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Detection and Monitoring of Axial Cracks in Cylindrical Structures Using Torsional Wave Generated by Piezoelectric Macro-Fiber Composite

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ABSTRACT

In cylindrical structures such as pipelines and pressure vessels, cracks are most likely to occur along the longitudinal (axial) direction and they can be fatal to the serviceability of the structures. Unfortunately, the conventional ultrasonic crack detection techniques, which usually use longitudinal wave, are not very sensitive to this type of cracks. This paper focuses on the detection and monitoring of axial cracks in cylindrical structures using torsional wave generated by piezoelectric macro-fiber composite (MFC). The first order torsional wave is a kind of non-dispersive pure shear wave which propagates at a fixed wave speed. Torsional wave is utilized in this work because, intuitively, it is more sensitive to axial cracks than the family of longitudinal waves. Numerical simulation has been performed using ANSYS to show the effectiveness of torsional wave in detecting and monitoring axial cracks. The time of flight (TOF) of the waves is used to determine the crack position, while the crack propagation is monitored by measuring the variation in the crack induced disturbances. Experiments have also been conducted to investigate the feasibility of the proposed method. MFC transducers oriented at 45° against the axis of the specimen are used to generate and receive torsional waves. The experimental results demonstrated that the crack position can be indentified and its growth can be well monitored with the presented approach using torsional wave.

Keywords: MFC, torsional wave, pipe, health monitoring, axial-direction crack

1. INTRODUCTION

Cylindrical structure is one of the most popular types of structures used in many industries such as oil, chemical and power generation industries. In such industries, failure could causes billions of dollars in losses. Furthermore, irreversible damage is brought to not only the environment nearby but also the human beings who work or live in that area. So the safety of those structures must be well monitored and the damages in them need to be identified at the very beginning stage.

Structure health monitoring (SHM) of tubular structures has gained more and more focus in recent decades. Non-destructive testing (NDT) techniques are often used in SHM. The most commonly used NDT methods like X-ray^[1], eddy current^[2] and magnetic flux^[3] methods can also be used in cylindrical structure health monitoring. But because of their point-to-point inspection scheme and human efforts involved during inspection, such methods cannot be cost effective when applied widely on structures that cover large areas such as pipelines. When continuous structures are being inspected, the most effective way is to use ultrasonic waves which propagate in the structures. When such waves meet the discontinuity, the change of waves can be picked up by sensors. PIG method^[4] can generate bulk wave in pipes for pipeline SHM. But the testing equipment is large in scale and the installation is hard to perform.

Some of the researchers have performed experiments with small size actuators that generated controllable guided wave in cylindrical structures. Joseph Rose and his team^[5-8] analyzed the guided wave propagating in cylindrical structures. With the help of multiple piezoelectric ultrasonic probes and multi-channel function generators, desired wave modes can be focused at any specific position on the pipe to achieve cylindrical structure SHM. Most of the researchers used longitudinal wave mode, which has the fastest wave speed, for damage detection to avoid wave pack overlapping. Kannan etc.^[9] used magnetostrictive tapes and alternative magnetic field to generate torsional wave for SHM of

cylindrical structures. Their results show that radial saw cuts and drilled holes can be detected using their experiment setup.

When cylindrical structures are used as pressure vessels, the inner pressure will tend to cause crack to happen along the axial direction rather than along the circumferential direction. However, once the crack orientation is parallel to the wave propagation direction, the reflected longitudinal waves from any defect will not be big enough to be detected because the particle motion direction of longitudinal wave modes are also parallel to the crack direction. The sensitivity of such pulse-echo based detection method is thus decreased. Compared with longitudinal wave modes, torsional wave is relatively stable and sensitive to this type of crack since its particle motion is perpendicular to the crack orientation. Under such condition, detecting and monitoring the axial direction crack growth using torsional wave is of great importance to the SHM of cylindrical structures.

This paper presents an innovative in-situ self-sensing monitoring system for the detection and monitoring of axial direction crack growth in cylindrical structures. This closed loop self-sensing monitoring system consists of three pieces of MFC transducers. One piece of MFC is used as actuator to generate the necessary torsional wave pack. The other two pieces of MFC are used for axial crack position identification and crack growth monitoring, respectively. The first section briefly introduces wave propagation in cylindrical structures, which is the foundation of this research. The following sections cover numerical simulation which is the proof of concept, and experimental study. The concept of an integrated system for SHM of continuous cylindrical structures is illustrated in Section 4. The last section is the conclusion and discussion of future works.

1.1 Ultrasonic wave inspection

Ultrasonic wave inspection is one of the most commonly used NDT techniques. Usually, the actuators generate the desired waveguides and the sensors pick up the waves propagated in the structures. When discontinuity like crack, corrosion or delamination exists along the propagation path of the waveguides, any changes of wave structures can be captured by the sensors. The detail information of the defects can be identified with the help of digital signal processing (DSP) techniques. Pulse-echo method can find additional wave pack reflected from discontinuity, which is widely adopted in ultrasonic wave inspections. In the pulse-echo method, the actuators and sensors are located at the same side of the crack. Baseline signature of the undamaged structure is usually needed to differentiate between the damaged specimen and the undamaged specimen. The position of the crack can be calculated based on the time of flight (TOF) of the additional wave pack reflected from the crack. Root mean square deviation (RMSD) method is another way to evaluate the change of wave structures. In RMSD method, the actuators and sensors are placed on both side of the crack to measure the disturbances caused by the crack. Baseline signature and subsequent signatures are compared to evaluate the crack growth.

In this paper, a combination of both pulse-echo method and RMSD method is used. Pulse-echo method is used to identify the axial position of the axial direction crack, and RMSD method is used to monitor the crack growth. Because of the complexity of wave modes and overlapping of wave packs, only the first two or three wave packs of the signatures are used.

1.2 Wave propagation in cylindrical structures

Lamb^[10] is the first to investigate the symmetric and antisymmetric wave modes in plate. At low frequency range of ultrasonic wave inspection, only the most fundamental symmetric waves S_0 and anti-symmetric waves A_0 exist in the plate. Compared with waves in plate like structures, waves propagating through cylindrical structures are more complicated. The wave modes that propagate in cylindrical structures can be grouped into axisymmetric wave modes and non-axisymmetric wave modes. Gazis^[11, 12] gives an analytical solution of wave propagating through an infinitely long hollow cylinder. Based on his equation, dispersion curves of the first few order wave modes are plotted in Figure 1.

Figure 1 shows the dispersion curves of phase velocity and group velocity of an aluminum pipe with 102mm diameter and 3mm wall thickness. In Figure 1, all the axisymmetric wave modes are denoted by bold lines. The first torsional wave mode $T(0,1)$ is in red and the two blue bold lines denote the first and the second order longitudinal wave modes $L(0,1)$ and $L(0,2)$. In the bracket (m,n) , m stands for the circumferential order and n stands for the wave family number. As shown in Figure 1(a) and Figure 1(b), flexural wave modes with the same wave family number n have almost the same velocity especially at the high frequency range. The flexural waves $F(m,n)$ get closer to the axisymmetric wave modes as the actuation frequency increases. There are infinite numbers of wave modes existing at the same time during wave propagation. Each wave mode has its own cutoff frequency. If the actuation frequency is below the cutoff

frequency, corresponding wave mode cannot be actuated. The group velocity represents the wave pack travelling speed which is used in the result analysis.

Even though complexity of flexural wave modes exists, they still share some similar characteristics. Table 1 lists the group velocities of different wave modes under 4 different actuation frequencies. The flexural wave modes that share the same family number n are grouped with the axisymmetric wave mode that is closest to them. In fact, not only the wave group velocities are similar, the particle motions of flexural wave modes are also similar to their closed axisymmetric wave modes.

Figure 1 (a) Dispersion curves of phase velocity; (b) Dispersion curves of group velocity of aluminum pipe (OD: 102mm, wall thickness: 3mm), only the first 5 order flexural wave modes are considered.

Table 1 Group velocities of different wave modes at 100 kHz, 150 kHz, 250 kHz and 400 kHz actuation (m/s)

	100 kHz	150 kHz	250 kHz	400 kHz
L(0,1)	2570	2869	3109	3178
L(1,1)	2567	2867	3108	3178
L(2,1)	2559	2861	3105	3176
L(3,1)	2545	2851	3100	3173
L(4,1)	2526	2837	3092	3168
L(5,1)	2500	2819	3082	3163
T(0,1)	3149	3149	3149	3149
L(1,2)	3131	3142	314	3148
L(2,2)	3076	3120	3140	3145
L(3,2)	2984	3084	3128	3140
L(4,2)	2855	3033	3111	3132
L(5,2)	2685	2966	3090	3123
L(0,2)	5412	5389	5282	5023
L(1,3)	5324	5353	5271	5018
L(2,3)	5052	5246	5236	5004
L(3,3)	4561	5061	5179	4980
L(4,3)	3770	4789	5097	4946
L(5,3)	2438	4416	4990	4903

When longitudinal wave propagates in cylindrical structures, its particle motion direction is parallel to the axial crack orientation. Thus, once crack happened along the axial direction, its influence on the longitudinal wave pack is very limited. Compared with longitudinal waves, torsional waves' particle motions are along the pipe circumference. Once axial-direction crack occurs, large disturbance will occur in both the reflected and forwarded signals. When the crack size increases, larger disturbances on the torsional wave pack can be captured by the sensors, which can be used as indicators for crack position identification as well as crack growth monitoring.

2. FEM SIMULATION OF SHM USING TORSIONAL WAVE

2.1 Numerical model

The purpose of the FEM simulation is to investigate the feasibility of locating axial direction crack position and monitoring crack size growth using torsional wave pack. Under full actuation condition, only axisymmetric wave modes can be activated. For the reason of simplification, only full actuation condition has been performed in the FEM analysis.

The FEM simulation of guided wave propagation in a 2.4m long aluminum pipe is performed using ANSYS, an FE analysis software. SHELL63 element is used and penetrated axial direction crack at the center position of the pipe is modeled using nodal release method. The growth of crack is simulated by releasing more nodes on the shared boundaries of two pieces of structures. Due to the limitation of time, only preliminary investigation has been performed. Figure 2 shows the numerical model of the undamaged specimen. At the crack position, as shown in the zoomed in part of Figure 2, the DOF of the nodes are released to prevent displacement and other physical measurements transfer. More DOF from nodes on the common boundary will be released as the crack grows. At one end of the pipe, fixed boundary condition is applied to prevent rigid body movement.

Figure 2 Numerical model of 2.4 meter aluminum pipe and the crack propagation mechanism

2.2 Actuation signal

The actuation signals in ultrasonic wave inspection are very important. Good actuation signal can greatly improve the test results. Five circles Hanning windowed sine wave burst, which is one of the most commonly used signals in ultrasonic testing, is adopted in this research. With the help of its concentrated wave pack center, the accuracy of locating the axial crack position is improved, and with its narrowed bandwidth, the dispersion effect of wave modes is limited.

2.3 Simplification of actuator and sensors

As shown in Figure 3a, the MFC actuator is placed at the left side of the crack; Sensor 1 is placed at the right side of the crack to monitor the crack growth; and, Sensors 2 and 3 are placed at the left side of the actuator to receive the signal reflected from the crack.

Force boundary conditions have been applied on both the axial direction and circumferential direction, as plotted in Figure 3 (b). Under such force boundary conditions, only axisymmetric wave modes can be activated. The wave structures are simple and only longitudinal wave modes $L(0,2)$ and $L(0,1)$, and torsional wave modes $T(0,1)$ exist in the output results.

Figure 3 (a) Transducers distribution; (b) full actuation loading boundary condition

2.4 Sensor output analysis

Simulation results of sensor 2 and sensor 3 are plotted in Figure 4(a) and Figure 4(b) respectively. Output from the undamaged specimen has been compared with the output from specimen with a 10mm axial direction crack at the center of the pipe. In Figure 4, clear additional wave packs are found from both the longitudinal wave mode L(0,2) and torsional mode T(0,1). Since torsional wave pack is more sensitive to axial direction crack, the torsional wave pack reflection is greater than the longitudinal wave pack reflection which is why torsional wave pack is used to calculate the TOF. Since the distance from actuator to target sensor is known, based on the TOF of this wave pack and the first order torsional wave T(0,1) group velocity from the dispersion curve, the position of the crack can be located. If the distance from actuator to crack position is denoted by X , it can be calculated by

$$X = (TOF_p \times V_p - S_{A \text{ to } S})/2 \quad (1)$$

where TOF_p is the TOF of target wave pack that travels from the actuator position to the target sensor position; V_p is the group velocity of target wave pack; $S_{A \text{ to } S}$ is the distance between the actuator and the target sensor. Substitute the torsional wave pack TOF $225\mu\text{s}$ from sensor 2 and $235\mu\text{s}$ from sensor 3 into Eq(1), the estimated crack positions are 27.90cm and 27.78cm away from the actuator respectively, which are very close to the exact crack position of 27.5cm from the actuator. The data used to calculate the axial position of the crack are listed in Table 2. The crack position calculated from longitudinal wave pack gives poor accuracy compared with the value calculated from torsional wave pack. The reason for the poorer accuracy of longitudinal wave pack comes from its low sensitivity to the axial direction crack (as shown in Figure 4). Thus, torsional wave is a better choice in locating the axial direction crack position.

Figure 4 Comparison between undamaged and 10mm cracked numerical simulation outputs from (a) sensor 2 and (b) sensor 3

Table 2 Calculation of axial crack position from numerical simulation results

Data from	Wave pack used	TOF_p (μs)	V_p (m/s)	$S_{A \text{ to } S}$ (m)	Calculated crack position X (m)	Actual crack position (m)	Error (%)
Sensor 2	T(0,1)	225	3149	0.15	0.279	0.275	1.5
Sensor 2	L(0,2)	150	5412	0.15	0.33	0.275	20
Sensor 3	T(0,1)	240	3149	0.2	0.278	0.275	1.1
Sensor 3	L(0,2)	155	5412	0.2	0.3	0.275	9.1

3. EXPERIMENTAL STUDY ON LOCATING CRACK AND MONITORING CRACK GROWTH USING TORSIONAL WAVE

3.1 MFC piezoelectric transducers

MFC actuator is first developed at the NASA Langley Research Center ^[13]. MFC consists of active rectangular piezoceramic fibers aligned in a unidirectional manner, with interdigitated electrodes and an adhesive polymer matrix. Due to its manufacturing process and its structure, MFC shows different electromechanical characteristic along its long and short edges. Compared with a typical through-plane poled piezoceramic actuator device, the maximum free strain performance of MFC is considerably larger, and is also more endurable under various electrical and mechanical cyclic loading conditions. Most importantly, MFC is rather soft as compared with the normal piezoceramic transducers. It can be bended to match the curvature of a cylindrical shell very well, which is the main reason for its use in our experiment.

3.2 Experimental setup

The specimen is an aluminum pipe with length 2.4m, outer diameter 102mm and wall thickness 3mm. The aluminum pipe is supported by 4 stands at the bottom. Four pieces of MFC actuators are bonded on the surface of the pipe, 45° oriented to the axial direction, as showed in Figure 3a - one actuator and 3 pieces of sensors. The actuator generates guided ultrasonic waves that propagate in the specimen and the sensors pick up all the signals. Because the actuator does not fully cover the circumference of the pipe, flexural wave modes need to be taken into account. Penetrated crack is initiated at the center of the pipe with initial length of 3mm. The crack length increases at 1mm increment until it reaches 50mm.

The experimental setup consists of a Tabor Electric ww1701 arbitrary function generator, a Terk PZD350A high power amplifier and a National Instruments (NI) integrated digital signal acquisition (DAQ) system as shown in Figure 5. When MFC is used as actuator, it needs to be driven by high voltage actuation signals. The signal from an arbitrary function generator is first monitored by the oscilloscope and then amplified from 1V peak-to-peak to 100V peak-to-peak. The sensors are connected to the NI multi-channel switching box to receive the signal simultaneously. An additional cable from the function generator is connected to the DAQ device to synchronize the data acquisition process. To eliminate the influence of background noise, 16-times cycle averaging is used.

Figure 5 Experimental setup for torsional wave SHM of pipe using MFC transducers

3.3 Axial direction crack size growth monitoring

Experimental data within target frequency bandwidth (60 kHz – 200 kHz) are collected at each crack size. When a MFC sensor is placed at another side of the crack, only the first pass wave packs with disturbance from the crack are used. 100 kHz actuation experiment results of sensor 1 from the undamaged specimen and the specimen with 50mm cracked specimen are compared in Figure 6(a). The difference between two curves clearly shows that the longitudinal wave is not sensitive to the axial direction crack growth. Even though the axial crack has reached 50mm, the longitudinal wave pack is almost the same as the one from the undamaged specimen. On the other hand, torsional wave pack is obviously affected by the axial direction crack. To calculate the differences between two relevant data series, RMSD method is used to quantify the disturbance on torsional wave pack caused by the axial-direction crack. The RMSD index is calculated as

$$RMSD = \sqrt{\frac{\sum_{i=1}^n (x_i - x_0)^2}{\sum_{i=1}^n x_0^2}} \times 100 \quad (2)$$

where x_0 is the data from the reference baseline signature and x_i is the data from the target signals. Signals from specimen with any dimension can be used as reference baseline signatures. The index will change if the baseline signature changes. With 100 kHz actuation, the wave pack will cover 50 μ s. Since the distance from actuator to sensor 1 is 55cm, the TOF of torsional wave pack starts at 175 μ s. So the RMSD crack index based on torsional wave pack are calculated from the experiment data in between 175 and 225 μ s. Figure 6(b) is the RMSD crack growth index based on the experiment results collected at 100 kHz actuation versus the corresponding crack size. The linear fit of those RMSD value suggests that the data is almost linear in pattern, which can be used to monitor the axial direction crack growth.

Figure 6 (a) Comparison of undamaged and 50mm cracked experiment results at 100 kHz actuation; (b) RMSD crack index at 100 kHz actuation.

3.4 Locating axial direction crack position

Locating the axial direction crack from the experimental results is also based on the TOF. 100 kHz experiment output from sensor 2 and sensor 3 are plotted in Figure 7(a) and Figure 7(b). The undamaged signal is compared with signals collected from the specimen with 3 mm crack and 8 mm crack. Due to the existence of flexural wave modes, the additional reflected torsional wave from the crack is buried into the overall signal. However, we can still assume that the additional reflected torsional wave contributes the most to the increase of transferred wave energy.

Since there are additional wave packs reflected from the crack, the total energy within the wave pack is increased when crack is initiated. Assuming that the center of the torsional wave pack reflected from the crack is at t , the total energy difference between torsional wave packs from cracked specimen and undamaged specimen is calculated by

$$E_{diff}^i(t) = \sum_{t-half\ span\ of\ T(0,1)}^{t+half\ span\ of\ T(0,1)} [A(t)_i^2 - A(t)_0^2] \quad (3)$$

where the two time spots represent the starting and ending time of the calculation. $A_i(t)$ represents the corresponding amplitude of the i th experiment. Based on Eq(3), the energy change chart of sensor 2 and sensor 3 are plotted in Figure 8(c) and Figure 8(d), respectively.

The actual position of the crack is 27.5cm from the actuator. The center-to-center (C-to-C) distance from actuator to sensor 2 and sensor 3 are 70cm and 75cm respectively. Using the group velocity of torsional wave listed in Table 1, the analytical TOFs of torsional wave pack is plotted (vertical dash line) in Figure 8(c) and Figure 8(d). As compared with the analytical solution, TOF from the center of the actuating signal (which is 25 μ s) to the center position of the peak from the transferred energy difference of torsional wave pack is shorter. Based on Eq (1) and signal from sensor 2, the resulted position of axial direction crack is 25.6 cm away from the actuator. Similarly, based on sensor 3's output, the resulted position of axial direction crack is 24.7 cm away from the actuator. The slight difference between the axial position from analytical prediction and experimental results are from the transducers dimension. The different wave paths between c-to-c and tip-to-tip distance are plotted in Figure 7. Taking the transducer's dimension into consideration, the accuracy of calculated axial crack position is increased as shown in Table 3.

Table 3 Calculation of axial crack position from experimental results

Data from	Wave pack used	TOF _p (μ s)	V _p (m/s)	C-to-C S _{A to S} (m)	Modified S _{A to S} (m)	C-to-C actual crack position (m)	Calculated axial crack position (m)	Modified actual crack position (m)	Calculated axial crack position (m)	Error (%)
Sensor 2	T(0,1)	210	3149	0.15	0.135	0.275	0.256	0.26	0.263	1.14
Sensor 3	T(0,1)	220	3149	0.2	0.185	0.275	0.247	0.26	0.254	3.42

Figure 7 Center-to-center distance and modified distance from actuator to sensors

Figure 8 Wave structures of output signal from (a) sensor 2 and (b) sensor 3; Transmit energy difference chart from (c) sensor 2 and (d) sensor 3 (At 100 kHz actuation)

4. INTEGRATION OF SELF-SENSING SHM SYSTEM FOR CONTINUOUS CYLINDRICAL STRUCTURES

With both sensors for locating the axial crack position and monitoring the axial direction crack growth serve their purposes, an integrated self-sensing SHM system can be designed. This integrated system consists of many pieces of MFC, and any of them can be used as either sensor or actuator. The distance between each of them is equally spaced as shown in Figure 8. When region 1 is being scanned, transducers 1, 2 and 3 will be used, in which transducer 2 is actuator, sensor 1 is for location identification, and sensor 3 for crack size monitoring. When region 2 is being scanned, the switching box will switch the working transducers to 2, 3 and 4. For continuous monitoring, more pieces of transducers are needed.

Figure 9 Conceptual design of self-sensing system for SHM of continuous cylindrical structures

5. CONCLUSIONS

This paper presents a preliminary research on a close loop self-sensing and monitoring system for axial direction crack occurred in cylindrical structures. In this system, one MFC transducer works as the actuator; the other two MFC transducers work as sensors to detect the axial position of the crack and monitor the crack size growth, respectively. When MFC is being used as sensor to monitor the crack growth, RMSD method is adopted to evaluate the crack size. On the other hand, TOF based method is adopted to find the axial position of the crack in the pipe. Both numerical simulation and experimental investigation are conducted for proof of concept and verification. The results show that both the axial position and crack size growth of the axial direction crack can be well located / monitored using this close loop sensing system. For better inspection and monitoring results of axial direction crack on cylindrical structures, further investigations into the optimized sensor distribution and computer-aided intelligence is needed.

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