A wideband structural health monitoring system based on omni-directional SH wave piezoelectric transducers

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Abstract: Structural health monitoring (SHM) can be used to detect the early degradation of structures and thus become more and more important in modern industries. Guided wave based inspection is a useful tool in SHM due to its capability of long distance and rapid detection. In recent years, the fundamental shear horizontal (SH0) wave has been paid more and more attentions to since it is the unique non-dispersive wave mode in plate like structures. In this work, we proposed an omnidirectional SH wave piezoelectric transducer (OSH-PT) based on a thickness poled, thickness-shear (d15) piezoelectric ring consisting of twelve elements and developed a sparse array SHM system using OSH-PTs. Firstly, the working principle and performance of this OSH-PT was introduced. Then experiments were carried out on a 2 mm-thick aluminum plate with prefabricated through-thickness holes. Results indicated that this SHM system has super resolution which can detect a defect as small as 0.12λ (or 4mm) with the location error less than 2.5% from 90 kHz to 150 kHz. It can also be used for multiple defects localization based on the baseline subtraction method. Because of the single mode, non-dispersion and thus long working distance, this SHM system can detect larger area using a few sensors. Meanwhile, the variable-frequency characteristic of this SHM makes it adaptive for detection of different sized defects. Finally, we presented a simplified OSH-PT based on two thickness poled half-ring, and its performances were examined and compared with the other three available OSH-PTs. The half-ring based OSH-PT is more applicable for practical SHM applications where many transducers are required.

1. Introduction

Structural health monitoring (SHM) has been more paid more and more attentions to in modern industries in recent years. For large area and long distance monitoring, ultrasonic guided wave inspection is more promising for its rapid detecting and small attenuation[1]. In the past two decades, Lamb wave based SHM techniques had been intensively studied because Lamb wave can be easily generated and received by thickness-poled PZT wafers. A large amount of works had been done on practical applications of Lamb wave based inspections. However, the inherent dispersion and multi modes have greatly limited the further applications of Lamb wave based SHM system. Some strategies such as frequency turning and modulating wave signal into special function window must be used to realize quasi-single mode Lamb wave with little dispersion, which makes the SHM system only operated at a fixed frequency.

In comparison, the fundamental shear horizontal (SH) wave is totally non-dispersive. Since the displacement of SH waves is uncoupled with that of Lamb waves, it is possible to generate single mode SH wave independently. Besides, SH wave also exhibits some other attractive advantages such as less mode conversions and low attenuations. Based on Lorentz force[2], magnetostrictive effect[3] and piezoelectric effect[4,5], several directional transducers had been developed. However, for practical
SHM applications, omni-directional transducers were more desirable with which a sparse transducer array can cover the full monitoring area. So far, very few omnidirectional SH wave transducers have been raised. Seung et.al developed the omnidirectional SH wave MPT[6] and EMAT[7], respectively. But these two transducers are bulky and heavy with high power consumption, which were not suitable for SHM. Borigo et.al proposed a design of omni-directional SH wave piezoelectric transducer (OSH-PT) based on circumferentially poled PZT half-ring, which can only be realized in theory[8]. Later, Belanger et.al proposed an OSH-PT by using six thickness-shear (d_{15}) PZT elements[9]. More recently, Miao et.al fabricated an OSH-PT using twelve face-shear (d_{24}) PZT elements[10]. Actually, the latter two OSH-PTs aimed at synthesizing uniform circumferential polarization, which is also difficult to realize and thus their performance was not desirable.

In this work, we proposed the thickness poled, thickness-shear (d_{15}) mode in PZT wafers and developed a new OSH-PT based a PZT ring consisting of twelve elements. Its performance in wave generation and reception were systematically examined by using simulations and experiments. Results indicated that this new OSH-PT can generate and receive single mode SH\(_0\) wave in wideband with uniform sensitivity over all directions. Then a sparse array SHM system was developed based on this OSH-PT, and experiments for defects localization were also carried out. Results showed this SHM system can detect the defects with the best resolution of 0.12\(\lambda\) and the localization error less than 2.5\%. Besides, it can be operated in wideband from 90kHz to 200kHz. Finally, another OSH-PT based on two thickness-poled PZT half-rings was presented, which is very easy to fabricate and its performance is also acceptable. This work is expected to greatly promote the wide applications of SH\(_0\) wave based SHM.

2. The thickness poled OSH-PT

2.1 Principle

![Figure 1. (a) Principle of the thickness poled, thickness shear mode; (b) configuration of the proposed OSH-PT.](image)

For traditional thickness shear d_{15} mode in a PZT wafer, its poling is in-plane and the electric field is applied along the thickness direction. In order to achieve an axisymmetric shear force for omni-directional SH wave generation, uniform circumferential poling needs to be realized, which is rather difficult in reality. However, the directions of poling and electric field were alternative for a PZT wafer. This means that if poling is along thickness and electric field is applied in-plane, thickness shear mode can also be formed, as plotted in figure 1(a). Based on this new thickness shear mode, a new OSH-PT was proposed. A PZT ring was poled in thickness firstly and then divided into twelve identical elements along its diameter. All elements were bonded together again after preparing the electrodes on lateral faces, as shown in figure 1(b).
The poling direction of adjacent elements was always opposite thus they can share the common electrodes. Under this configuration, the OSH-PT would form the circumferential thickness-shear deformation for omnidirectional SH wave generation when an AC voltage is applied. Since the ring was thickness poled and the uniform circumferential electric field was quite easy to realize, the improved performance of this OSH-PT was thus expected.

2.2 Performance of the twelve-element OSH-PT

2.2.1 Finite element simulations

Firstly, finite element simulations were carried out in ANSYS to demonstrate the performance of the proposed thickness poled, thickness shear OSH-PT consisting of twelve elements. An aluminum plate with dimensions of 400 mm × 400 mm × 2 mm was modeled as waveguide and the OSH-PT was bonded on the center of it. The transducer was excited at 210 kHz with the drive voltage of 30 V. More details of the simulations can be found in our recent work[11]. Figure 2 presented the results of simulations. It can be found in figure 2(a) that the tangential displacement was perfect axisymmetric, which means SH$_0$ wave was generated omni-directionally with uniform sensitivity along all directions. By referring to the amplitude of total displacement in figure 2(b), it can be concluded that the amplitude of Lamb waves was almost negligible.

![Figure 2. Finite element simulated results of the proposed OSH-PT in SH$_0$ wave generation. (a) Tangential displacement component, (b) Total displacement.](image)

2.2.2 Experiments

![Figure 3. Experimental results of the proposed OSH-PT at 210 kHz. (a) Wave signals excited by the OSH-PT and received by a d$_{36}$ PMN-PT wafer; (b) wave signals excited by a d$_{36}$ PMN-PT wafer and received by the OSH-PT; (c) the omni-directivity of the OSH-PT in SH$_0$ wave generation and reception.](image)
Experiments were then carried out on a 1000 mm × 1000 mm × 2 mm aluminum plate to further examine the performance of the proposed OSH-PT. The size of the OSH-PT used here was same as that in the simulations. Firstly, the OSH-PT served as the actuator while a $d_{36}$ PMN-PT wafer was used as the sensor to check the performance of SH wave generation. Figure 3(a) showed the results at 210 kHz with the applied voltage of 20 V. It can be seen that only one wave package appeared in the received signals with the same waveform as that of the input. The corresponding wave mode can easily be inferred to be $SH_0$ wave via the wave velocity. Besides, it can be calculated that the signal-to-noise ratio (SNR) of the proposed OSH-PT in $SH_0$ wave generation was up to 26 dB. Then, the $d_{36}$ PMN-PT wafer was used as the actuator while the OSH-PT served as the sensor to check its performance in wave reception. The result was shown in figure 3(b). Again, only $SH_0$ wave appeared in the received signal and the corresponding SNR was up to 23 dB. Considering that the $d_{36}$ PMN-PT wafer can generate both Lamb waves and $SH_0$ wave, these results showed that the proposed OSH-PT can generate single mode $SH_0$ wave and receive $SH_0$ wave only like an inherent wave filter. The omni-directivity of the proposed OSH-PT were also examined and the results were plotted in figure 3(c). Within the 180° plotted in figure 3(c), the maximum deviation for $SH_0$ wave generation and reception was both less than 7%, which is considerably better than that in previous reports[9,10]. The good performance of this OSH-PT was benefited from the uniform properties since all elements composing the OSH-PT came from the same PZT ring.

3. The OSH-PT based SHM system

3.1 Defects localization

A sparse array SHM system based on OSH-PTs was developed to check the validity of the $SH_0$ wave based inspection. Three through-thickness holes named Defect 1, Defect 2 and Defect 3 were introduced and detected based on the baseline subtraction method. The details of experimental setup and signal process can be found in our recent
work[12]. Figure 4 presented the imaging results of Defect 1 with the diameter of 4 mm and 10 mm at 90 kHz, 120 kHz and 150 kHz. As shown in figure 4(a), it can be found that even for the 4 mm defect at 90 kHz (about 0.12λ), it can be detected accurately by the proposed SHM system with the localization error no more than 12 mm, i.e. 2.5%. The super resolution was benefited from the employed single mode non-dispersive SH0 wave, which could greatly decrease the difficulties in signal identification. With the increasing drive frequency, the ripples in the imaging results gradually faded away, as shown in figure 4(b) and (c). The corresponding localization error was also decreased, to be about 8 mm. The similar tendency also appeared in figure 4(d), (e) and (f) for the 10 mm defect. It should be noted that this SHM system is adaptive to different sized defect detection because of its variable operating frequency, which is obvious superior to the Lamb wave based SHM system which must be operated at a fixed frequency to get the quasi-single wave mode.

The imaging results for multi defects were presented in figure 5 where the operating frequency was kept at 120 kHz. It can be found that multi defects can also be located accurately by the proposed SHM system without artifacts based on the baseline subtraction method. The corresponding localization error was also less than 12 mm, which is much better than that of 27.6 mm for Lamb wave based inspection[13]. This is also benefited from the employed single mode non-dispersive SH0 wave.

4. A practical OSH-PT based on two half-rings

4.1 Configurations

For the convenience in practical applications, the concept of half-ring based OSH-PT was presented, which was also derived from the thickness poled thickness shear d13 mode PZT ring. As for the OSH-PT, the more elements were used, the more

![Figure 6. (a) Configuration of the half-ring based OSH-PT; (b) a photo of the actually-fabricated OSH-PT.](image-url)
complicated fabrication process would be. In order to achieve circumferential electric field, at least two elements were required, i.e., two half rings. The configuration of two half-ring based OSH-PT was shown in figure 6(a). Again, the poling directions of two half rings were opposite so that they can share the common electrodes. When an AC voltage is applied, a fairly uniform circumferential electric field is generated, resulting in omni-directional SH wave generation. Figure 6(b) presented a photo of the fabricated OSH-PT based on two half-rings. Compared with the OSH-PT consisting of twelve elements, the half-ring based OSH-PT was very easy in fabrication and more suitable for practical applications if its performance is acceptable. Experiments results indicated that the half-ring based OSH-PT can omni-directionally generate and receive \( \text{SH}_0 \) wave with a little noise. And the maximum deviation for its omni-directivity is about 14\% for both generation and reception, which is not desirable but acceptable for most applications.

4.2 Performance comparisons of different OSH-PTs

![Figure 7](image)

Figure 7. Comparisons of different OSH-PTs in \( \text{SH}_0 \) wave generation. Configuration of (a) in-plane poled \( d_{15} \) mode-based, (b) face shear \( d_{24} \) mode-based, (c) thickness poled \( d_{15} \) mode-based and (d) half-ring based OSH-PT. (e), (f), (g) and (h) were corresponding displacements generated by the OSH-PTs.

So far, totally four types of OSH-PTs had been proposed in literatures, i.e., the six-element in-plane poled \( d_{15} \) ring by Belanger and Boivin[9], the twelve-element face-shear \( d_{24} \) ring by Miao et al[10], and the two types thickness-poled \( d_{15} \) ring presented in this work. The configurations of these four types OSH-PTs were comparatively presented in figure 7(a)-(d), and their performances were simulated by finite element analysis and presented in figure 7(e)-(h). It can be seen that for the in-plane poled \( d_{15} \) ring OSH-PT in figure 7(a), the wave field shown in figure 7(e) was dominated by the tangential displacement component \( u_y \), i.e. \( \text{SH}_0 \) wave. However, the amplitudes of the radial displacement component \( u_x \), i.e., \( S_0 \) wave and the out-of-plane displacement component \( u_z \), i.e. \( A_0 \) wave were up to 35\% of that of \( \text{SH}_0 \) wave. Besides, its sensitivity deviation at different directions was more than 20\% in generation and not validated in reception[9]. For the face shear \( d_{24} \) ring OSH-PT[10] whose configuration was shown in figure 7(b), the simulated results in figure 7(f) indicated that it will also generate both \( \text{SH}_0 \) wave and Lamb waves. But the relative amplitude of Lamb waves
was lower than that of the in-plane poled $d_{15}$ ring OSH-PT. The deviation of its omni-directivity in both generation and reception was about 15%[10]. Note that these two OSH-PTs actually required uniform circumferential polarization, which is very different to realize in practice. As for the thickness poled $d_{15}$ mode-based OSH-PT[11] consisting of twelve elements shown in figure 7(c), the simulated results plotted in figure 7(g) indicated that it can generate single mode $SH_0$ wave with negligible Lamb waves. Its omni-directivity is also considerably good with deviation about 7% in both generation and reception[11]. For the half-ring based OSH-PT as shown in figure 7(d), the simulated results in figure 7(h) indicated that it can also generate $SH_0$ wave accompanied by a small amount of Lamb waves. The deviation in $SH_0$ wave generation and reception was about 14% for different directions. Although the performance of the half-ring based OSH-PT was not as good as that of the twelve-element counterpart, it is acceptable and easiest in fabrication, which is more promising for practical SHM applications where a large amount of OSH-PTs are required. Finally, to comprehensively compare the four types OSH-PTs, their performances was listed in Table 1, from which it can be seen that the latter two types OSH-PTs presented in this work are obviously superior to the former two.

<table>
<thead>
<tr>
<th>Configurations</th>
<th>Fabrication</th>
<th>SNR in generation</th>
<th>Omni-directivity in generation</th>
<th>SNR in reception</th>
<th>Omni-directivity in reception</th>
</tr>
</thead>
<tbody>
<tr>
<td>in-plane poled $d_{15}$ mode[9]</td>
<td>difficult</td>
<td>low</td>
<td>over 20%</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>face-shear $d_{34}$ mode[10]</td>
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<td>moderate</td>
<td>about 15%</td>
<td>moderate</td>
<td>about 15%</td>
</tr>
<tr>
<td>thickness poled $d_{15}$ mode[11]</td>
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<td>high</td>
<td>about 6%</td>
<td>high</td>
<td>about 7%</td>
</tr>
<tr>
<td>half-ring $d_{15}$ mode</td>
<td>easy</td>
<td>moderate</td>
<td>about 14%</td>
<td>moderate</td>
<td>about 14%</td>
</tr>
</tbody>
</table>

5. Conclusions

In summary, we proposed a thickness poled, thickness shear $d_{15}$ mode based OSH-PT consisting of twelve elements. Both simulations and experiments indicated this OSH-PT can generate and receive single mode of $SH_0$ wave omni-directionally with uniform omni-directivity. Then a sparse array SHM system was developed using four OSH-PTs. Experimental results showed this SHM system has a super resolution of $0.12\lambda$ for defects inspection with the localization error less than 2.5% in a wide frequency range from 90kHz to 150kHz. It also has capability for multi defects localization based on the baseline subtraction method. The good performances of this SHM system were benefited from the single mode non-dispersive $SH_0$ wave generated by the proposed OSH-PT. Finally, to meet the need in practical SHM applications where a large number of OSH-PTs are required, a new OSH-PT based on two thickness-poled $d_{15}$ mode half-rings was presented and its performance was validated to be acceptable. This work is expected to greatly promote the wide applications of $SH_0$ wave based SHM.

Acknowledgments

This work is supported by the National Natural Science Foundation of China under
Grant No. 11672003.

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