The Design of a Novel Line-Array Type of Laser Source for Non-contact Guided Waves to Inspect the Integrity of Plates

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Abstract Popular guided waves (GW) transducers employed for emitting and receiving GW when inspecting the integrity of different objects include the contact and non-contact ones. Contact transducers that must be physically mounted on the objects are piezoelectric transducers (PZT) and magnetostrictive sensors (MsS). The non-contact method can consist of laser-based transducers. However, the contact transducers could be difficult to apply to some operating situations, such as measuring objects that have high surface temperature, moving target, complex geometries and rough surfaces, and hazardous environment etc. These operating situations limit the possibility of mounting the contact transducers on the inspected objects. Therefore, it is necessary to design a non-contact type of GW transducer. This paper reports the feasibility of using laser to generate the desired GW wave mode, the novel design of optical transducers based on an integrated optical Mach-Zehnder interferometer (IOMZ), and the results of using such novel laser-based GW to inspect the defects occurred in plates. With the help of such IOMZ system to generate the required laser-based GW wave mode, the location and geometrical extents of any defect occurred in an aluminium plate can be successfully determined.

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1 Introduction

Inspection using guided waves (GW) has multiple distinguishing features. It includes the long distance inspection with less energy attenuation and the use of a single transducer to emit GW and receive the reflected GW signals. One of the promising applications including the use of GW to detect defects occurred in aluminium alloy beams and plates. To use of GW methods for the detection or identification of macroscopic anomalies such as defect, corrosion and incipient buried micro-cracks, even in the early fracture stage is very important for ensuring structural safety and integrity. The popular transducers employed by GW include the contact and non-contact ones. The contact transducers that must be physically mounted on the objects are piezoelectric transducers (PZT) and magnetostrictive sensors (MsS). The non-contact ones can be laser-based transducers. In the past two decades, laser technology has been widely and rapidly developing. It has attracted great interest to engineers and scholars to employed laser technology in non-destructive testing (NDT) applications.

Normally, there are two kind of typical laser sources - the point and the line array. In 1980, the laser heated point source was considered as a thermoelectricity means to generate elastic waves that propagating inside metallic structures [9]. However, a major weakness associated with laser technology is its poor signal-to-noise ratio (SNR). To conquer this weakness, in 2000, line source was designed for laser systems. According to the experimental result, line source laser can provide amplitude directivity pattern, which is identical to that produced by point source in an aluminium half-cylinder [2]. Laser-based GW that employed point source to inspect thin tube was discussed in [8]. However, due to the broad bandwidth characteristics of the laser source, the emitted GW signal contained infinite GW wave modes that propagated in all directions, making complications in the analysis of the received GW signal. Fomitchov et al. made laser beam into a line rather than a circular spot so that more GW energy could be emitted into the inspecting object while keeping the energy density at a low level [4]. Sohn et al. used scanning laser-generated line source instead of the conventional GW's pulse-catch or pulse echo method for emitting and receiving GW signals [10]. Such source increased the performance in SNR of GW signals and proved that the thermo-elastic line source could be generated as a monopolar surface wave, which dramatically helped to indicate the presence of the defects. During the experiment, an arrayed line slit method was used in the laser beam as the GW emitter and a set of dual air-coupler as the GW receiver. Although the laser line source improves the directivity in GW wave propagation, the received GW signal still has a broad bandwidth characteristic.

In order to generate the appropriate GW mode by using the non-contact laser method, Kim et al. proposal a laser line array for GW inspection [5]. The arrayed laser beam was emitted to the surface of an aluminate plate in order to enhance the focusing ability and spatial resolution. For this purpose, a slit mask was designed to convert the laser point source to a line array source [5–7]. The mask could help to shorten the board bandwidth characteristics of laser so that desired GW mode in narrower band could be emitted. However, different masks have to be made in order to emit different type of wave mode. Moreover, the mask would absorb part of the emitted GW energy. To avoid the shortcomings of mask, in this paper, an innovative and novel laser-based GW inspection has been developed. The emission of the desired GW mode is performed by an integrated optical Mach-Zehnder interferometer (IOMZ). It is made from totally optical lens to form the desired laser beam pattern for converting the laser point to desired line array, which ultimately can be used to generate the desired GW mode for inspection purpose.

2 The Design of IOMZ for Emitting the Desired GW Mode in a Non-contact Means

To achieve the proposed method of using laser interferometry, a green laser system based on IOMZ interferometer is proposed for the actuator to emit the GW. The experimental setup is containing of a pulsed Nd:YAG laser with wavelength of 532 nm with lenses as shown in Fig. 1. First, the laser beam is passing through a beam splitter, which divides the incident light and sends them in two line mirrors and then recombines them through the beam combiner.

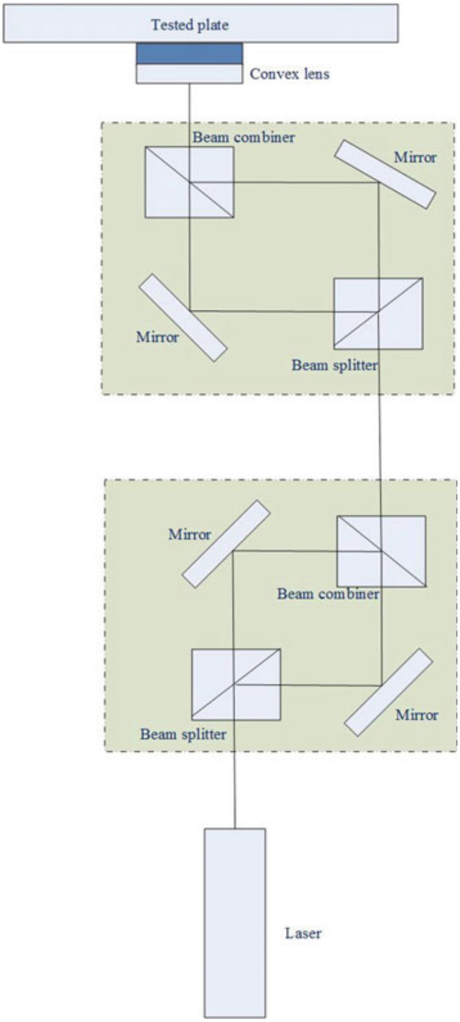
The conventional Mach-Zehnder interferometer (MZ) uses a pair of beam splitters to separate the laser beam into two arms and then merges them back to form interference fringes [3]. The principle of MZ is used here again as the polarizing cube beam splitters divide and recombine different laser beams traveling from different directions to achieve the effect of laser interferometry. The resultant laser beams then pass through another pair of beam splitters/combiner and mirrors to ultimately form the expected laser lines. The convex lens are then used to adjust the shape and size of the final lines which are belonged to light interference fringes. The above setup by using totally optical lenses to convert the laser point source to line array with specific number of lines and width of each line is named by us as IOMZ, which is a completely new design to generate the expected laser-based GW mode and signal for inspecting the integrity of plates and beams.

To determination of the width of each laser line which is generated by the interference of laser light, the wavelength matching method [1] is used to select the desired GW mode according to the dispersion curves:

$$V = f\lambda = f\Delta s = fd\left(\frac{\Delta s}{d}\right) \tag{1}$$

where V is the phase velocity of the A_0 mode propagate in a thickness of $d = 2$ mm aluminum plate. fd is the frequency of desired mode propagating in 2 mm thickness and Δs is the space of line-arrayed source. The relation between the wavelength λ, frequency f, the phase velocity V refer to the desired mode of guided wave, thickness of material d, and then the Δs can be calculated. Once the desired propagation mode have confirmed, the relevant slit space of the interference of laser can be calculated.

Fig. 1 The scheme of making the laser based IOMZ



The selection of desired GW mode is depended on the dispersion curves as shown in Fig. 2. The A_0 mode is characterized predominantly by the out-plane displacement, while the S_0 mode is characterized predominantly by the in-plane displacement. The reason we chosen A_0 mode is because the laser receiver is sensitive to the out-plane displacement. Therefore, the A_0 mode was applied in this study. A desired GW A_0 mode can be emitted by satisfying an appropriate spacing of line-arrayed source in terms of wavelength of A_0 mode. Equation 1 could be applied to other materials such as aluminum, steel, and other isotropic materials.

According to Eq. 1, the slop = $\Delta s/d$, the velocity, $V = 2$ mm/μs and the fd = 0.3 MHz ×2 mm = 0.6 MHz-mm, which is the space of line-array source, is 6.6 mm as indicated in Fig. 3 with the picture of the generated line-array laser source.

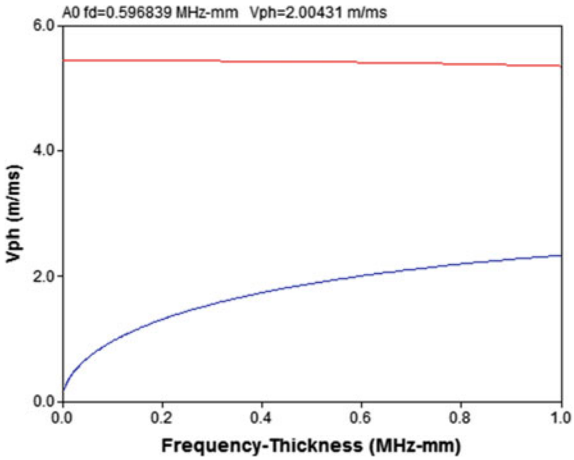


Fig. 2 The dispersion curve of the tested aluminium plate and the selected GW mode, A_0, and the expected emission frequency

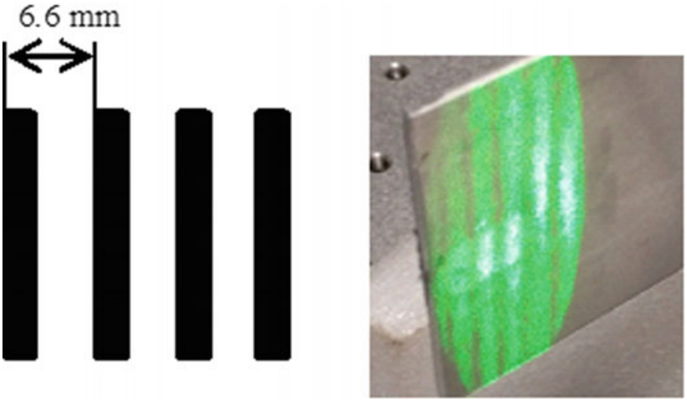


Fig. 3 The space width of the generated line-array laser source (left diagram) and the image of the line array by IOMZ (right diagram)

3 Experimental Verification and Result Analysis in Aluminum Plate

To validate the effectiveness of IOMZ, an aluminum plate with a thickness of 2 mm in health condition and in defective condition were investigated. A piece of iron with epoxy adhesives was stuck to part of the surface of the tested plate to simulate as a defect. The experiments were conducted using a Nd:YAG pulsed laser equipped with the IOMZ to emit the desired GW A_0 mode. The GW signal reflected the defect and the other end of the plate were received by the laser Doppler vibrometer. The drawing of the tested plate, its length, the location of defect is shown in the top diagram of Fig. 4. The two GW propagating paths, which include the distance of the GW propagating from the laser emission point (excitation) to the laser measurement point (path A) and from the laser emission point to the defect location and then propagated back to the laser measurement point (path B) are shown in the bottom diagram of Fig. 4.

The experimental setup and instruments of the laser-based GW system for inspecting the plate in pulse-echo mode are depicted schematically in Fig. 5. The Nd:YAG pulsed laser was used to emit the GW at a normal angle. A laser vibrometer was used to receive the reflected GW signal. When the GW signal was emitting as a conventional laser point source into the tested plate, the GW signal, which was reflected by the defective plate, was received by the laser vibrometer. Figure 6a shows the temporal waveform of the propagating GW signal (top left diagram) and its corresponding frequency spectrum (bottom left diagram). To ease revealing the relationship of time and frequency of the received GW signal, the collected signal was further analysed by a signal processing method, called continuous wavelet transform (CWT) as shown in Fig. 6b. The received GW signal reflected by the defect was inevitably contaminated by noise and disturbance as can be seen in Fig. 6b. The existence of high noise and disturbances were due to the board bandwidth characteristic of the laser-based GW transducer that collected all signals from low to high frequencies. Hence, even if the reflected GW signal was filtered by CWT, the true defect-related GW signal was not easy to be revealed in Fig. 6b.

With the help of IOMZ, the emitted laser-based GW signal becomes narrower in bandwidth and the emitted GW frequency range can be selected by laser lines that are separated by a specific width. Again, Fig. 7a shows that the application of an IOMZ interferometer-based laser excitation system to the normal plate can greatly improve the SNR and facilitate the interpretation of the signals as compared to those generated by a laser spot source. The IOMZ interferometer-based laser

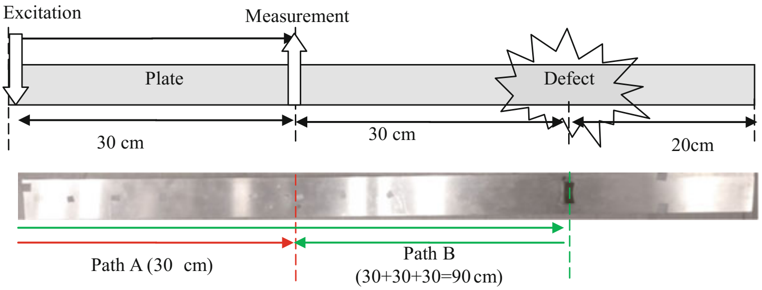


Fig. 4 The tested plate, its length and the location of defect (top diagram) and the GW propagating paths from laser emission point to the laser measurement point (path A) and to the defect location (path B) (bottom diagram)

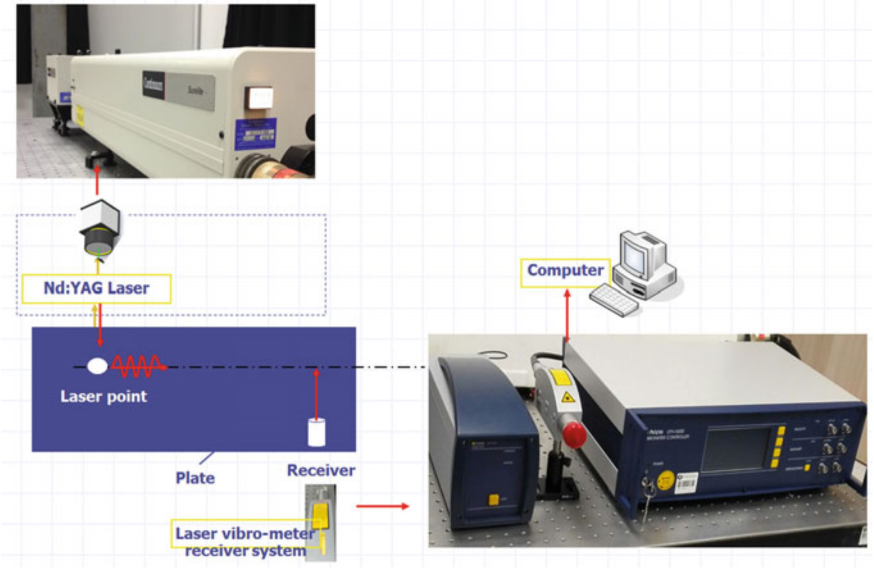


Fig. 5 Experimental set-up of the laser-based GW system for emitting (Nd:YAG pulsed laser, top-left diagram) and receiving by 1D vibrometer (bottom right diagram)

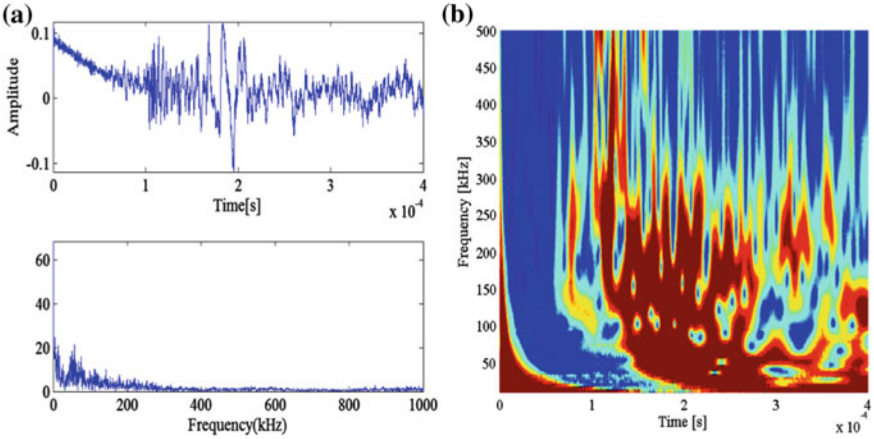


Fig. 6 GW signal emitted as a laser point source and then received from **a** a defective plate in its temporal waveform (top diagram) and its frequency spectrum (bottom diagram) and **b** its time-frequency in 2.5D signal after reconstructed by CWT

excitation system was also further applied to the defective plate as shown in Fig. 7b. This time, the received GW signal reflected by the defect can be observed due to the effect of minimizing noise and disturbance by the narrowed bandwidth of GW signal emitted by the IOMZ. From the time interval of the occurrence of defect

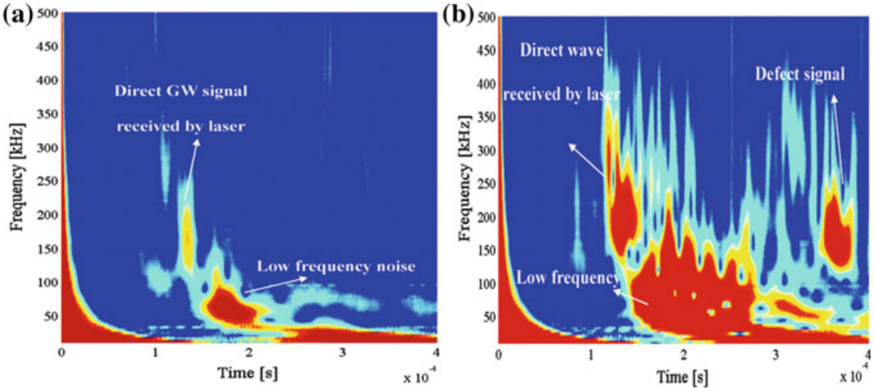


Fig. 7 GW signals received from **a** a normal plate after reconstructed by CWT and **b** a defective plate after reconstructed by CWT

signal in Fig. 7b, and with the known GW velocity of the A_0 mode, one can determine the starting and end time of the defective signal. Hence, the length and the location of the defect can be determined accordingly.

4 Conclusion

The research work on the design of a novel line-array laser source for producing a non-contact GW transducer to inspect the integrity of plates is reported here. The concept and method to design and implement such line-array laser source by using the novel IOMZ have been discussed in details. By using the conventional laser point source to emit the GW signal into the inspected plate, the true defect related signal can hardly be seen from the temporal and frequency plots of the collected GW signal. Even when the collected signal was processed by a popular signal processing method, the CWT, the defect's information could not be revealed from the time-frequency plot due to the existence of high noise and disturbances. The main reason is the broad bandwidth characteristic embedded in the emitted laser point source.

To overcome this deficiency, an innovative approach that totally used optical lens to create the line array like that generated by conventional GW's PZT transducers was invented. With the help of IOMZ that can convert the laser point source into line array source with the capability of selecting a proper GW frequency range by adjusting the width of each laser line, both the location and the axial length of the defect can be clearly revealed in the CWT time-frequency plot. Hence, the feasibility and capability of the innovative design of laser-based IOMZ for emitting the desired GW mode have been tested and verified respectively.

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