laser system consisting of a spatial array illumination source. The generated wave modes were detected using a two-wave mixing based laser interferometer. The wavelength-matched method enabled generation of specific lamb wave modes for in-situ inspection of additively manufactured components.

INTRODUCTION

Non-destructive testing (NDT) techniques such as ultrasonic testing and X-ray computed tomography have been demonstrated by various researchers to inspect additively manufactured (AM) components [1,2]. Ultrasonic inspection is one of the major techniques that has gained wider acceptance for a variety of purposes in recent years. Conventionally, contact piezoelectric transducers have been used to generate and receive ultrasound. However, this technique has drawbacks related to use of liquid couplant between the transducers and the sample, operation in harsh environments etc. Non-contact ultrasonic testing, on the other hand, has the potential to operate in harsh environments without the use of a couplant. A technique of great interest is laser ultrasonics (LU), which is highly versatile in terms of both offline and real-time inspection of AM components [3].

LU uses a high energy, very short duration (~ nanosecond) pulse to generate ultrasound. When a high energy pulsed laser is incident on the surface of a material, a part of the energy is absorbed and converted to heat leading to rapid localized temperature rise. This leads to rapid thermal expansion or ablation of the incident region generating and propagating ultrasonic waves [4]. The ultrasonic generation is said to be thermoelastic when the optical power is below the ablation threshold of the material. When the optical power is above the ablation threshold, some portion of the material surface evaporates creating a strong ultrasonic wave. The former regime is the preferred regime for true NDT. The ultrasonic waves travel within the material and interact with internal features and defects before being detected. Laser ultrasonic testing (LUT) has the advantages of being non-contact (flexibility and increased speed of inspection), couplant independent (absolute measurements), broadband (more information) and being able to provide high spatial resolution with a very small footprint.

By measuring the time of arrival of an ultrasonic signal, various characteristics of a defect such as size and location can be measured. When the thickness of the sample is comparable to the wavelength of the ultrasonic wave, however, the data provided by this method is no longer accurate. For thin materials, guided waves are generated, which exhibit very different characteristics compared to the bulk waves that travel in thick structures. Guided waves such as Lamb

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waves travel through the cross section of the structure and are widely used because of their potential to inspect large area and their sensitivity to a wide variety of defects.

Conventionally, an array of sources has been employed for the generation of Lamb waves using laser [5-12]. The development of these systems has been primarily motivated by the fact that the maximum ultrasonic signal amplitude that can be generated by a single laser source is limited by the damage threshold of the material under inspection. By distributing the laser energy in both time and space, the generated acoustic signals can be focused at the desired location, the acoustic signal bandwidth can be narrowed, and the signal-to-noise ratio (SNR) of laser ultrasonic systems can be improved. One method of great interest in the narrowband laser generation of ultrasound is by using a pattern source [13, 14]. To create a pattern source, the laser beam is first expanded before passing through a shadow mask with slits. The obvious result is that a portion of the laser beam passes through the slits and the remainder is blocked (reflected or absorbed) by the mask. The effect of the generated pattern source can be treated as independent line sources illuminating on the surface of the sample simultaneously. Because of constructive interference over the space, narrowband ultrasound with the designated wavelength can be created, as determined by the spacing of the mask. The resulting narrowband signal can be captured by a sensor (e.g., a laser interferometer). By selecting the dominant wavelength in the signals, the complexity of laser generated broadband signals can be greatly reduced and the speeds and frequencies of traveling ultrasounds at the selected wavelength can be easily determined using dispersion curves (i.e., graphs that show relationships between wave velocity, frequency and thickness of specimen in dispersive systems).

Conventional shadow masks are effective and easy to implement, but have few disadvantages. These include, but are not limited to:

- The need to create narrow slits using expensive methods.
- The number of processes involved in finally implementing the masks for inspection are large and hence time consuming.

In our study, we propose a new method for efficient laser generation of narrowband ultrasonic waves. This method uses an integrated slit mask that is ‘3D printed’ on to the AM component to generate narrow band Lamb waves. In addition to providing time/cost effectiveness and efficiency, this method retains the non-contact benefits of conventional pattern source methods.

METHODS

Experimental Setup

A block diagram of the experimental setup is given in Fig. 1. The experimental arrangement consists of the following: 1) a 1064nm Nd-YAG pulsed generation laser with a pulse width of 9.80ns and a maximum energy of 210mJ/pulse operating at a Pulse Repetition Frequency (PRF) between 0-21Hz. 2) a 1550nm continuous wave fiber laser (detection) with a maximum power capacity of 2W. 3) a two-wave mixing based interferometric unit to record the surface displacement. 4) an oscilloscope and 5) a computer with software for motion control and data acquisition. The entire setup (Fig. 2) was mounted on a vibration isolation table. The laser receiver produced a time-varying analog signal that was proportional to the instantaneous surface displacement on the specimen. The output signals from the laser receiver were digitized at 8 bits by an analog-to-digital board converter, triggered by the pulsed laser, and transferred to a desktop computer for further signal processing and display. An expanded pulsed laser beam of energy 140mJ/pulse and a PRF of 20Hz was implemented. A beam separation of 32 mm was used for the study.

Specimen

A 0.8 mm thick aluminium alloy specimen with an integrated slit mask was fabricated using Selective Laser Melting (SLM) process as depicted in Fig. 3. Slit mask with an element width and element gap of 0.4 mm was designed and fabricated. The slit mask had an average element spacing of 0.82mm as measured using optical microscopy. An expanded pulsed laser beam was incident on the slit mask for ultrasound generation.

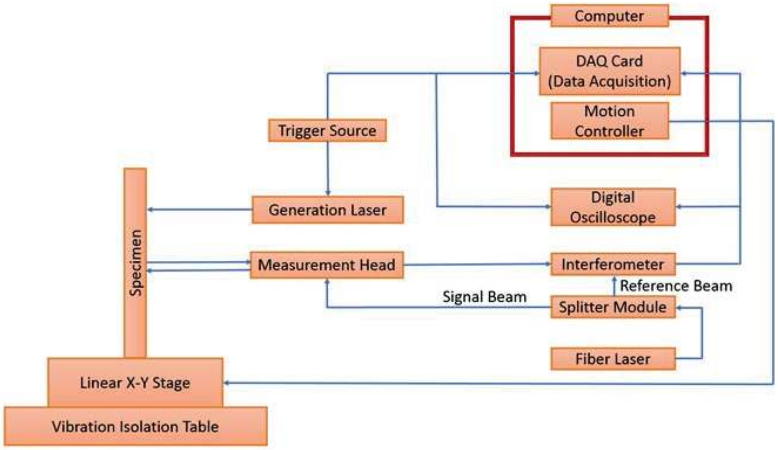

FIGURE 1. Block diagram of the experimental setup.

FIGURE 2. Experimental setup for LUT studies.

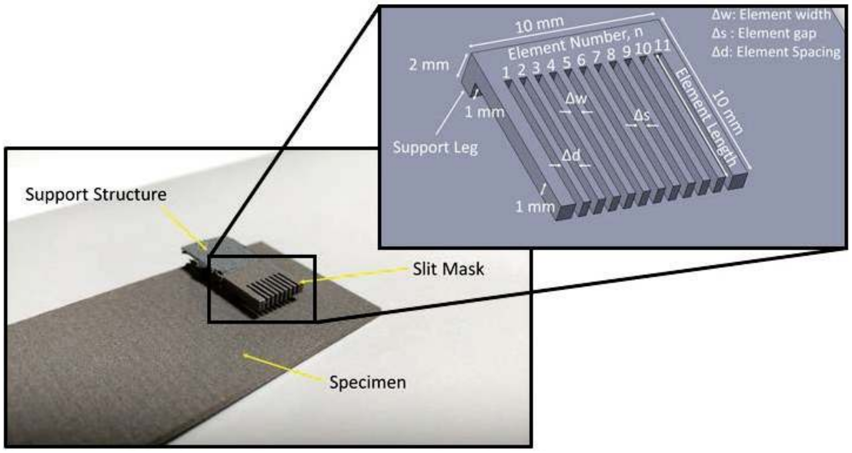

FIGURE 3. Photograph of the sample with the integrated slit mask (additively manufactured). Inset: slit mask terminology and geometry used for the experiment.

Lamb Wave Generation Using Slit Mask

Numerous Lamb wave modes exist at a certain frequency. Each of them differs in terms of their wave structure across the thickness of the material of investigation, resulting in different stress and displacement patterns across the cross-section. Thus, the selection of mode and frequency of operation are crucial in the development of any inspection system. The phase and group velocities of each Lamb wave modes vary with frequency. This is attributed to its dispersive nature. Considering that laser generated ultrasound is broadband in nature and because the different wave modes are dispersive, signal interpretation becomes challenging. One method of addressing this problem is by generating narrowband Lamb waves with a constant wavelength, however, that contain a dominant frequency, which can enable the traveling speeds of different modes to be determined from the dispersion curves.

Figure 4 shows the phase velocity dispersion curves for a 0.8 mm thick aluminium alloy plate. In the plot (phase velocity dispersion curves), wavelengths can be represented as straight lines passing through the origin with a slope equal to the wavelengths. If the value of wavelength is known beforehand, then the wave modes and their frequencies can be pre-determined by the intersection points (operating points) of the constant wavelength line and the phase velocity dispersion curves.

The element spacing used for the study was 0.82 mm with the number of slits being 7. This spacing is the pre-determined wavelength of generation for the different wave modes with different frequencies. In Fig. 4, for example, the x-coordinate of the intersection between the straight line of 0.82 mm wavelength and A0 mode is at approximately 3.25 MHz and approximately 4.40 MHz for S0 mode.

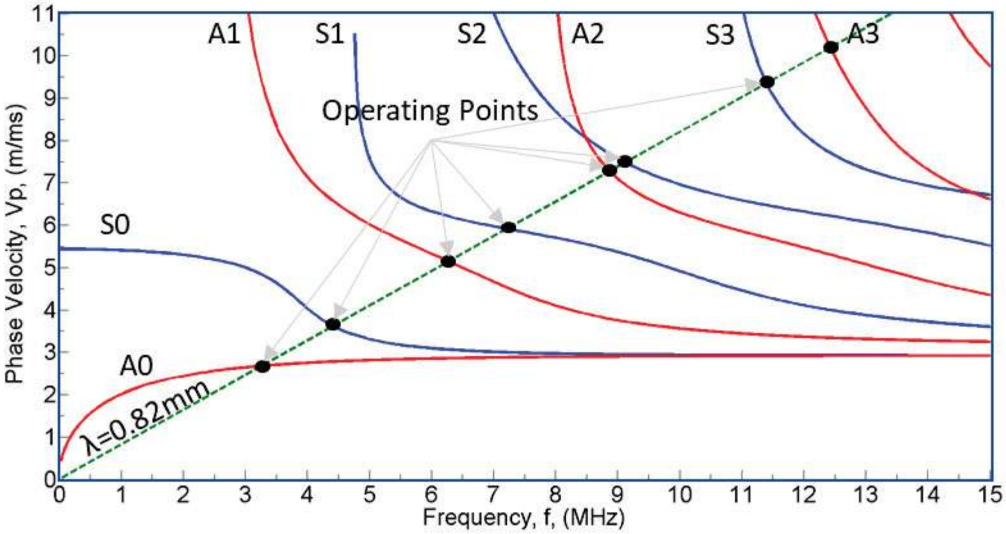

FIGURE 4. Phase velocity dispersion curves obtained for a 0.8 mm thick aluminium alloy plate showing the operating points for the Lamb wave modes using an additively manufactured slit mask.

EXPERIMENTAL RESULTS

The experiment was carried out in a pitch-catch configuration. A laser beam was directed through a slit mask to form line sources that illuminated the surface of the sample to generate ultrasonic waves. The out-of-plane displacements from the specimen surface at 32 mm from the slit mask was received using a detection laser. The signal obtained was inherently noisy which was averaged and filtered to obtain a clean signal (Fig. 5). The corresponding frequency domain (normalized) of the signal (Fig. 6) was obtained by carrying out a Fast Fourier Transform (FFT) on the time domain signal. It can be clearly seen that the lower order modes such as A0 (3.25 MHz) and S0 (4.40 MHz) are clearly identified and are as predicted in Fig. 4. The higher order modes, though lower in amplitude, are approximately as predicted using the dispersion curves.

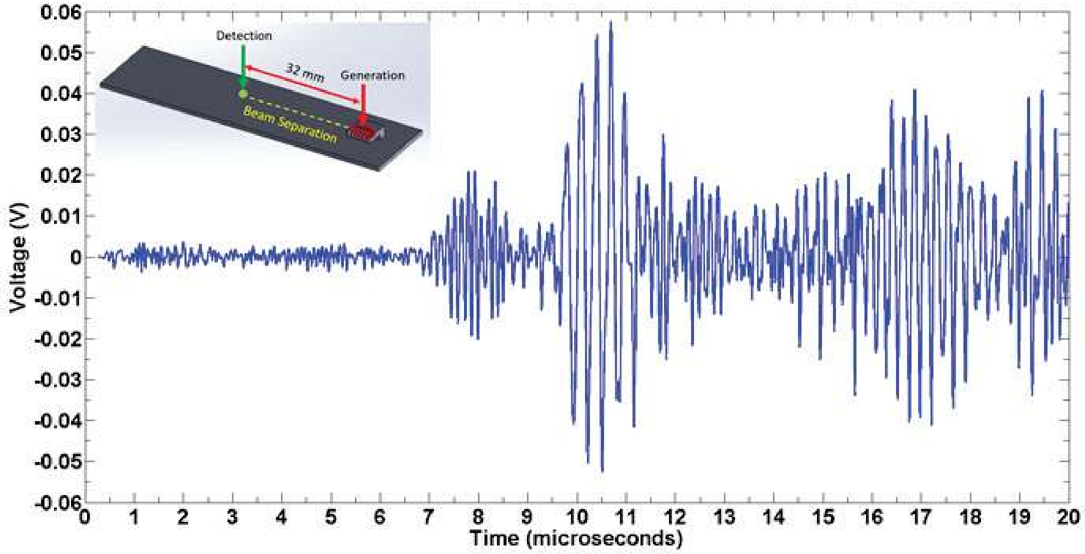

FIGURE 5. Plot of averaged and filtered time domain signal proportional to the out-of-plane displacement of the specimen surface at 32 mm from the slit mask received using a detection laser.

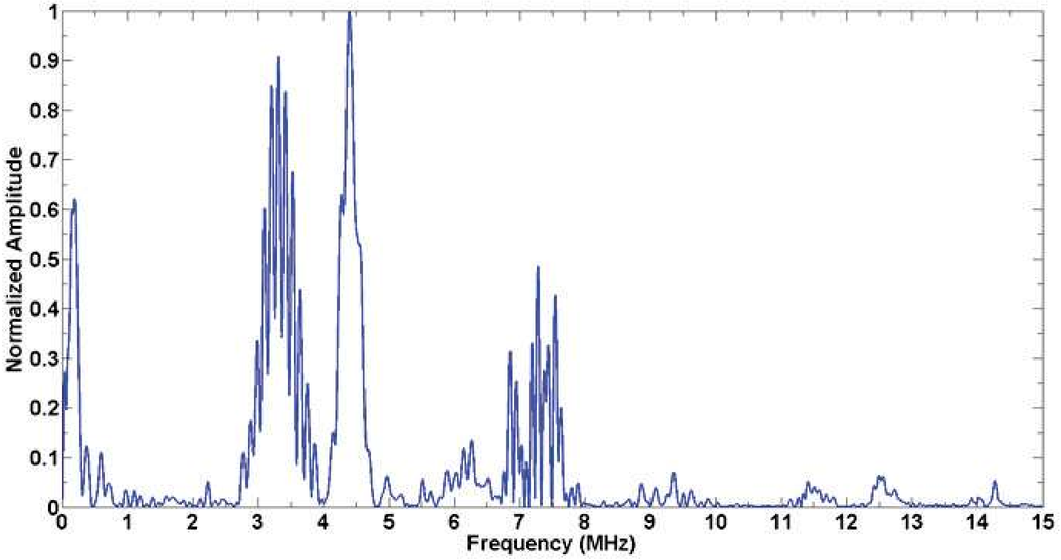

FIGURE 6. Frequency domain plot of the time domain signal obtained in Fig. 5.

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SUMMARY

A novel non-contact method for providing laser generated ultrasound utilizing an integrated slit mask for in-situ inspection of additively manufactured components has been proposed and demonstrated. The slit mask is '3D printed' as an integral part of the component while the component is being fabricated. The slit mask can hence effectively become a part of the component for an in-situ inspection. Narrowband Lamb waves with a dominant wavelength according to the pitch of the slits were successfully generated, and the different modes were identified using dispersion curves. This method can be used for non-destructive evaluation of any additively manufactured component.

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