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Feasibility of MFC (Macro-Fiber Composite) Transducers for Guided Wave Technique

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Abstract Since MFC(macro-fiber composite) transducer has been developed, many researchers have tried to apply this transducer on SHM(structural health monitoring), because it is so flexible and durable that it can be easily embedded to various kinds of structures. The objective of this paper is to figure out the benefits and feasibility of applying MFC transducers to guided wave technique. For this, we have experimentally tested the performance of MFC patches as transmitter and sensors for excitation and reception of guided waves on the thin aluminum alloy plate. In order to enhance the signal accuracy, we applied the FIR filter for noise reduction as well as used STFT(short-time Fourier transform) algorithm to image the guided wave characteristics clearly. From the results, the guided wave generated based on MFC showed good agreement with its theoretical dispersion curves. Moreover, the ultrasonic Lamb wave techniques based on MFC patches in pitch-catch manner was tested for detection of surface notch defects of which depths are 10%, 20%, 30% and 40% of the aluminum plate thickness. Results showed that the notch was detectable well when the notch depth was 10% of the thickness or greater.

Keywords: Lamb Waves, Pitch-Catch, MFC(Macro-Fiber Composite), SHM(Structural Health Monitoring), Notch

1. Introduction

In the past two decades, with the increasing awareness of structural health, many researchers have tried to develop an effective method for SHM (structural health monitoring) such as acoustic emission, infrared thermography and so on [1-3]. Among them, those based on ultrasonic waves have many great advantages over the others in terms of resolution, practicability and detectability. Especially, Lamb wave seems to be a judicious technique, featuring that not only can it propagate long distance and have little attenuation in a thin sheet-like plate but also can propagate fast, disseminate in an omni-directional way and be highly sensitive to the surface and interface defects in its propagation paths [4-6].

Structural health monitoring (SHM) consists of transducer selection and allocation, the signal activation and collection and the data feature extraction, as an effective maneuver of evaluating the health conditions (e.g., fatigue, corrosion, crack and so on) of a structure under the monitoring. Recently, a new type of high performance piezoelectric transducer, MFC (macro-fiber composite), has been developed, which is greatly expected to be useful to SHM due to its flexibility, durability and reliability in a cost competitive devices [7]. As well as, it can be easily embedded on curved and other shaped structures.

In this paper, we have tested the performance of MFC transducer for transmission and reception of Lamb waves. Firstly, we embedded two MFCs to the thin aluminum alloy plate, one serving as an actuator and the other serving as an active sensor. With respect to the received signals, the short-time Fourier transform analysis was carried out to obtain time-frequency information and

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compare the TOF (time of flight) with the theoretical analysis.

In addition, with a view to demonstrating the effectiveness of defect detection based on Lamb waves generated by MFC, we have just investigated the performance of the surface notch detection. For this, aluminum plate specimens fabricated with different notch depths, 10%, 20%, 30% and 40% of the thickness were prepared. According to the different notch depths, the variation of the transmitted signals were analyzed.

2. Micro-Fiber Composite (MFC) Transducer

2.1 MFC Introduction

MFC, recently invented by the NASA Langley Research Center, is a relatively new type of piezo-electric transducer that shows superior ruggedness and flexibility compared to traditional PZT. Since its flexibility, it can be embedded to structures without the concern about accidental breakage or additional surface treatment; especially it can be applied to the curved surface or other complicated shape of structures, which is much more difficult to inspect their property by using traditional PZT.

In terms of the durability, MFC is also cheaper to fabricate than conventional PZT. The use of low-cost piezo-ceramic wafers that are sliced into rectangular fibers with a dicing saw is the key component of the manufacturing process that keep the overall low cost of MFC. Additionally, the MFC uses interdigitated electrodes that capitalize on d33 effect piezo-electric coupling coefficient, allowing it to produce higher forces and strain than typical monolithic piezo-ceramic materials [7-9].

The specific MFC structure is composed of rectangular piezo-ceramic rods sandwiched between layers of adhesive, electrodes and polyimide film. The electrodes are attached to the film in an interdigitated pattern which transfer the applied voltage directly to and from the ribbon shaped rods as shown in Fig. 1. In this paper, the typical type of MFC applied is M2814-P1 (Smart Material Corp.), which is shown in Fig. 2. This type of MFC, which is available in d33 operational mode, actuates and senses along the length of the MFC patches. The specific properties of MFC are listed in Table 1.

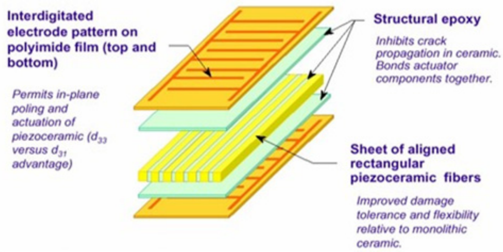

Fig. 1 Schematic diagram of MFC structure[9]

Fig. 2 MFC Type P1 M2814 (made by Smart Material Corp.)

Table 1 Properties of MFC Type P1 M2814

Operational voltage	-500 V ~ 1500 V
Active dimensions	28 mm × 14 mm
Overall dimension	38 mm × 20 mm
Capacitance	0.61 ppm
Free strain	1550 ppm
Thickness	300 μm
Actuator bandwidth	0 Hz ~ 700 KHz
Sensor bandwidth	0 Hz ~ 1 MHz

3. Experiments

In our experiments, five thin aluminum alloy (Young's modulus E=70 GPa, Poisson's ratio v=0.33, Density ρ=2700 kg/m^3) plates (600×

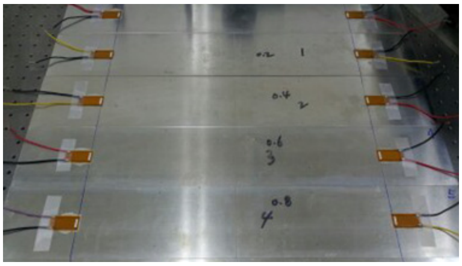

Fig. 3 Aluminum plate specimens with bonded MFC patches

Table 2 Dimensions of used notches

Specimen	#1	#2	#3	#4	#5
Notch Depth [mm]	0	0.2	0.4	0.6	0.8
Depth / Thickness [%]	0	10	20	30	40

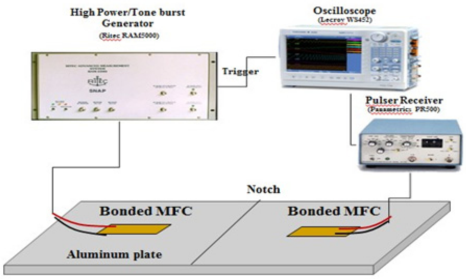

Fig. 4 Experimental set-up

100×2 mm) were used. One of them is pristine specimen (sample #1). The other four have notch on the surface with different notch depth, 0.2 mm, 0.4 mm, 0.6 mm and 0.8 mm, respectively. Fig. 3 shows the specimens.

Two MFC patches were aligned and mounted to each thin plate surface with 430 mm active distance using the two-part epoxy. We excited one of the boned MFC patch as actuator to generate guided wave. And the other served as sensor to receive the Lamb waves.

The actuator was excited with 3-cycle tone burst signals by using a pulser (RITEC Advanced Measurement System RAM-5000). Driving frequency was 0.3 MHz to conduct experiment, which was selected from the operational bandwidth of transducer. At this frequency, the two kinds of modes, symmetric S0 mode and anti-symmetric A0 mode, can be generated, which will be discussed later.

The experimental setting shows in Fig. 4. There were two experiments. Firstly, with an aim to show the effectiveness of MFC patches for Lamb wave technique, we conducted experiment with using the intact specimen without notch. Secondly, in order to verify the technique based on MFC patches for defect detection, we conducted another experiment to inspect the specimens with various depth dimensions notches as shown in Table 2.

A typical pitch-catch method was applied. Due to MFC patches are sensitive, there may be some noise accompanying with the Lamb wave signals. So, we have applied FIR filter algorithm to enhance the SNR(signal noise ratio).

4. Results and Analysis

4.1 Dispersion Curves

In order to analyze the properties of Lamb wave in aluminum alloy plate, the analytical dispersion curves for the 2 mm thickness aluminum plate were calculated by using a MATLAB based program.

The dispersion curves for group velocity of the aluminum alloy plate and applied frequency are shown in Fig. 5. Selected modes have been labeled in the dispersion curves. Dashed line presents the applied frequency of 0.3 MHz of MFC patches experiments. At this frequency, there will be just two modes propagating along

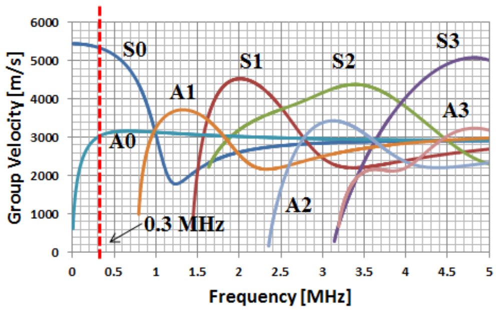

Fig. 5 Group velocity dispersion curves of Lamb wave for 2 mm thick aluminum plate

the plate (A0 mode and S0 mode). Since each mode has different group velocity, they will be separated from each other with the 430 mm distance.

4.2 Lamb Waves Signal Generated and Received by MFCs

Firstly, we carried out the experiment in pristine plate as above mentioned. The experimentally obtained signal was shown in Fig. 6. We can see that the selected two modes, S0 and A0 mode, were clearly generated and received with the signals reflected from the ends of the plate. In order to identify the mode of the signal, the TOF (time of flight) was compared with the TOF calculated from the theoretical group velocity. The results are shown in Table 3. It is obvious that the results from the theoretical analysis and experiment are almost the same. In addition, we have processed the received signals by using the STFT algorithm to verify each mode in the theoretical dispersion curves as shown in Fig. 7.

We can see clearly that two mode signals are matched well with its group velocity dispersion curves, which turned out to be feasible to use MFC transducers for guided wave technique.

4.3 Notch Detection

After making the MFC feasible to generate the guided wave in plate, we conducted another experiment to detect the notch defect. Fig. 8 shows the received signals of each specimen, where the amplitude was normalized by the peak amplitude of the bang (electrical interference) signal to eliminate the influence of the MFC patches bonding condition. As can be seen from the series of the signal, there may be mode conversion due to the notch [10,11].

However, the most important point of this paper is to show the feasibility of MFC patches for guided wave technique and detect the surface notch. So that, we did not focus on the details of mode conversion. Herein, we have focused on S0 and A0 mode only.

Subsequently, we applied the Hilbert transform to investigate the each specimen's wave energy distribution to make sure MFC workable or not. The results are shown in Fig. 9. The red dashed curve is the pristine specimen, which is the reference. The other is obtained from other specimen with various depth notches. By comparing the result with the reference, it is clear that MFC based guided wave technique is sensitive to inspect the defects.

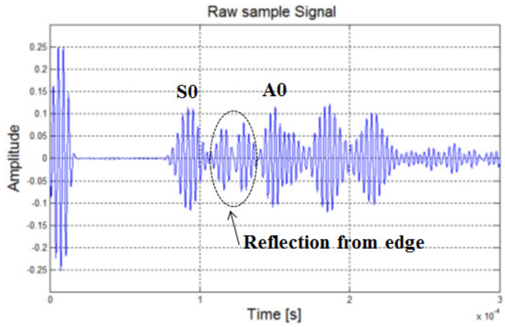

Fig. 6 Typical signal obtained from the pristine specimen

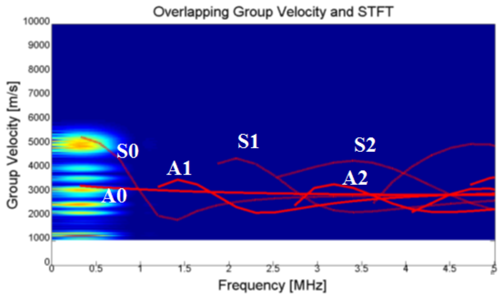

Fig. 7 STFT result of the signal shown in Fig. 6 and its superposition on the group velocity dispersion curves

Table 3 Theoretical and experimental TOF

0.3MHz	Theoretical TOF	Experimental TOF
S0 [μs]	81.03	79.12
A0 [μs]	143.33	140.56

Fig. 10 shows the transmission coefficients of the S0 and A0 mode for all specimens, where the transmission coefficients are calculated by following Eq. (1).

$$\text{Transmission Coeff.} = \frac{\text{Transmission wave energy}}{\text{Reference wave energy}} \quad (1)$$

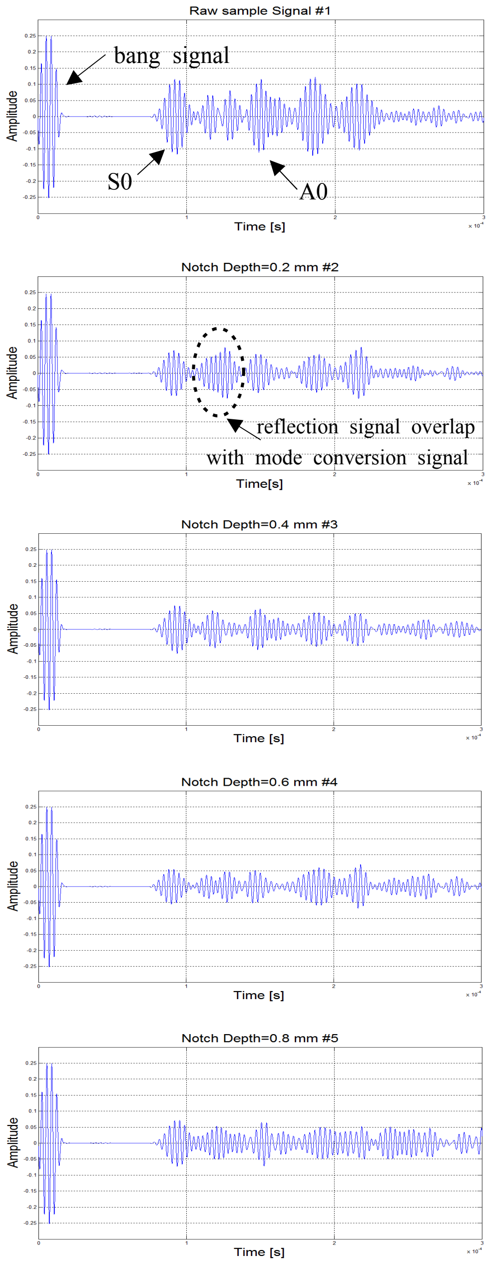

Fig. 8 Signals obtained from each specimen

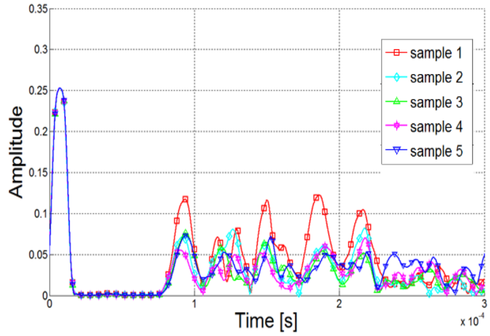

Fig. 9 Envelopes of Lamb wave energy distribution of each signal in Fig. 8

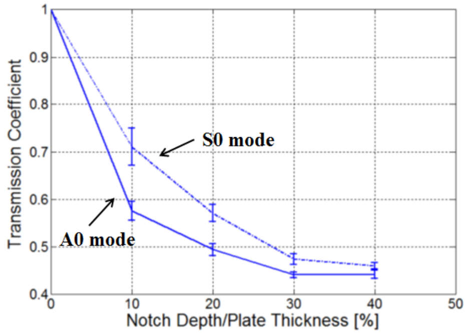

Fig. 10 Transmission coefficients vs notch/plate thickness for A0 and S0 modes

Where, reference wave energy was obtained from the specimen #1.

We can see that the transmission coefficient is decreasing with the increasing of the notch depth. Note that the decrease of transmission coefficient between without and with notch is dominant. From these, the guided wave technique based on MFC patches demonstrated that it is feasible to generate and receive Lamb wave and it can be effective for defect detection as well.

5. Conclusions

In this paper, we figured out that the micro-fiber composite patches are pretty feasible for generation and reception of guided wave by showing that the experimentally obtained Lamb wave signals are matched well with the theoretical dispersion curves for 2 mm thick aluminum plate. Furthermore, we have conducted experiments to verify the effectiveness of MFCs embedded on the surface of the aluminum plate specimen to detect the notch defect by Lamb waves. By using the pitch-catch methods, coupling with FIR filter for noise reduction, the transmission coefficients were obtained. From our research, notch could be clearly detectable when the notch depth was 10% of the thickness or greater.

MFC is a new type transducer featuring flexibility, sensitivity and durability, therefore, a network of MFC patches may be quite promising to monitor the structural health in real time, which is a pivotal upper hand over traditional PZT transducer.

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