Improved shear horizontal wave piezoelectric fiber patch (SH-PFP) for structural health monitoring applications

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Abstract. Controlling the wave directivity of transducers is an important aspect of guided wave based structural health monitoring (SHM), because a strong directivity is not only energy efficient but also has an advantage of simple signal analysis. The fundamental shear horizontal (SH0) wave is gaining its popularity due to its non-dispersive characteristics. Piezoelectric fiber patches (PFP) are lightweight, thin, and flexible and therefore adaptable to curved surfaces. PFP can be designed to preferentially generate and receive either Lamb or shear horizontal guided waves. Building on previous work for a SH-PFP transducer [1] its geometry is modified to optimize the mode purity and the directivity. Finally, a new version of SH0 wave PFP with improved directivity is proposed. The new transducer concept and its working principles are explained, and the numerical simulation is conducted to validate its performance. Results show that the new transducer can generate almost pure SH0 waves along the desired direction with high directivity.

Introduction

Non-destructive testing (NDT) denotes a procedure to verify, whether a material or object has still the properties relevant for its intended use without affecting the object's ability [2]. Therefore it is normal that NDT technique is accompanied by technicians who can use test equipment. In contrast to that, structural health monitoring (SHM) denotes either the permanent monitoring of a structure with sensors or the periodic reading out of such permanently installed sensors [3]. Therefore, the importance of reliable SHM techniques in aerospace industry increases because of their lightness and non-human dependable nature.

Guided wave (GW) is one of the most promising technique in SHM implementation. GW uses wave propagation in a structure and investigates signal changes such as reflection and mode conversion, which could be considered as indicators of damage in the structure. There are various types of modes in GW, and most of them are dispersive. Dispersive characteristic means that the speed of the wave is frequency dependent. This makes the measured signal more complex and more difficult to analyze to detect damage.

Compared with the dispersive wave modes, the non-dispersive fundamental shear horizontal (SH0) wave in plate-like structures or the fundamental torsional [T(0,1)] wave in pipe-like structures is more promising in practical application [4]. In the past decades, SH0 wave considered to be limited in NDT techniques such as EMAT and used for metallic structures

[5, 6]. Obviously, such techniques are not suitable for SHM in aerospace due to their relative large size and low energy conversion efficiency [7].

Wilcox et al. employed a thickness-shear (d15) mode piezoelectric transducer to generate SH0 wave [8]. However the signal-to-noise ratio (SNR) of this transducer is rather small without any backing forces or seismic mass. Miao et al. proposed face-shear d24 PZT transducer [7]. Since the face-shear transducers don't need a backing force, they show superior to thickness-shear ones. Miao used these face-shear transducers to introduce an omnidirectional SH0 wave ring array in their further research. However, the array has limitations in complex geometry and brittle material problems. Koehler et al. proposed a new type of SH0 transducer using piezoelectric fiber path (SH-PFP) based on flexible piezoelectric fibers using double layer crossed fiber arrangement [1]. Even though SH-PFP is already very fascinating SH0 wave transducer, further work is needed to utilize the full potential of the transducer, especially with the mode purity and the directivity.

In this work, we propose a new version of SH0 wave PFP with improved directivity. The new version of SH-PFP, so called Dual SH-PFP is made out of two original SH-PFP. We will show that Dual SH-PFP (DSH-PFP) can generate SH0 wave in only two opposite directions with rather high purity. The configuration and the working principles of the suggested new transducer is explained, and the numerical simulation is conducted to validate its performance.

1. Configuration and working principle

1.1 Original SH-PFP

Two rectangular shaped PFPs with fiber orientations tilted at ±45° relative to the patch length orientation are used to make the original SH-PFP [1]. As shown in Figure.1, when two different PFPs with same electrodes are overlapped, SH0 waves are generated from 4 of each side of the SH-PFP.

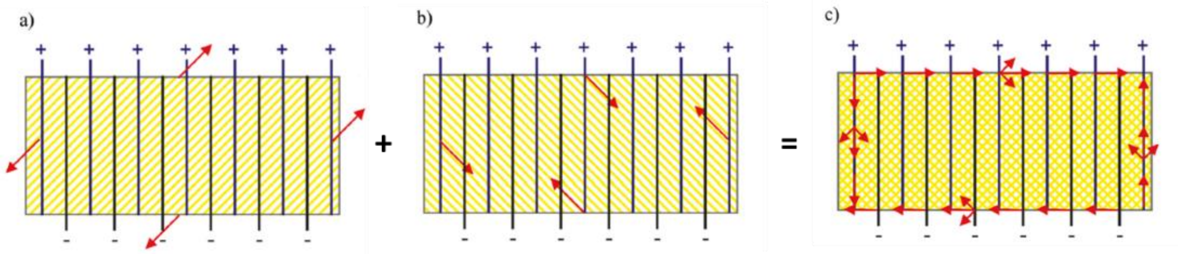

Figure 1. Configuration of the original SH-PFP [1]: The yellow lines show the piezo fiber directions, and the red lines show the directions of surface traction when a voltage is applied

Since the shape of a PFP is rectangular, there are two main directions and minor directions of wave propagation. To increase the directivity, the effect of two minor directions should be eliminated, while the wave propagation from the main directions should be maintained. The general method is to choose the length of the PFP as a multiple of the wavelength (λ) of target SH0 wave, while the width as an odd multiple of the half wavelength. However, since input signals are normally modulated by a window, even though the width of the PFP is matched as an odd multiple of the central frequency half wavelength, near-central frequencies will not be completely eliminated.

1.2 New version of SH0 wave PFP: Dual SH-PFP

To eliminate the effects of minor directions and to increase the directivity, a new version of SH0 wave PFP is proposed. As shown in Figure 2, two SH-PFPs with different piezo fiber directions are used. For example, the first SH-PFP (Left, from Figure 2) has a bottom PFP with +45° tilted fiber direction, and a top PFP with -45° tilted fiber direction. The second SH-PFP (Right, from Figure 2) has -45° tilted fibers for bottom PFP, and +45° tilted fibers for top PFP. Green arrows show the surface tractions driven by bottom PFPs, and red arrows show the surface tractions driven by top PFPs.

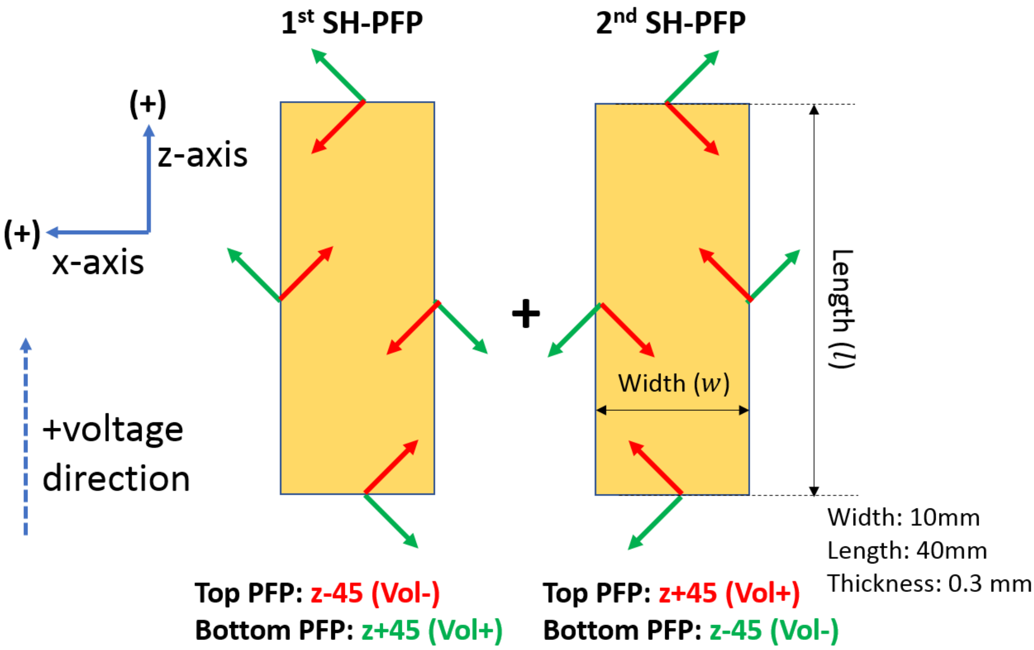

Figure 2. Configuration of the Dual SH-PFP. The red and green arrows show the surface tractions driven by the top and the bottom PFPs respectively.

The driven surface tractions are symmetric with respect to the z-axis. Therefore, when the two different SH-PFPs are put side by side, the surface tractions along the width of each PFP are of opposite sign. The sum of the tractions is zero and thus the effect of the guided wave will cancel out to a large extend. This will result in bi-directional SH0 wave propagation as shown in Figure 3.

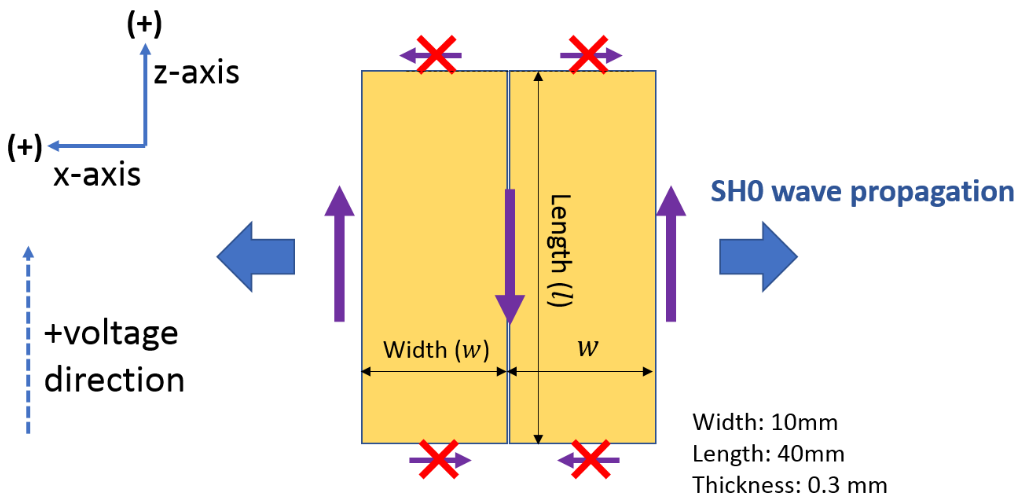

Figure 3. Dual SH-PFP wave propagation. The surface tractions along the width of each PFP are marked with red crosses, because they nearly cancel out in their effect on the generated wavefield.

The purple arrows show the summation of the driven surface tractions, and the blue arrows show the SH0 wave propagating directions. No matter what frequency is used for driving signal, the minor side surface tractions always cancel each other out.

2. Numerical simulations and results

Commercial finite element method (FEM) simulation software ANSYS was used to compare the performance of the new Dual SH-PFP with that of the original SH-PFP. Each PFP has an active area of 40 * 10 mm^2 and 0.3 mm of thickness. The actual configuration of PFP is too complicated to be modelled in ANSYS, so a homogenized PFP design was used as described in [9]. A steel plate of 2mm thickness was used as a target structure. The theoretical SH0 wave speed on the structure was 3250 m/s. The transducer was driven by a 3-cycle Hanning windowed sine signal and the central frequency was varied from 40 to 225 kHz.

2.1 General comparison

The Figure 4 shows the calculated tangential velocity component of the wavefield snapshots of the original SH-PFP (Figure 4 (a)) and the Dual SH-PFP (Figure 4 (b)) in a cylindrical coordinate system.
As shown in Figure 4 (a), the original SH-PFP generates SH0 waves along 4 orthogonal directions; two main directions (0° and 180°) and two minor directions (90° and 270°). In comparison, for the Dual SH-PFP only the main wave packets are visible. Other wave packets perpendicular to that might be present, but they are too weak to be visible in the image.

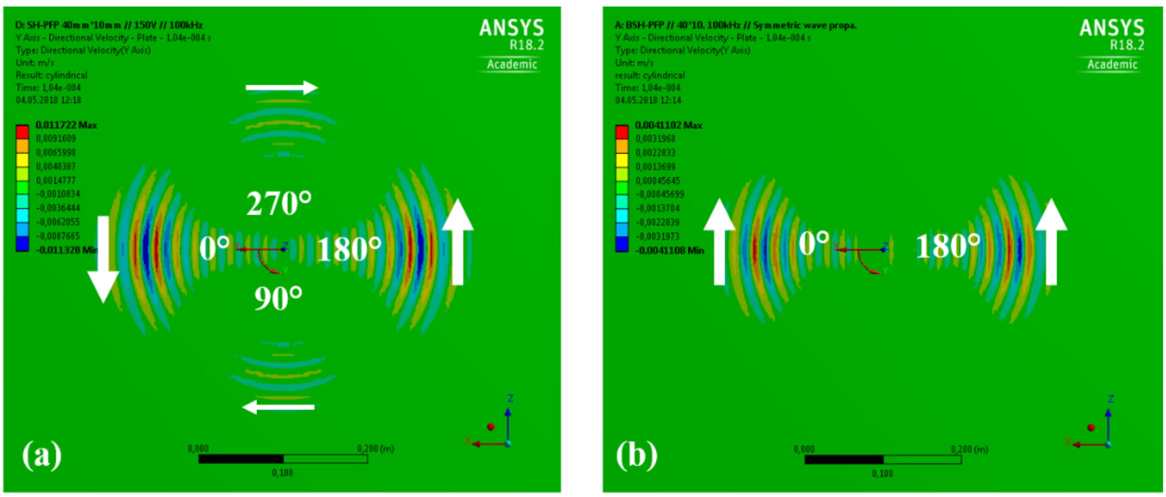

Figure 4. Tangential velocity wave fields of (a) the original SH-PFP and (b) the Dual SH-PFP

2.2 Directivity comparison

High directivity is preferred because it simplifies the signal analysis. The length of a PFP is 40 mm, which is comparable with the half wavelength of the SH0 wave at 40 kHz (40.6 mm). In this case, strong wave propagations are expected not only from the main directions but also from the minor directions of the original SH-PFP. 40 kHz central frequency signal was driven to both SH-PFP transducers to compare their directivity. Figure 5 shows the result.

The x-axis indicates one of the main wave propagating direction (0°) and the y-axis indicates one of the minor direction (90°). Due to symmetry of the transducers, we restricted the plot of the directivity to the first quadrant. The amplitudes were normalized by the maximum amplitude value of the Dual SH-PFP.

As shown in the graph, the Dual SH-PFP generates SH0 wave mainly along the main direction, while original SH-PFP generates SH0 waves along both main and minor directions.

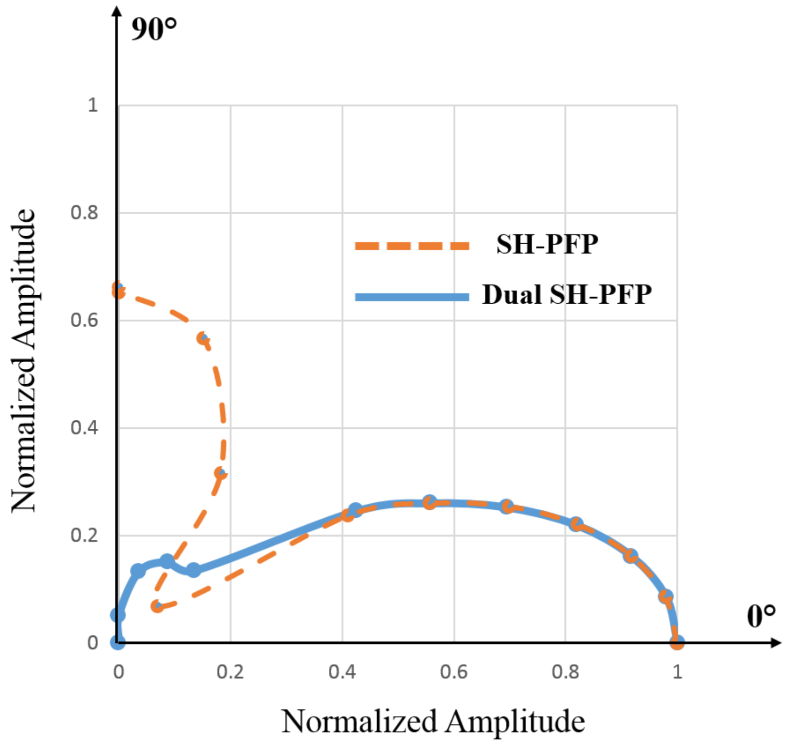

Figure 5. Directivity comparison of SH0 wave between the SH-PFP (Orange dotted line) and the Dual SH-PFP (Blue line) from 0° to 90°. The amplitudes are normalized by the maximum amplitude of the Dual SH-PFP. The central frequency is 40 kHz

2.3 Purity comparison

At the corners of a SH-PFP, two surface tractions from both adjacent sides add up under 90° leading to a resulting traction acting under 45°. This can be considered as the source of the S0 lamb wave [1]. Since the surface tractions along the minor sides of the Dual SH-PFP are working against each other and cancelling each other out partially, the amplitude of the generated S0 lamb wave is expected to be smaller. So the purity ratio defined as a ratio between the SH0 and the unwanted S0 signal amplitudes is expected to be improved.

To confirm this expectation, we compare SH0 and S0 signal amplitudes for both transducer types. Figure 6 shows graphs of the tangential velocity wave fields (SH0 wave, blue) and the radial velocity wave fields (S0 lamb wave, orange) at 50 and 100 kHz central frequency signals from 0° (x-axis) to 90° (y-axis). The amplitudes are normalized by the maximum amplitude value of each transducer at each central frequency.

As it is shown in the graphs, not only the directivity but also the purity is improved in the Dual SH-PFP. To quantitatively evaluate the purity improvement, the purity ratio is calculated for each case. The maximum purity ratio of the original SH-PFP was 5.52 at 150 kHz central frequency, while the Dual SH-PFP shows the maximum purity ratio of 9.01 at 100 kHz central frequency (Table 1).

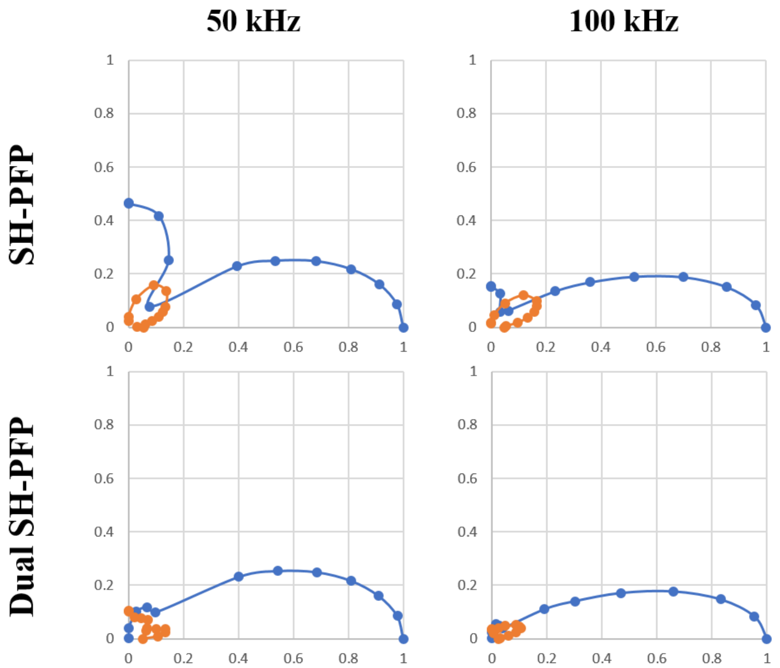

Figure 6. Purity comparison of the SH-PFP (Upper) and the Dual SH-PFP (Lower): SH0 wave amplitudes (Blue) and S0 lamb wave amplitudes (Orange) are normalized by the maximum amplitude of each transducer at each central frequency; at 50 and 100 kHz

Table 1. The purity ratio comparison

Frequency	**40kHz**	**50kHz**	**100kHz**	**150kHz**	**200kHz**
Dual SH-PFP purity ratio	6.08	7.25	9.01	5.92	6.21
Original SH-PFP purity ratio	3.33	5.21	5.15	5.52	5.05
Purity ratio increment	183%	139%	175%	107%	123%

2.4 Amplitude comparison

The new design also affects the maximum amplitudes. Figure 7 shows the amplitude comparison at the main direction (0°) between the original SH-PFP (Orange) and the Dual SH-PFP (Blue) from 50 to 225 kHz of central frequencies. The amplitudes are normalized by the maximum value of the Dual SH-PFP. The amplitudes of the Dual SH-PFP are indicated in parentheses as a percentage of the original SH-PFP at each central frequency. It is shown that the Dual SH-PFP can generate stronger SH0 wave, while maintaining the superiority of the directivity and the purity. Both transducers will have their maximum amplitudes when the PFP width equals to the half wavelength ($\lambda/2$) of the signal, but the increment of the Dual SH-PFP is much larger.

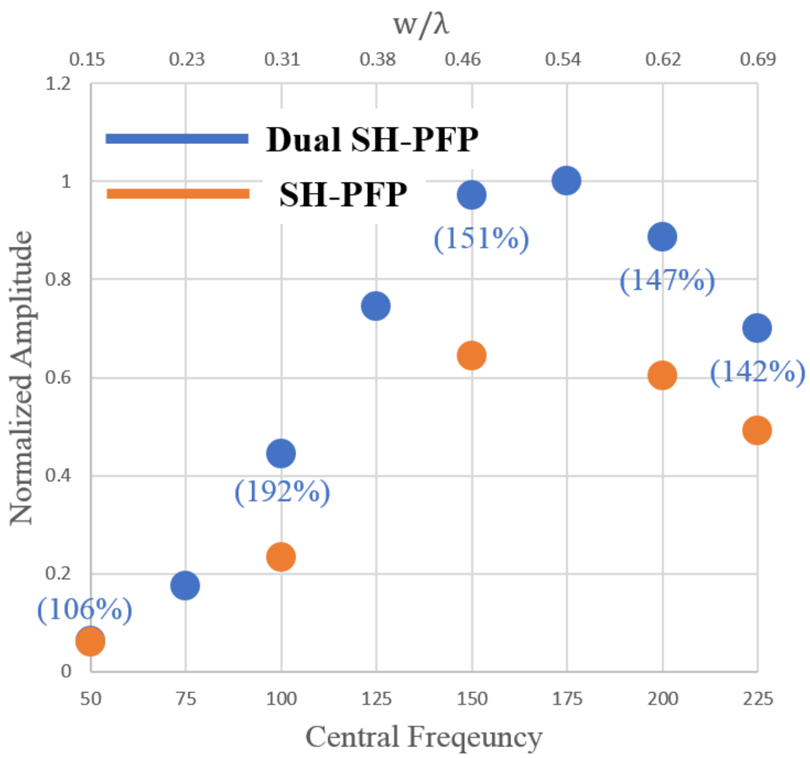

Figure 7. Amplitude comparison of the Dual SH-PFP (Blue) and the original SH-PFP (Orange). Normalized by the maximum amplitude of the Dual SH-PFP. The horizontal axis at the top of the graph is the ratio between the patch width (w) to the wavelength (λ).

3. Summary and conclusions

In this study, a new version of SH-PFP, so called Dual SH-PFP for the high directivity SH0 wave propagation is proposed. The configurations and the working principles of the original SH-PFP and the Dual SH-PFP were shown. The performance of the Dual SH-PFP was investigated by comparing with the original SH-PFP. Results show that the new transducer can generate almost pure SH0 waves along the desired direction with high amplitude. The high directivity and the high purity of the proposed new transducer suggest that this new version of SH-PFP could be widely used for SHM techniques in aerospace industry.

Acknowledgement

This research was supported by the NDTonAIR project (Training Network in Non-Destructive Testing and Structural Health Monitoring of Aircraft structures) funded under the action: H2020-MSCA-ITN-2016- GRANT 722134

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