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Guided wave-based pipe damage inspection by ultrasonic fiber optic sensor

*Wensong Zhou[1), Yongkang Dong[2), Hui Li[1) and Yawen Xie[3)

[1), 3)] *Key Lab of Structures Dynamic Behavior and Control of the Ministry of Education, Harbin Institute of Technology, Harbin 150090, China*
[2)] *National Key Laboratory of Science and Technology on Tunable Laser, Harbin Institute of Technology, Harbin 150001, China*
[1)] *zhouwensong@hit.edu.cn*

ABSTRACT

Ultrasonic fiber optic sensors (UFOS) based on Mach-Zehnder (M-Z) interferometer is proposed to detect guided waves propagating in the pipe, which is common structural component in aerospace, mechanical or civil structures. The sensitivity of UFOS depends on the long sensing distance, while winding around the circumferential direction of the pipe provides arbitrary sensing length as well as small covering area along the axial direction of the pipe. By the combined analysis of the characteristics of guided waves propagating axial direction of the pipe and the working principle of M-Z interferometer, the sensitivity of UFOS are investigated theoretically at first. Subsequently, a series of experiments are conducted on an aluminum pipe to demonstrate the guided wave sensing and damage inspection performances, including impact loading identification and guided waves reflected from the crack. Results indicate the UFOS has potential for providing quantitative estimation of damage in the pipe structures.

1. INTRODUCTION

Fiber optic sensors (FOS) have been proven that they have the potential to detect high-frequency ultrasonic signals (Bucaro *et al*., 1977, Gachagan *et al*., 1995, Pierce *et al*., 1996, Gachagan *et al*., 1999, Atherton *et al*., 2000, Gong *et al*., 2001, Zhou *et al*., 2015), in structural health monitoring field which refers to generally acoustic emission signals from active structural damages and guided waves excited by ultrasonic actuators and propagating in waveguide.

The type of optical fiber sensors can be differentiated according to the modulated physical parameters, such as by modulating the light phase, wavelength and so on.

[1),2)] Professor
[3)] Graduate Student

Bucaro *et al*. (1977) of U.S. Naval Research Laboratory demonstrated the possibility of using an optical fiber to detect the ultrasonic signal by the phase modulation method. Experiments were carried out over the 40-400 kHz frequency range. Gachagan *et al*. (1995) used M-Z interferometer to demodulate acoustic signal propagating in the plate. This experimental result can be considered as a fundamental basis for a structure health monitoring using the M-Z interferometer-based optical fiber sensors. With the same interferometer, Pierce *et al*. (1996) compared the effectiveness of surface-bonded and embedded optical fibers for the detection of ultrasonic Lamb waves in steel, carbon fiber reinforced plastic and glass reinforced plastic plates. Gachagan *et al*. (1999) generated ultrasonic Lamb waves in thin composite plates by mean of a low profile acoustic source constructed using a flexible piezocomposite material, and detect the propagating waves by an optical fiber sensor, where light signal was demodulated by M-Z interferometer. The optical fiber embedded in the plate or bonded on the surface of the plate kept straight shape in their experiments. Atherton *et al*. (2000) compared the ultrasonic signals detected by M-Z and Michelson interferometers. The sensitivity of surface bonded and embedded fibers were also compared. All experimental results provided a greater insight into the detection mechanism and sensitivity of the M-Z interferometer. Gong *et al*. (2001) proposed an amplitude-division-multiplexed interferometric sensor array for locating acoustic emission. Their experiments were conducted with a modified M-Z interferometer consisting of two sensing arms and one reference arm.

For the pipe structures, which are used widely in modern industries to transport high-temperature, high-pressure, explosive, inflammable gas/liquid, toxic, even radiant fluid, guided wave based damage detection methods have been also proven to be effective an promising. In pipes, guided waves can propagate along the span of the pipe at long distances as well as the hoop direction. For the former, they are further divided into longitudinal modes (L), flexural modes (F) and torsional modes (T). In general, piezoelectric transducers are used frequently to excite and receive guided waves propagating in the pipe (Silk and Bainton, 1979, Alleyne and Cawley, 1996, Liu et al., 2006, Ratassepp et al., 2010). The optical fibers cannot excite any waves in the structures, but as the sensor or receiver, in comparison to the piezoelectric transducers, which are affected more easily by electromagnetic interference, optical fiber sensors are immunity to electromagnetic interference and they have very small dimensions and light weight and can be embedded unobtrusively within structures, have wide temperature operating range, and are capable to transmit signal over a very long distance (Xiong and Cai, 2012).

In this work, UFOS based on M-Z interferometer is proposed to detect guided waves propagating in the pipe. In the remaining part of this paper, the principle of M-Z interferometer will be presented first. Then, the guided wave properties along the axial direction of pipes are analyzed. Lastly, guided wave sensing by UFOS is investigated through experiments, in which piezoelectric wafers are also used for comparative purpose.

2. UFOS BASED M-Z INTERFEROMETER AND ITS RESPONSES TO GUIDED WAVE IN THE PIPE

2.1 M-Z Interferometer

M-Z interferometer is a kind of optical device, which is used to measure the relative phase shift variations between two light beams within two optical fibers, which are derived by splitting light from the same light source. The two optical fibers can be considered as sensing arm and reference arm respectively. As the indication by its name, the sensing arm is used to detect the acoustic field introduced by any mechanical behavior, i.e. ultrasonic guided waves in this work, while the reference arm keeps free. The M-Z interferometer is schematically presented in Fig. 1 (Zhou *et al*., 2015).

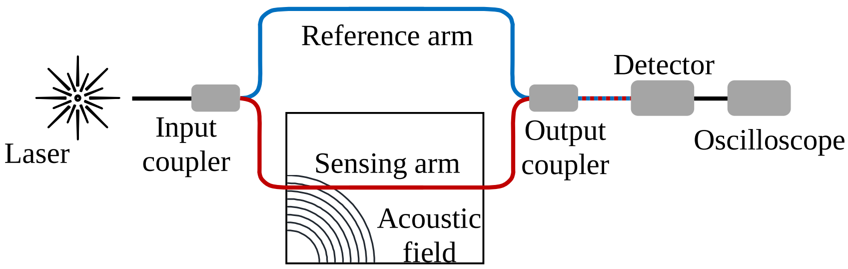


Fig. 1 Schematic of a M-Z interferometer

The basis mechanism of M-Z interferometer is the pressure induces the phase shift of the light beam. In general, the relative phase change can be expressed with three strain components (Hocker, 1979):

$$\Delta\phi \approx \beta L\varepsilon_{11} - \frac{1}{2}\beta L n^2 \left(p_{11}\varepsilon_{11} + p_{12}\varepsilon_{22} + p_{12}\varepsilon_{33} \right) \tag{1}$$

where β is propagation constant of a single mode, $\beta = k_0 n$. k_0 is propagation constant of free-space propagation constant, and n is core index of the optical fiber. L is the length of optical fiber. ε_{11} is the strain in the direction of light propagation, i.e. the longitudinal direction of the optical fiber. p_{11}, p_{12} and p_{13} are the elements of the strain-optic tensor for a homogeneous isotropic material.

2.2 Guided Waves in the Pipe

Guided waves in hollow pipes propagating along the axial direction were first studied by Gazis (1959), who reported the exact solutions of the Pochhammer-Chree (PC) frequency equation. For the wave propagating along the axial direction, these solutions lead to three different classes of wave propagating modes: the axisymmetric torsional modes T(0, *n*) and longitudinal modes L(0, *n*), and the non-axisymmetric flexural modes F(*m*, *n*). Here, *m* stands for the circumferential order and *n* stands for the wave family number. For F mode waves, they have the displacement component u_r, u_θ and u_z, while for L mode waves, they are u_r and u_z. And for T mode waves, the only displacement component is u_θ. Since the optical fibers will be wound around the pipe (see Fig. 2), they can only sensing the deformation along the longitudinal direction of the optical fiber. This deformation is related to u_r only, thus the proposed UFOS is able to sensing F and L mode waves, which have the displacement u_r. In addition, the optical fibers are wrapped enough loops around the pipe in order to obtain high sensitivity. The signal received by the oscilloscope is related to the integral of strain around the circumferential direction. Due to the tiny diameter of the optical fiber, the covering area is also very small on the pipe.

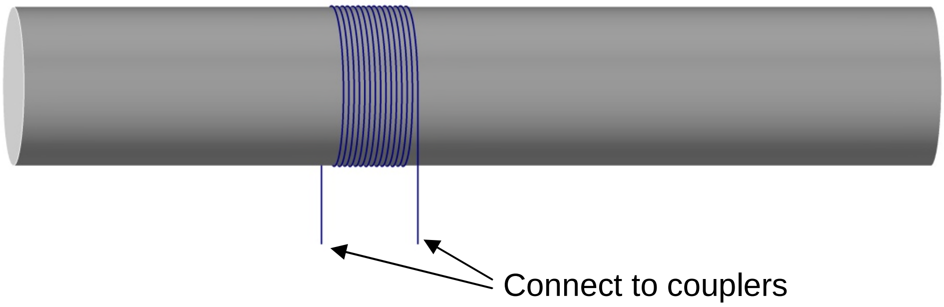


Fig. 2 UFOS attached on the outside surface of the pipe

3. EXPERIMENTAL INVESTIGATIONS

3.1 Experimental Setup

A series of experiments were conducted to demonstrate the guided wave sensing and damage detection by UFOS. A 2.5 m-long aluminum pipe with outside diameter of 100 mm and wall thickness of 1.3 mm was used for the demonstrations. Sixteen PZT wafers were mounted around the pipe circumferentially at 22.5 degree interval onto its outer surface. These symmetric arrangement PZT wafers were used as actuators to excited L mode guided waves. The optical fibers with different loops were attached by cyanoacrylate adhesive on the surface of pipe as sensor to receive guided waves. The axial distance between PZT wafers and optical fibers is 60 cm. The PZT wafers were driven by a function generator (AFG3252C, Tektronix, Inc.). The excitation signal is a five-peaked narrow band signal with varying center frequencies. A wideband (DC-2MHz) power amplifier (TEGAM 2350) was used to amplify excitation voltage. The M-Z interferometer used in this work consists of one RIO ORION Laser Module and one Thorlabs FPD510 photodetector mainly. The signals induced from the sensor were collected directly by a digital oscilloscope (DPO 2024, Tektronix, Inc.) without any voltage amplifier.

3.2 The Basic Characteristics of Guided Wave Signals Received by UFOS

Fig. 3 shows the guided wave signals received by a 13-loops (about 4.08 m) optical fiber at 30 kHz and 210 kHz center frequencies, respectively. According to the group velocity of L mode, L(0, 2) mode can be recognized readily. Since the arrangement of wafers is not strictly symmetry, F mode, i.e. the asymmetric mode may be also found in Fig. 3.

The center frequencies of excitation signal are varied from 30 kHz to 350 kHz in increments of 20 kHz, Fig. 4 gives the amplitudes of voltage responses for all frequencies. The UFOS used in this work has larger voltage response at 30 kHz and around 270 kHz respectively. Moreover, this curve depends on the wavelength, wave structure as well as the wave amplitude excited by PZT wafers.

Fig. 5 shows the voltage responses for different loops at 30 kHz. It indicates that longer optical fiber results in larger amplitude of guided wave signals.

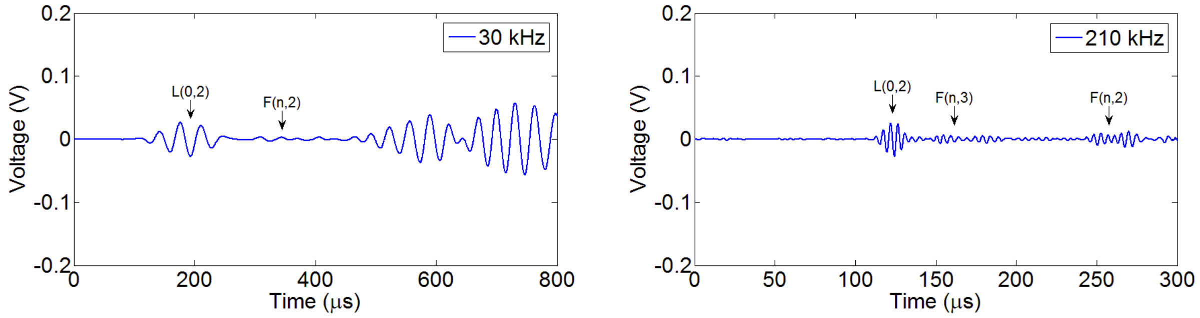


Fig. 3 Guided wave signals received by UFOS

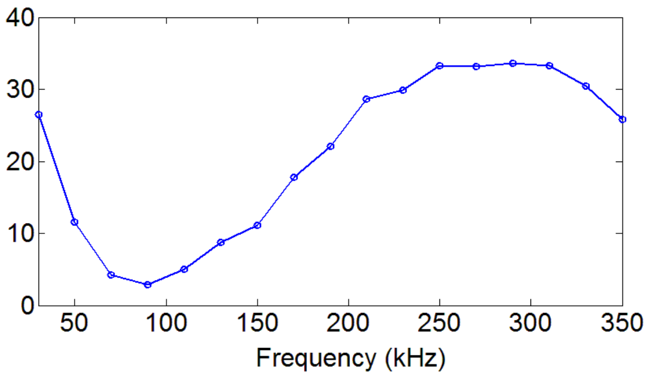


Fig. 4 Frequency tuning curve for UFOS in the pipe

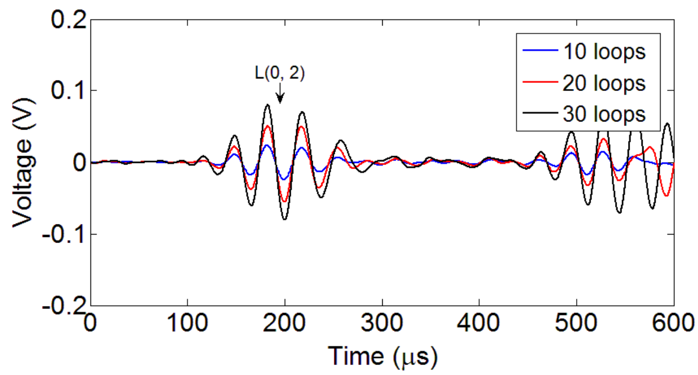


Fig. 5 Voltage response with respect to different loops

3.3 Damage Detection by UFOS

In this work, two simple circumferential notches were cut by the grinder to simulate the real damage in the pipe, and demonstrate the damage detection ability of the proposed UFOS. Fig. 6 shows the layout and location of PZT actuators and UFOS as well as the artificial damages. For the notch, two different depths were used to investigate their effects to the signals received by sensors. Fig. 7 gives the experimental results of pristine and damaged pipe respectively and their differences. For both low and high excitation frequencies, the guided wave signals received UFOS have been affected obviously. The deeper notch results in larger loss of the guided wave signals.

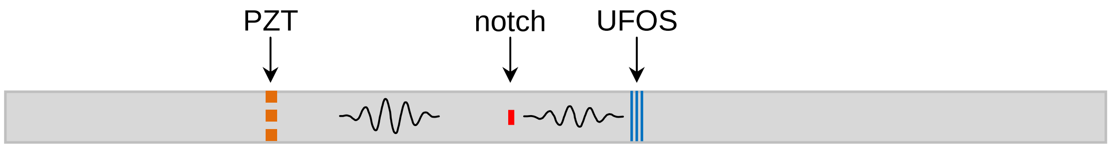
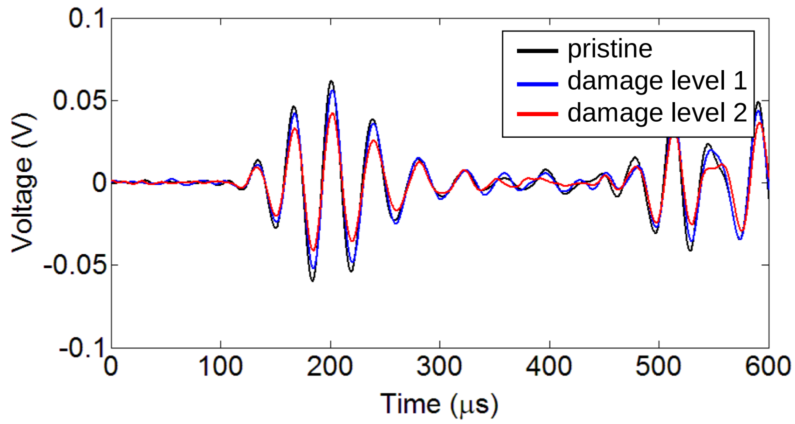
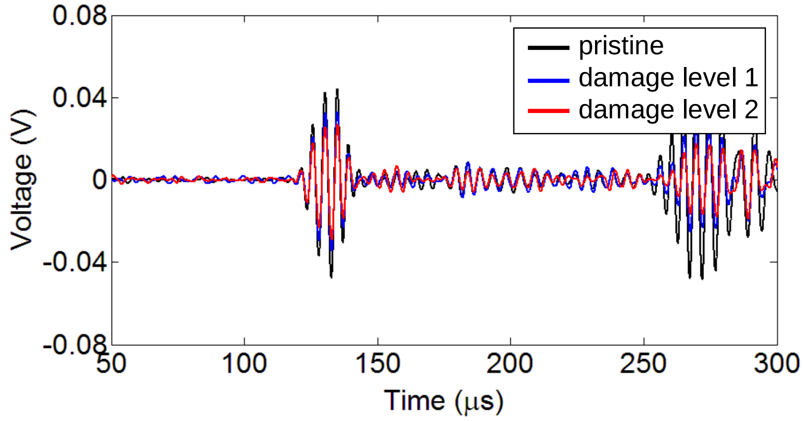


Fig. 6 Layout and location of transducers and the artificial damage



(a)



(b)

Fig. 7 Sensor outputs for the pristine and notched pipe: (a) 30 kHz; (b) 210 kHz

4. CONCLUSIONS

The UFOS based M-Z interferometer was used to detect guided waves propagating in the pipe in this work. The UFOS may be wrapped around the pipe with a lot of loops for obtained higher sensitivity; meanwhile it covers only with very small area. In the experiments, the UFOS can receive the guided wave signal excited by the PZT wafers at low and high frequencies. Due to the feature of optical fibres, they are more sensitive to L mode guided waves propagating in the pipe. Furthermore, the artificial damage was made in the pipe to investigate the damage detection through the proposed UFOS. Results indicated that the UFOS has potential for providing quantitative estimation of damage in the pipe structures for both low and high frequencies.

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