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An anisotropic ultrasonic transducer and its application

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ABSTRACT

An anisotropic ultrasonic transducer is proposed for passive damage or impact localization. This transducer was used for ultrasonic guided waves generation and sensing first by Zhou et al (2014). It is made from a PMNPT single crystal, and has different piezoelectric coefficients d_{31} and d_{32}, which are the same for the conventional piezoelectric materials, such as Lead zirconate titanate (PZT). Different piezoelectric coefficients result in directionality of guided wave generated by this transducer, in other words, it is an anisotropic ultrasonic transducer. In comparison with conventional ultrasonic transducer, anisotropic one can provide more information related to the direction when it is used as sensors. This paper first shows its detailed properties, including analytical formulae and finite elements simulations. Then, its application is demonstrated. In detail, the transducer rosette is designed to receive passive acoustic emission signals from more different sources, and further separate the overlapped acoustic emission signals using blind source separation (BSS) technique. The results indicate that this type of ultrasonic transducer has potential to provide more information about damage in structural health monitoring.

1. INTRODUCTION

The structural health monitoring (SHM) methods and techniques based ultrasonic guided waves theory have proven useful for the detection, localization and quantification of structural damages, which are critical issues in the SHM field (Cawley and Alleyne, 1996; Raghavan and Cesnik, 2007). In applications of ultrasonic guided waves, the key device or component is the transducer, which can implement the conversions between guided wave signal and a signal in another measurable form,

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such as electric signal. The transducers used to generate the guided wave propagating in structures are called ultrasonic actuators or transmitters, while those used to capture the guided waves propagating in structures and convert to measurable signal are called ultrasonic sensors or receivers. Actually, most of transducers can work as these two roles.

In general, guided waves can be actively excited and sensed through a number of means. The most commonly used transducers are piezoelectric transducers (piezoelectric wafer, piezoelectric wedge transducer, PVDF and macro fiber composites (MFC), etc.), electromagnetic acoustic transducers (EMATs), air-coupled techniques, magnetostrictive transducers, etc. From the view of the material properties, most of above transducers can be considered as isotropic guided wave transducers, which can excite uniform Lamb wave around the transducer on the plate. Fig. 1 shows the displacement distribution of Lamb wave excited by a square PZT. A circular PZT can also excite the same displacement field. Another type of transducer is anisotropic, such as MFC. It consists of unidirectional rectangular piezo ceramic rods sandwiched between layers of adhesive, electrodes and polyimide film, so it can actuate and sense directionally. In comparison with the isotropic transducer, the guided wave generated or received by anisotropic one contains more information related to the direction when it is used as sensors. Matt and Scalea (2007) proposed the piezoelectric transducer rosettes to identify passive damage or locate impact loading in anisotropic or geometrically complex structures.

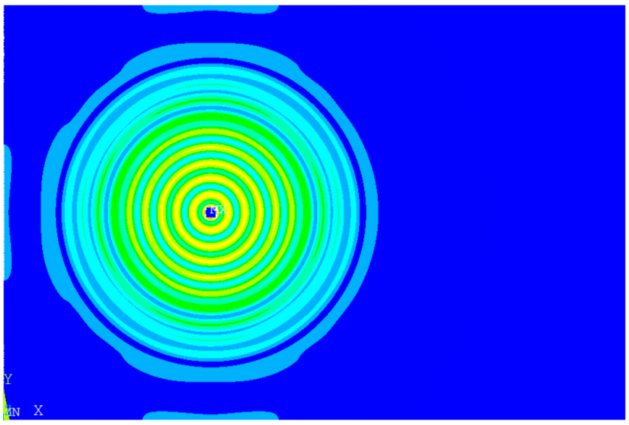


Fig. 1 Total displacement component of Lamb wave excited by a square PZT

In this work, a single crystal material is proposed to work as the anisotropic transducer because of its anisotropic material properties. Zhou et al. (2014) employed this material to generate and receive shear horizontal wave propagating on the plate, and discussed further its fundamental characteristic when generating and receiving both Lamb wave and shear horizontal wave. This paper will describe this material at first, and then utilize its anisotropic property, combining the blind source separation algorithm, to identify different damages from an overlapped acoustic emission signals.

2. THE ANISOTROPIC PIEZOELECTRIC WAFER

Relaxor-$PbTiO_3$ single crystals, including $Pb(Mg_{1/3}Nb_{2/3})O_3$-$PbTiO_3$ (PMNPT) and $Pb(In_{0.5}Nb_{0.5})O_3$-$Pb(Mg_{1/3}Nb_{2/3})O_3$-$PbTiO_3$ (PIN-PMN-PT), have been extensively investigated in last two decades, due to their superior piezoelectric coefficients (d_{33}>1500 pC/N) and electromechanical coupling factors (K_{33}>90%) when poled along the crystallographic direction [001], which is indicated in Fig. 2. Furthermore, different poling directions can produce larger piezoelectric coefficients (Zhang et al. 2006). Experimental results showed that the [011] direction is another promising poling direction to obtain better multidomain piezoelectric materials (Zhang et al. 2006), shown in Fig. 2. Zhang et al. (2011) calculated the piezoelectric strain coefficients and dielectric permittivity of a [011] poled PMNPT28 crystals in the original coordinates and presented the corresponding full matrix of material constants.

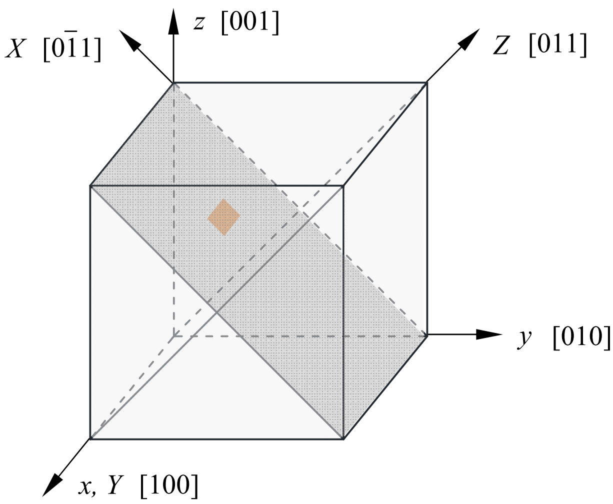


Fig. 2 Poling direction of PMNPT material

Therefore, a PMNPT wafer cut from the plate indicated in Fig. 2 has following elastic compliance matrix (Zhang et al. 2011):

$$\mathbf{S} = \begin{bmatrix} 14.4 & -23.6 & 15.5 & 0 & 0 & 0 \\ -23.6 & 58.1 & -37.6 & 0 & 0 & 0 \\ 15.5 & -37.6 & 30.5 & 0 & 0 & 0 \\ 0 & 0 & 0 & 14.7 & 0 & 0 \\ 0 & 0 & 0 & 0 & 101 & 0 \\ 0 & 0 & 0 & 0 & 0 & 18.8 \end{bmatrix} \times 10^{-12}\, m^2/N \,, \quad (1)$$

While the piezoelectric strain coefficient and dielectric permittivity matrices are shown as:

$$\mathbf{d}=\begin{bmatrix} 0 & 0 & 0 & 0 & 1630 & 0 \\ 0 & 0 & 0 & 239 & 0 & 0 \\ 460 & -1188 & 890 & 0 & 0 & 0 \end{bmatrix}\times 10^{-12}\ C/N\ , \tag{2}$$

$$\grave{o}=\begin{bmatrix} 6410 & 0 & 0 \\ 0 & 1470 & 0 \\ 0 & 0 & 3800 \end{bmatrix}, \tag{3}$$

At first, from Eq. (1), $S_{11}\neq S_{22}$, $S_{13}\neq S_{23}$, $S_{44}\neq S_{55}$ and $S_{66}\neq 2(S_{11}-S_{12})$, that's different with the conventional transversely isotropic material, such as the PZT. Moreover, From Eq. (2), it can be found that just like the conventional piezoelectric material, there are also five non-zero piezoelectric coefficients, but the difference is all five coefficients are independent, i.e. $d_{31}\neq d_{32}$ and $d_{24}\neq d_{15}$, which are equal normally for conventional piezoelectric materials. Moreover, in Eq. (3), $\epsilon_{11}\neq\epsilon_{22}$. Above equations indicate that the PMNPT wafer can be considered as the anisotropic transducer, which is expected to exhibit a highly directive response to ultrasonic guided waves. For this wafer, when an external electric field is applied to the wafer in the z direction, the different in-plane strain in two directions will be induced by d_{31} and d_{32}.

When the direction of external electric field E is along the z-axis and is perpendicular to the surface of the wafer, which is bonded on the surface of plate structure, the linear piezoelectric equations can be simplified as:

$$\begin{aligned} \varepsilon_{11} &= d_{31}E_3 = d_{31}V_{in}/h_p \\ \varepsilon_{22} &= d_{32}E_3 = d_{32}V_{in}/h_p \\ D_3 &= \varepsilon_3 E_3 + d_{31}\sigma_{11} + d_{32}\sigma_{22} \end{aligned} \tag{4}$$

where V_{in} is the external voltage, h_p is the thickness of the PMNPT wafer.

3. FE ANALYSIS OF THE PMNPT WAFER IN GUIDED WAVE APPLICATION

Finite element simulation can provide clear and intuitive displacement field of guided waves induced by the proposed wafer. ANSYS is employed to analyze the ultrasonic guided wave generation and propagation, induced by a PMNPT wafer, which is bonded on the surface of an aluminum plate. The plate (180 mm × 180 mm × 1 mm) is modeled by the SOLID185 element in ANSYS, while the PMNPT wafer (4 mm × 4 mm × 0.2 mm) is modeled by the SOLID5 element, which has 3-D piezoelectric and structural field analysis capability with coupling between the fields. Material properties shown as Eq. (1) ~ (3) are assigned to the PMNPT wafer in the finite element model. Between the PMNPT wafer and the plate, there is no adhesive layer in this work. Fig. 3 shows the position of wafer on the plate, in which the 70 mm distance away from the edges can avoid effects of the reflection signals.

The external voltage applied on the PMNPT wafer is a 5-cycle sinusoid tone burst signal with a fixed center frequency 160 kHz. This signal is defined by Eq. (5). It is a narrow band signal, which can reduce the dispersive effects during the wave propagation.

$$V_{in}(t) = P[H(t) - H(t - 5/f_c)](1 - \cos\frac{2\pi f_c t}{5})\sin 2\pi f_c t \quad (5)$$

where *P* is the amplitude of the signal, f_c is the center frequency and *H*(*t*) is a Heaviside step function.

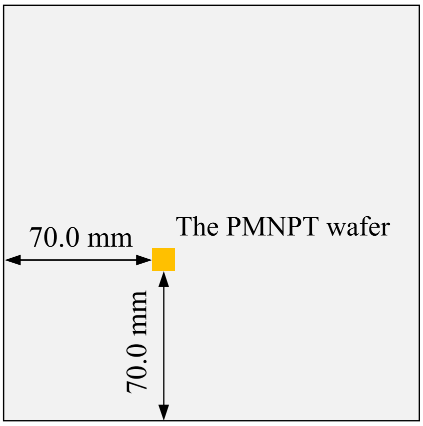
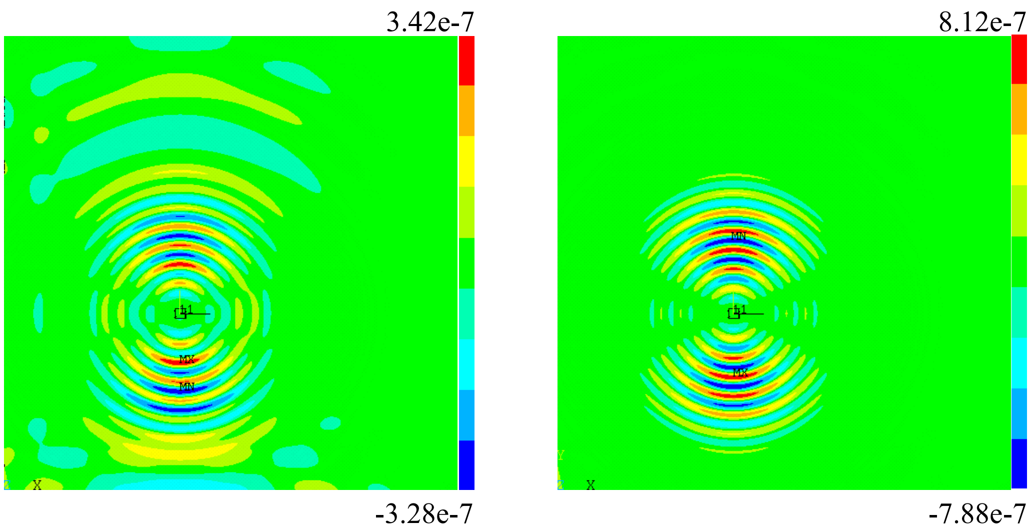


Fig. 3 Layout of the PMNPT wafer and the plate.



(a) (b)

Fig. 4 Displacement field in local coordinate induced by the PMNPT wafer: (a) displacement component *u* in *x* direction, (b) displacement component *w* in *z* direction.

Fig. 4 shows the displacement field of guided waves excited by the PMNPT wafer on the top surface of the aluminum plate at 30 *μs*. Both figures are plotted in the local cylindrical coordinate. Namely, the directions of both displacement component and wave propagation are the radial direction. Above two displacement components indicate that the Lamb wave are generated and propagates in the plate. Moreover, from Fig. 4, it can be found that the amplitude of Lamb wave is dependent on the angle of wave propagation, which is different to Fig. 1.

Absolute values of the maximum amplitude of these two displacement components are plotted versus the angle of wave propagation, shown as Fig. 5, in which the curves are extracted at different time. They just show the relative magnitude of Lamb waves' amplitude in various angles. Both Fig. 4 and Fig. 5 indicate that Lamb wave with maximum amplitude propagates along the y axis, while the minimum amplitude the x axis. According to FE analysis, it's also known that the proposed wafer can be the anisotropic sensor that has various responses to guided waves from different directions.

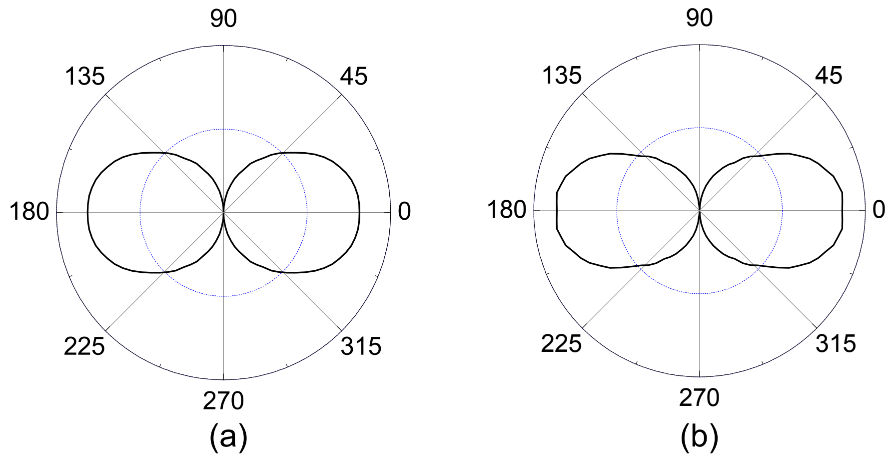


Fig. 5 Displacement amplitude versus direction of wave propagation: (a): displacement component *u*, (b) displacement component *w*.

4. THE APPLICATON OF ANISOTROPIC TRANSDUCER

4.1 Multiple damage sources problem

Anisotropic ultrasonic transducer can provide more information about the wave signals than the conventional transducers. Matt and Scalea (2007) investigated the directivity of the MFC response, and employed MFC rosettes to obtain the wave source location. In this work, the proposed PMNPT wafer is employed to separate the overlapped signals in multiple damage sources problem, with help of blind source separation (BSS) method. The multiple damage sources problem means that several acoustic emission signals are generated from multiple damage sources. During propagation, these signals will overlap each other. In this case, each guided wave sensor receives the overlapped signals containing information of different damage sources. This situation may be instanced by Fig. 6.

Assume that signals denoted by s_1, s_2 … s_n are generated from n sources, and m sensors are fixed at different orientations to catch m orthogonal overlapped signals denoted x_1, x_2 … x_m. The signal mixing procedure may be expressed as the linear equations:

$$\begin{aligned} x_1 &= a_{11}s_1 + a_{12}s_2 + \cdots + a_{1n}s_n \\ x_2 &= a_{21}s_1 + a_{22}s_2 + \cdots + a_{2n}s_n \\ &\cdots \\ x_m &= a_{m1}s_1 + a_{m2}s_2 + \cdots + a_{mn}s_n \end{aligned} \tag{6}$$

where a_{11}, a_{12}, a_{21}… a_{mn} are the parameters that depend on the location/orientation of the sensor and their properties as well. Anisotropic sensor can provide different coefficients a_{11}, a_{12}, a_{21} … a_{mn} due to their directivity. Nasser and Zhou (2011) employed independent component analysis, i.e. BSS method to solve Eq. (6) and recovered the original signals from each signal source. In this work, the proposed PMNPT wafer will be used to receive overlapped signals, which are analyzed by BSS method subsequently. In following subsection, a numerical case shows this procedure.

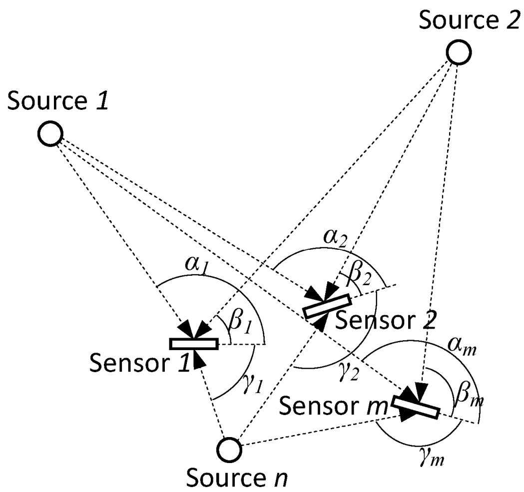
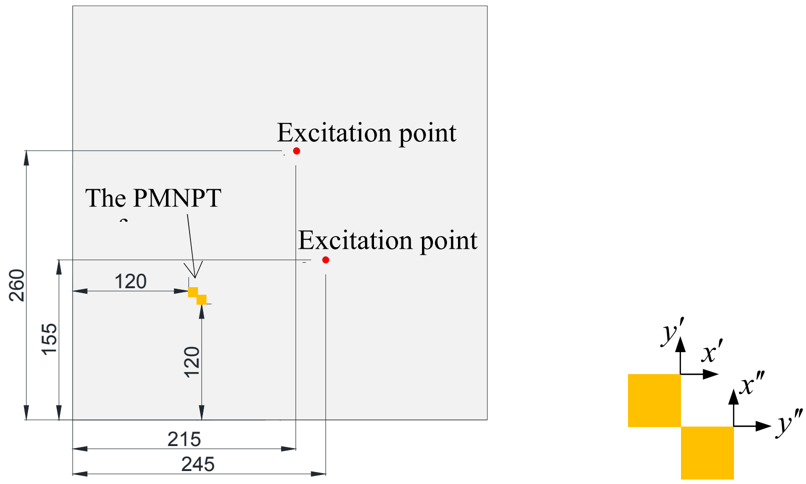


Fig. 6 Piezoelectric sensors and multiple damage sources

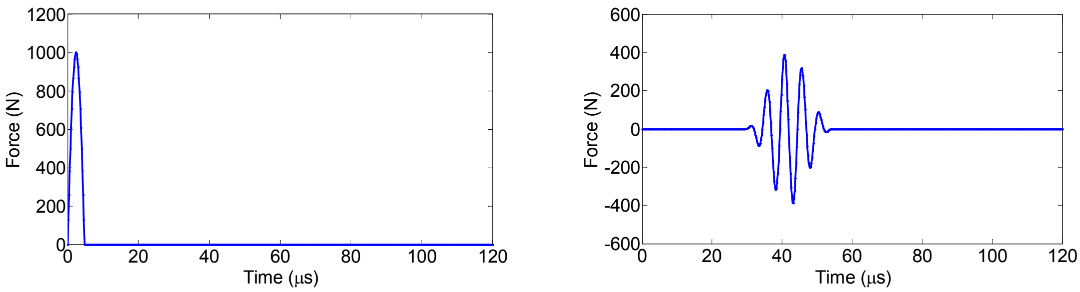
4.2 Numerical investigation

The simulation was conducted on the aluminum plate (400 mm × 400 mm × 1 mm), on which two PMNPT wafers were attached. The detailed layout is shown as Fig. 7(a). The wafers were placed together to avoid the dispersive effect due to different distance from excitation points, but these two wafers were arranged with different directions, shown as Fig. 7(b), i.e. they were in different local coordinate systems. The excitation signals were emitted from two points; one is the broadband pulse signal, while another is the narrowband 5-peaked signal, shown as Fig. 8. The overlapped



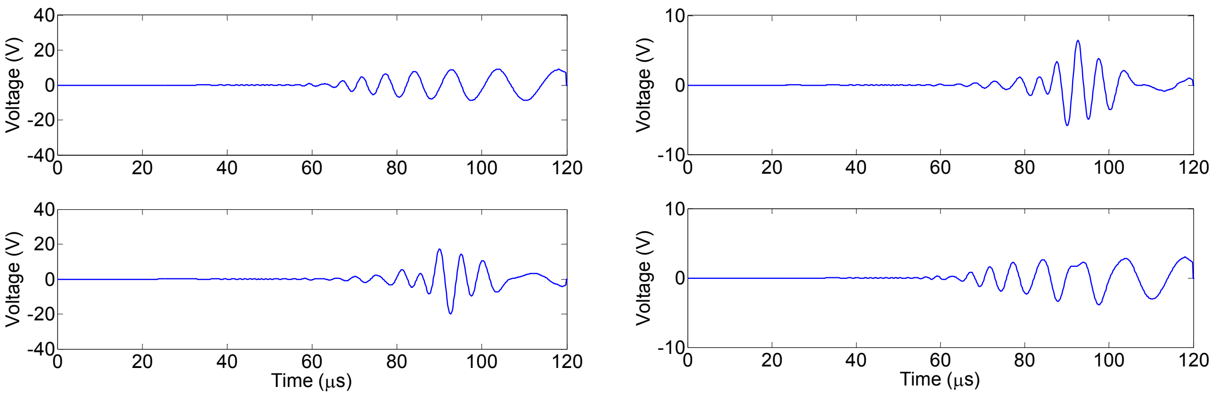
(a) (b)

Fig. 7 Layout of the PMNPT wafers and excitation points.



(a) (b)

Fig. 8 Excitation signals used in simulation: (a) broadband signal, (b) narrowband signal



(a) (b)

Fig. 9 Overlapped and recovered signals using BSS method voltage responses obtained from FE simulation are shown in Fig. 9(a). Fig. 9(b) gives the recovered signals with BSS method. Since the narrowband excitation signal would keep its original shape during the propagation, the upper figure in Fig. 9(b) indicates that the narrowband signal is separated successfully.

5. CONCLUSIONS

In this work, an anisotropic transducer made of PMNPT single crystal was proposed to generate and receive Lamb wave. The PMNPT wafer, which is cut in a special direction with respect to its growth direction, has anisotropic elastic and piezoelectric coefficient matrices. Finite element simulation on a plate indicates that Lamb wave excited by this wafer is not uniform around the wafer. It has maximum displacement response along one axis, while minimum another axis. Subsequently, this wafer was used to identify independent acoustic emission signals from overlapped signals, with help of BSS method. Numerical investigation indicates that the PMNPT sensor array can recover the single acoustic emission signal from overlapped ones.

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