Applied Acoustics 141 (2018) 234–239

Contents lists available at ScienceDirect

Applied Acoustics

journal homepage: www.elsevier.com/locate/apacoust

Mode conversion detection in an elastic plate based on Fizeau fiber interferometer

Wen-Bo Yan[a,b], Ya-Xian Fan[a,*], Huan Liu[a], Ren-Zhong Zhang[a], Zhi-Yong Tao[a,b,*]

[a] Key Laboratory of In-Fiber Integrated Optics, Ministry Education of China, Harbin Engineering University, Harbin 150001, People's Republic of China

[b] Physics Research Center, College of Science, Harbin Engineering University, Harbin 150001, People's Republic of China

ARTICLE INFO

Keywords:
Elastic wave modes
Mode-converted waves
Scanning laser line source technique
Depth identification

ABSTRACT

Based on laser ultrasonic techniques, the mode-converted waves in an aluminum plate with a rectangular groove have been investigated by a Fizeau fiber interferometer. A Q-switched Nd:YAG laser was used for ultrasonic generation, and mode conversions occurred when ultrasonic waves interacted with the groove. Increasing the distance between the detection point and the groove could lead to the obvious changes in time domain signals. Experimental results showed that the ultrasonic waves induced by the pulsed laser were extremely sensitive to the surface-breaking cracks due to elastic wave mode conversions, and as the distance increased, the discrimination between different mode-converted waves was gradually enhanced. Furthermore, the depth of the groove was quantitatively measured through the analysis of the mode-converted Rayleigh waves. Our interferometer exhibited an outstanding performance in detecting elastic waves, which could be used not only in exploring the mechanism of mode conversions but also in evaluating structure cracks.

1. Introduction

Over the years, laser ultrasonic techniques have been developed into an important branch of non-destructive evaluations (NDE) because of their significant advantages, such as broadband range, noncontact, easy to focus, and remote diagnosis [1–5]. For surface crack detections, researchers usually concentrate on Rayleigh waves in experimental measurements and simulations, and the reflected and/or refracted Rayleigh waves have been used to identify surface cracks for years [6–18]. Nevertheless, the incident lasers can always generate multimode elastic waves such as longitudinal and shear waves at the same time. Because of interactions between waves and defect boundaries, mode conversions occur when these waves propagate through cracks. Studying body waves and their mode conversions caused by cracks can definitely benefit the ultrasonic transmission characteristics, elastic property evaluations, and internal defect detections. However, due to the high requirements on the resolution and accuracy of detecting systems, these mode conversion phenomena are still unsolved mysteries.

To detect elastic wave mode-conversions, the detection equipment requires a high space-time resolution due to very short intervals between these various mode-converted waves. Conventional devices for detecting ultrasonic waves include piezoelectric ultrasonic transducers [19], electromagnetic acoustic transducer (EMAT) [20], polymer film transducers [21], and so on. These conventional methods have some limitations in practical applications such as contact detection, couplant requirements, and low space-time resolution due to their size. Beyond these devices, optical fiber sensors are more suitable for detecting tiny structures and analyzing mode-converted waves, especially the optical fiber interferometers are remarkable because of their high sensitivity, resisting electromagnetic interference, flexibility adaptation to special environment, high frequency response, remote detecting, and small size. In 1979, Jarzynsk et al. presented a fiber interferometry acoustic sensor with the Mach-Zehnder setup to detect ultrasonic waves in water [22]. In 1980, Imai et al. demonstrated an in-fiber Michelson interferometer for detecting vibrations [23]. And Alcoz et al. demonstrated a short gauge length (5–13 mm) intrinsic Fabry-Perot interferometer in 1990 [24]. The sensor was used to detect ultrasonic longitudinal waves between 0.1 and 5 MHz. Among fiber interferometers, Fizeau fiber interferometers are very simple and not sensitive to temperature and electromagnetic interferences. By using only one fiber, this kind of interferometers can effectively avoid the polarization state and coherent length matching of multiple fibers to ensure a higher sensitivity and detection accuracy [25].

In this paper, we demonstrated a Fizeau fiber interferometer system to detect the mode-converted waves in the specimens with grooves.

* Corresponding authors at: Key Laboratory of In-Fiber Integrated Optics, Ministry Education of China, Harbin Engineering University, Harbin 150001, People's Republic of China (Y.-X. Fan & Z.-Y. Tao).

E-mail addresses: yxfan@hrbeu.edu.cn (Y.-X. Fan), zytao@hrbeu.edu.cn (Z.-Y. Tao).

https://doi.org/10.1016/j.apacoust.2018.07.013
Received 7 May 2018; Received in revised form 23 June 2018; Accepted 13 July 2018

Based on the thermo-elastic mechanism, the elastic waves were generated by a Q-switched Nd: YAG laser. By using a precisely motorized translation platform, ultrasonic waves were detected at different locations. It was found that the mode-converted waves and the reflected waves could be clearly separated when the detecting position was precisely selected away from the groove. In the following section, we demonstrate the mode conversion detecting system with our Fizeau fiber interferometer and briefly explain how it works when the ultrasound propagates through the aluminum plates. Based on the interferometer system, we analyze the elastic wave mode conversion in a plate with a rectangular groove and show the differences between the near and far field measured signals in Sec. III. The high space-time resolution of interferometer can benefit the analysis of complex interactions between the incident waves and the groove. In Sec. IV, increasing the distance between the detection point and the groove leads to the clear separation of mode conversions and the different elastic wave modes have been observed experimentally. Moreover, the depth of the groove is quantitatively measured through the analysis of the mode-converted Rayleigh waves. Finally, our major findings are summarized and discussed briefly.

2. Fizeau fiber interferometer

To accurately analyze the elastic wave modes propagating in a plate, we built a Fizeau fiber interferometer in a detecting system as shown in Fig. 1, which consists of three parts: generation, specimen control, and detection. First, the elastic waves were generated by a pulsed Nd: YAG laser at 1064 nm with 6 ns pulse duration, the repetition rate of the laser source was 3 Hz. The pulse laser was divided into two beams by the splitter lens. One beam of the laser was received by a space photodetector (KG-PR-1G-A-FS from Conquer, Ltd.) as a reference signal for analysis. A cylindrical lens with 100 mm focal length was used to focus the other laser beam into a line, which irradiated the sample surface to excite the elastic waves based on the thermo-elastic mechanism. Beyond the point light, the line source can reduce radiation damages and improve radiation directivity. The sample of aluminum plate was placed on a motorized translation stage, which can be precisely moved in a step of 1 mm due to its high space resolution with the order of submillimeter. In the detection part, we used a narrow-line-width tunable laser as the probe light for the interferometer. The center wavelength was 1550 nm and the power was about 32 mW. The probe light was incident to the circulator through the isolator. Here, the isolator was used to avoid the detecting light coming back to the laser, which ensured the stability of the system. The interference signal of the probe and reflected laser beam was received by another photodetector through the circulator. Both electronic signals from two photodetectors were recorded by the oscilloscope (MOS-S-204A from Keysight, Inc.) for analyzing.

The Fizeau fiber interferometer is as simple as a single fiber, which is used as both the sample and reference arms. When the probe laser outputs from the circulator, there will be 4% of the energy reflection at the end of the fiber, and this part of the laser is used as a reference beam. At the same time, most of the laser from the end of the fiber irradiates the sample, and then is reflected by the sample surface, and finally irradiates the fiber back. This part of the laser is the signal beam. The signal beam interferences with the reference beam in the circulator, resulting in the interference signal. In the experiments, we carefully adjusted the fiber end to achieve the strongest interference signal, which guaranteed the similar reflected energy and the signal-to-noise ratio. The intensity of the interference laser beam can be expressed as

$$I = I_A + I_B + 2\sqrt{I_A I_B}\cos\Delta\phi \tag{1}$$

where I_A and I_B are the intensities of the signal and reference beam, respectively, and $\triangle\phi$ represents the phase difference between the two beams, which is related to the Fizeau cavity length x and can be expressed as

$$\Delta\phi = 4\pi n_0 x/\lambda \tag{2}$$

where n_0 is the refractive index of the medium in Fizeau cavity, and λ is wavelength in the Fizeau interferometer. By using the photodetector, interference signal is converted into the corresponding electric signal, and then we can get the waveform signal from the oscilloscope.

In the experiment, before the laser irradiation, the first thing was to adjust the interferometer system to ensure that both the reference and signal beams had a high contrast, which benefited the output signal from circulator with high stability and large amplitude. This system was based on the Fizeau fiber interferometer sensor principle. The changes of Fizeau cavity length led to the changes of the interference beam from the circulator, which was detected by the photodetector ultimately. In a certain range of changes, the intensity of the interference signal varied monotonically with the length of Fizeau cavity. Therefore, we must select the appropriate resonant point to achieve the high sensitive measurement.

In order to determine the specific location of the fiber

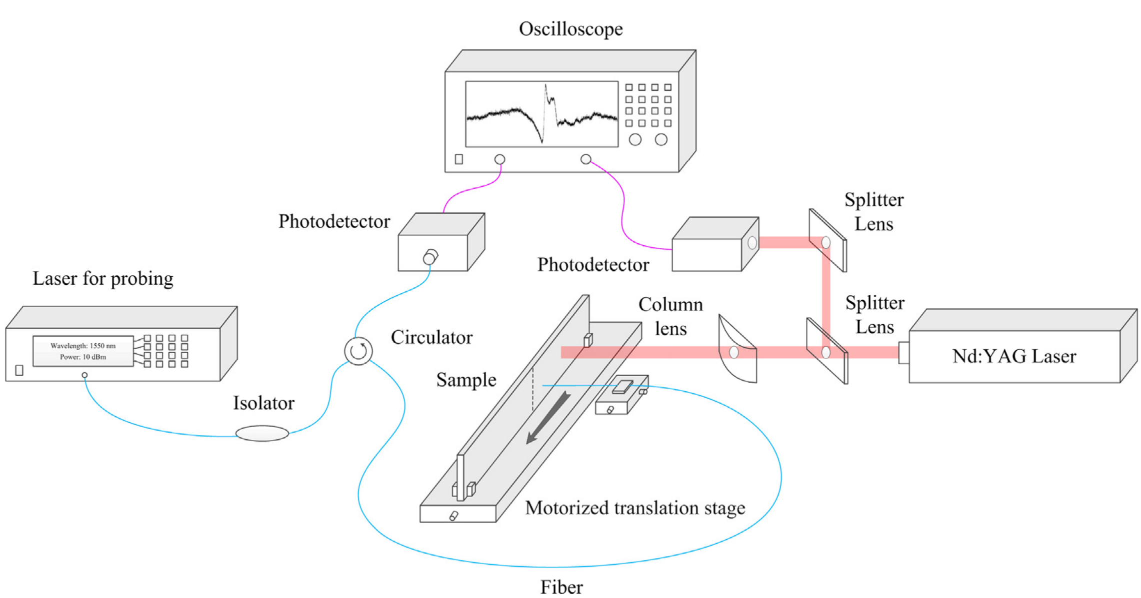

Fig. 1. Schematic diagram of the experimental setup.