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A new omnidirectional shear horizontal wave transducer using face-shear (d_{24}) piezoelectric ring array

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ABSTRACT

The non-dispersive fundamental shear horizontal (SH_0) wave in plate-like structures is of practical importance in non-destructive testing (NDT) and structural health monitoring (SHM). Theoretically, an omnidirectional SH_0 transducer phased array system can be used to inspect defects in a large plate in the similar manner to the phased array transducers used in medical B-scan ultrasonics. However, very few omnidirectional SH_0 transducers have been proposed so far. In this work, an omnidirectional SH_0 wave piezoelectric transducer (OSH-PT) was proposed, which consists of a ring array of twelve face-shear (d_{24}) trapezoidal PZT elements. Each PZT element can produce face-shear deformation under applied voltage, resulting in circumferential shear deformation in the OSH-PT and omnidirectional SH_0 waves in the hosting plate. Both finite element simulations and experiments were conducted to examine the performance of the proposed OSH-PT. Experimental testing shows that the OSH-PT exhibits good omnidirectional properties, no matter it is used as a SH_0 wave transmitter or a SH_0 wave receiver. This work may greatly promote the applications of SH_0 waves in NDT and SHM.

1. Introduction

Ultrasonic guided-wave-based inspection technique has been proven to be a very effective method for inspecting defects in large waveguide structures [1]. For example, an omnidirectional guided wave transducer phased array system can be used to inspect all the surrounding area of the plate up to a distance of several meters [2], since wave energy can be focused at any target direction and the omnidirectional B-scan can be ultimately performed [3]. In order to build such a phased array system, each individual array element is often expected to behave as an omnidirectional transducer, with equal transmission and reception sensitivity of the chosen wave mode in all directions [3]. In the past decades, various omnidirectional Lamb waves transducers have been proposed, based on electromagnetic acoustic principle [4–6], magnetostrictive effect [7] or piezoelectric effect [8–10].

Compared with the dispersive Lamb waves, the non-dispersive fundamental shear horizontal (SH_0) wave in plate-like structures or the fundamental torsional [T(0,1)] wave in pipe-like structures is more promising in practical applications[11]. Besides non-dispersion, SH_0 wave will not convert to Lamb waves when encountered with defects or boundaries, thus reducing the complexity of the received wave signals [12]. Furthermore, the attenuation of the SH_0 [or T(0,1)] wave is theoretically zero when the waveguide is surrounded by non-viscous fluids such as water [2]. In spite of these attractive features of the SH_0 wave, so far very limited omnidirectional SH_0 wave transducers have been proposed. Seung et al. developed a magnetostrictive electromagnetic acoustic transducer (EMAT) for exciting and measuring omnidirectional SH_0 wave [13]. Wei et al. proposed an omnidirectional SH_1 wave EMAT which is also based on the magnetostrictive effect [14]. Very recently, Seung et al. proposed a new omnidirectional SH_0 wave EMAT based on the Lorentz force [15]. Obviously, these omnidirectional SH_0 wave EMATs can only be used for NDT in metallic structures and are not suitable for structural health monitoring (SHM) due to their relative large size and low energy conversion efficiency.

Piezoelectric transducers are more promising in the fields of both NDT and SHM, due to their compact size and peculiar electromechanical coupling properties. In most cases, piezoelectric acoustic transducers are used in the d_{33} mode (normal probe for scanning) or the d_{31} mode (such as in exciting/receiving Lamb waves in plates). In recent years, there are some works on excitation/reception of SH waves (or torsional waves) based on piezoelectric shear mode transducers, most of which employed the thickness-shear (d_{15}) mode [16,17] and a few adopted the

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face-shear (d_{36} or d_{24}) mode [12,18,19]. All these SH wave piezoelectric transducers have strong directivity with one or two major directions, which is not suitable for sensor applications in SHM. So far, only one omnidirectional SH_0 wave piezoelectric transducer has been proposed, by Belanger and Boivin [20] based on a circular array of six d_{15} mode PZT patches. Their SH_0 wave transducer can generate omnidirectional mixed-mode SH_0 wave and Lamb waves, while the reception capacity was not demonstrated [20]. Actually, the omnidirectional properties are more important for wave receivers than for wave transmitters. Thus, it is necessary to develop an omnidirectional piezoelectric SH wave transducer which can behave as both a transmitter and a receiver. On the other hand, it has been shown in our recent work [19] that the face-shear piezoelectrics is superior to thickness shear piezoelectrics in driving SH waves because of its higher efficiency of energy transfer. Meanwhile, recently we have realized the face-shear d_{36} mode in $PbZr_{1-x}Ti_xO_3$ (PZT) ceramics [21,22] and successfully excited SH_0 wave in an aluminum plate using d_{36} mode PZT wafers [12]. Very recently, we proposed a face-shear (d_{24}) PZT transducer and successfully excited pure SH_0 wave over a wide frequency range [19]. Therefore, it is promising to develop an omnidirectional SH_0 wave transducer with higher energy conversion efficiency by using the face-shear piezoelectrics.

In this work, we proposed an omnidirectional SH_0 wave piezoelectric transducer, which can excite and receive pure SH_0 wave over full 360° in plate-like structures. The proposed omnidirectional transducer is made up of a ring array of twelve face-shear (d_{24}) trapezoidal PZT elements. First, the configuration and working principle of the proposed omnidirectional transducer is presented. Then finite element simulations were performed to investigate the omni-directivity of the SH_0 wave excited by the proposed transducer. Finally, experiments were conducted to examine the performance of exciting and receiving the desired SH_0 wave and the omni-directivity of the proposed transducer. For convenience, the proposed piezoelectric transducer is referred to as OSH-PT (omnidirectional SH wave piezoelectric transducer) in subsequent sections.

2. Configuration and working principle of the OSH-PT

As we know, a point transducer that can cause and measure in-plane particle vibrations could be used to excite and detect SH wave propagating perpendicular to the direction of particle's vibration (not in an omnidirectional manner) [23]. In order to excite the omnidirectional SH wave, a particular excitation force with axisymmetric distribution and polarized in the tangential direction is required as shown in Fig. 1(a) [2]. To realize such a particular excitation force, several identical face-shear d_{24} trapezoidal PZT elements with the thickness of 1.5 mm were used to constitute the OSH-PT, as shown in Fig. 1(b). Each face-shear d_{24} trapezoidal PZT element was individually bonded on the hosting structure to form a ring, and all the array elements were electrically connected in parallel. The height "ae" of the isosceles trapezoid was set to be the half wavelength of the target SH_0 wave at a given excitation frequency, ensuring the largest shear stresses appear on the upper line and baseline of the isosceles trapezoid, respectively. In order to optimize the face-shear performance of the trapezoidal PZT elements, the baseline "dc" of the isosceles trapezoid was set to be equal to its height "ae". As shown in Fig. 1(b) and (c), each d_{24} PZT element is in-plane poled along the "3" direction, thus the effective polarization of the OSH-PT tends to be a circumferential polarization. Obviously, if the angle θ between the two waists of the trapezoidal PZT elements becomes smaller, the effective circumferential polarization will be more uniform, but the size of the OSH-PT will become larger. Our analysis shows that $\theta \approx 30°$ is an appropriate value, rendering the number of the PZT elements to be twelve. The photo of actually-fabricated ring-shaped OSH-PT is shown in Fig. 1(d). Now let us explain how the circumferential shear stress could be produced. As shown in Fig. 1(c), the driving field of the trapezoidal PZT elements is along the "2" direction and the thickness is along the "1" direction. When voltage is applied to the trapezoidal PZT elements, pure face-shear deformation is expected to be obtained due to the face-shear piezoelectric d_{24} mode. Thus each trapezoidal PZT element can be regarded as shear point source in the OSH-PT and an effective circumferential shear stress is expected to be generated.

3. Finite element simulations

Firstly, finite element simulations based on ANSYS were performed to predict the generation of the desired SH_0 wave mode and the omni-directivity of the proposed OSH-PT. An aluminum plate with the dimensions of 400 mm × 400 mm × 1 mm was used in the simulation. Its Young's modulus, Poisson ratio and density were 69 GPa, 0.33 and 2700 kg/m^3, respectively. An OSH-PT with the desired working frequency of 190 kHz was used in the simulation. Therefore, the height "ae" and baseline "dc" of the trapezoidal PZT elements were set to be 8 mm (approaching the half wavelength of the desired SH_0 wave). The θ between the two waists of trapezoidal PZT elements was 30° and twelve elements were used. The material parameters of the PZT (PZT-5H) elements can be found in Ref. [24] and will not be listed here. The proposed OSH-PT was bonded on the aluminum plate using a thin bond layer with the elastic modulus of 500 MPa and thickness of 50 μm. In the simulation, the aluminum plate was modeled by SOLID185 elements and the OSH-PT was modeled by SOLID5 elements in the ANSYS software. A five-cycle Hanning window-modulated sinusoid toneburst was used to excite the proposed OSH-PT. The amplitude of the driving signal was set to be 20 V and its central frequency varied from 160 kHz to 220 kHz to investigate the frequency tuning characteristics of the OSH-PT. For the convenience of analysis, the group velocity dispersion curves of the SH_0 wave and Lamb waves (A_0 and S_0 modes) in the 1 mm-thick aluminum plate are first calculated and plotted in Fig. 2.

Fig. 3 shows the simulated displacement wavefields excited by the proposed OSH-PT at 190 kHz. As the particle vibration caused by the SH_0 wave is in-plane and perpendicular to the wave propagating direction, the tangential displacement component in the cylindrical coordinates can represent the SH_0 wave. Similarly, the radial displacement component and out-of-plane displacement component in the cylindrical coordinates can be used to roughly represent the S_0 wave mode and A_0 wave mode, respectively. As expected, Fig. 3(a) shows that the generated tangential displacement component is axisymmetric around the transducer, implying the good omnidirectional property of the SH_0 waves excited by the proposed OSH-PT. Meanwhile, Fig. 3(b) and (c) show that radial and out-of-plane displacement components are also generated, which is attributed to that the deformation of the trapezoidal PZT element is a quasi-perfect face-shear deformation. It is well known that piezoelectric deformation mode is strongly influenced by the geometry of sample. When the d_{24} piezoelectric transducer is a square wafer, its deformation is a perfect face-shear deformation. However, when the geometry of transducer is changed from the square to the trapezoid, its deformation turns to be slightly different from the perfect face-shear deformation. Note that the amplitude of the induced tangential displacement component is about one order higher than that of the radial and out-of-plane displacement components, as shown in Fig. 3(a)–(c). From Fig. 3 (a) and (d), it can be seen that the tangential displacement component occupies about 99.5% of the total displacement. These