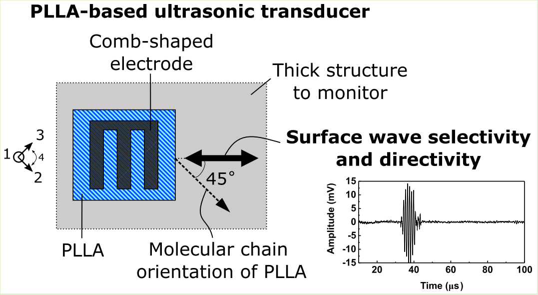
Ultrasonic Surface Wave Transducers Made of Piezoelectric Polylactic Acid for Structural Health Monitoring

Marilyne Philibert, *Member, IEEE*, Yasmin Mohamed Yousry, *Member, IEEE*,
Voon-Kean Wong, *Member, IEEE*, and Kui Yao, *Fellow, IEEE*

Abstract*—Ultrasonic-based structural health monitoring (SHM) allows continuous automated monitoring of structures for improved safety and reduced maintenance time and cost. Guided waves are often used for SHM for the long propagation distance with minimal attenuation. Conventionally, Lamb waves propagate in thin plate-like structures with thickness in order of magnitude of the wavelength. Therefore, they cannot propagate in very thick structures, whereas surface waves can be used for SHM of thick structures. Surface waves are usually generated using bulky ceramic-based transducers on a wedge or using polymeric-based transducers with comb-shaped electrodes. However, multiple wave modes, such as bulk longitudinal wave in thickness direction or high-order guided wave, may co-exist with surface waves due to the coexistence of both axial and shear-mode electromechanical coupling response in conventional piezoelectric materials. This work presents a flexible, lightweight, and low-profile poly-L-lactic acid (PLLA) polymer-based ultrasonic transducer with only in-plane electromechanical coupling for generation and detection of surface waves. The transducer comprises a piezoelectric film made of PLLA with the molecular chain orientation about 45° from the propagation direction of the surface wave. A method of SHM with surface waves in a thick shaft using such transducers is demonstrated, wherein the surface wave generated and detected by the PLLA transducers is used as the condition indicator. The PLLA-based transducers and their enabled ultrasonic SHM method offer the advantages of clearer targeted signal by eliminating the coexistence of other wave modes and long-term service stability by eliminating electrical poling process and any accompanied depoling degradation.



***Index Terms*— Piezoelectric, polylactic acid (PLA), structural health monitoring (SHM), surface wave, ultrasonic transducers.**

I. INTRODUCTION

REGULAR maintenance of in-service engineering structures is required to ensure its integrity and is performed using nondestructive testing (NDT). One of the most popular NDT technologies is using ultrasonic transducers to inspect the structure. Conventional ultrasonic industry methods for defect inspection are laborious, with low efficiency, prone to human factors, with accessibility and safety issues. Ultrasonic-based structural health monitoring (SHM) technologies aim to inspect and assess the integrity of a structure automatically and continuously by using ultrasonic transducers integrated to the structure [1], [2]. By detecting, localizing, and assessing damage at earlier stages and by forecasting the remaining service life of the structure, SHM allows increased safety and reduced maintenance cost and time. SHM is developed for many applications on aerospace, civil, and mechanical engineering structures, such as bridges, aircraft, buildings, or pipes [3], [4].

Guided ultrasonic waves are advantageous in SHM applications because they can propagate over a long distance on short timescales with minimal attenuation and are highly sensitive to defects or any irregularities [5], [6]. Guided waves can be used for monitoring engineering structures and detecting defects, such as cracks or corrosion with complex geometries. However, inspections using guided waves can be challenging because of the presence of multiples modes simultaneously and the dispersive nature, resulting in complex wave propagation, complicated analysis, and interpretation of ultrasonic signals.

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The authors are with the Institute of Materials Research and Engineering (IMRE), Agency for Science, Technology and Research (A*STAR), Singapore 138634 (e-mail: k-yao@imre.a-star.edu.sg).

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The most common guided wave is Lamb wave that propagates through the thickness of thin plate structures. For easier interpretation, low frequencies are often used to minimize the number of modes present simultaneously. However, this results in larger wavelength and hence lower sensitivity to small damage, because guided waves only interact with defect of size comparable to the wavelength. In contrast, Rayleigh waves propagate along the free surface of the structure at higher frequency or in relatively thicker structures than Lamb wave. Rayleigh wave allows simplified analysis due to the nearly nondispersive nature, higher sensitivity to damage, and lower geometrical attenuation [5], [6]. As the energy of the surface waves, such as Rayleigh waves, Stoneley waves, or Scholte waves, is concentrated near the surface of the structure, they are highly sensitive to near surface damage. Besides damage sensitivity, they may be the few feasible choices for monitoring very thick structures (relative to the wavelength), such as block or shaft, because conventional guided waves, such as Lamb waves, cannot be generated at all at realistic ultrasonic working frequencies. This can be explained by a shift of the dispersion curves to the lower frequencies for larger thicknesses, according to the frequency-thickness product. Nevertheless, bulk ultrasonic waves (longitudinal or shear bulk waves) propagating in the thickness direction and surface waves propagating along the surface can be generated in thick structures. Practically, the transition from Lamb waves to Rayleigh waves happens at higher frequency or in thicker structures, for a thickness to wavelength ratio between 2 and 4.

Surface wave can be efficiently generated or detected using bulky ultrasonic transducers made of piezoelectric ceramics on a wedge [7]. This method is not only cumbersome, but it also requires careful selection of suitable wedge angle for the generation and detection of surface wave with minimized generation or detection of other wave modes (for example, bulk longitudinal waves in thickness direction) [6]. The wedge angle is obtained through Snell's law and, hence, depends on the wedge and the structure's material properties. Another condition for this method is that the bulk longitudinal wave in the wedge should have a shorter wavelength than the Rayleigh wave in the structure. It is often challenging to ensure efficient energy transfer between the piezoelectric transducer and the wedge and between the wedge and the structure even when coupling agent is used.

To enhance generation and detection of surface wave, comb-shaped electrode made with at least three fingers can be applied on the piezoelectric material, wherein the periodicity of the comb shape corresponds to the surface wavelength and the length direction of the fingers is perpendicular to the surface wave propagation direction. Compared to conventional ultrasonic transducers that are made from bulky and fragile piezoelectric ceramics, the use of flexible, low profile, and lightweight piezoelectric polymeric-based ultrasonic transducers enables application on curved surfaces or any complex geometries with limited accessibility and allows minimized intrusion in the structure to be monitored. Many advances in flexible ultrasonic transducers have been reported in medical applications [8], as they can maximize alignment and energy transfer for imaging [9], be stretchable due to island bridge electrodes for wearable applications [10], [11], [12], and be fully printable, such as made of polyvinylidene fluoride (PVDF), for reduced costs [13]. Direct-write transducers made with PVDF have promising performances for SHM applications [14]. A conformal piezoelectric film made of PVDF with comb shape electrode can be used for enhanced surface wave generation and/or detection [15]. Previous work showed that surface cracks could be measured using Rayleigh waves generated by a Rayleigh angle beam wedge ultrasonic transducer and received using a Rayleigh wave receiver array made of PVDF polymer, with signal enhanced by a delay-and-sum algorithm [16]. However, due to multiple tensor piezoelectric coefficients of PVDF, other wave modes, such as bulk longitudinal waves, are largely generated and/or detected and thus causing complication in the analysis and interpretation of the ultrasonic signals. Moreover, conventional piezoelectric ultrasonic transducers require electrical poling and suffer from depoling-related degradation during long-term services. In contrast, polylactic acid (PLA), which is a low-cost biodegradable polymer and has good processability for large-scale production, exhibits piezoelectric properties determined by its asymmetric helical molecular structure without requiring electrical poling. Poly-L-lactic acid (PLLA) polymer is also known for its pure shear piezoelectric response [17].

Surface wave was previously generated on the end face of an actuator containing PLLA piezoelectric film for the controlled rotation of an object placed on the end face of the PLLA film [18]. Ultrasonic wave was also generated on the edge of an uniaxially drawn film containing PLLA with shear piezoelectricity, inclined at a 45° angle and cut into a square, as a resonator using its edge vibration [19]. However, both actuators were not mechanically coupled on a structure and were not used for generating or detecting surface wave propagating along the structure.

Our group previously developed guided shear ultrasonic transducer containing PLLA fibers mat with pure shear piezoelectricity [17]. The PLLA fibers' mat has molecular chain orientation direction along or perpendicular to wave propagation. The PLLA transducers were able to generate and detect shear guided waves (shear horizontal SH0 wave mode) for SHM in air or in water.

In this work, we will introduce how to use PLLA as surface wave ultrasonic transducer. It is challenging to selectively generate and/or detect surface wave using a flexible ultrasonic transducer that is lightweight, low-profile, and highly conformable. It has been taught in prior art that the generation of surface wave with the least coexistence of multiple wave modes can be done by using ultrasonic transducer with wedge. Alternatively, surface wave can also be generated and detected using comb-shaped pattern by carefully selecting the frequency using conventional piezoelectric polymer material, such as PVDF. There is no report of application of a flexible ultrasonic transducer made of piezoelectric PLA PLA for generation or detection of a surface wave.

Unlike the guided shear ultrasonic transducer made of PLLA [17], the ultrasonic transducer made of PLLA here is used to generate and detect surface waves in thick structures, due to a different molecular chain orientation that is about 45° from the propagation direction of the ultrasonic wave. This solution to generate and/or detect surface waves using

PLLA transducer allows advantages of low cost, lightweight, and conformable transducer with minimized disturbance of other wave modes. First, the theory behind the generation and detection of surface waves using the ultrasonic transducer made of PLLA with dedicated design will be explained, followed by the fabrication process of the ultrasonic transducers and outlines of the methodology implemented. Next, the performance of the ultrasonic transducers will be evaluated. Finally, an example for SHM application in a thick shaft structure will be demonstrated.

II. DESIGN OF PLLA ULTRASONIC TRANSDUCER AS SURFACE WAVE TRANSDUCER

The surface wave is a type of wave propagating along a structure whereas guided by one of the surfaces of the structure, for example, Rayleigh wave at free surface of a solid, Stoneley waves at the interface of two solids, or Scholte wave at the interface of fluid and solid. The surface wave propagates along the surface of the structure with an approximated depth of one wavelength, wherein the particles move in an elliptical motion with the major axis perpendicular to the structure surface (out-of-plane) and the minor axis parallel to the propagation direction (in-plane) [6]. The thickness of the structure is at least three times thicker than the surface wavelength. The surface wave interacts with the defect that is within a depth of one surface wavelength from the surface.

In the design of our previously developed guided shear ultrasonic transducer containing piezoelectric PLLA fibers mat [17], the molecular chain orientation direction is along or perpendicular to the guided shear wave propagation. This is because the guided shear wave propagates with in-plane particles motion in the direction perpendicular to the propagation direction, corresponding to the pure in-plane piezoelectric coefficient d_{14} of the PLLA fibers. The advantage is the absence of out-of-plane displacement that allows lower wave attenuation when the structure is in contact with liquid or other solid.

In the present design, the surface wave transducer containing piezoelectric PLLA film is configured with the molecular chain orientation slanted about 45° from the propagation direction of the surface wave. The surface wave motion is pushing the particles along the propagation direction, causing in-plane expansion along the ultrasonic wave propagation direction and in-plane contraction along the direction perpendicular from the ultrasonic wave propagation direction, further causing shear strain of the piezoelectric PLLA film with shear-mode piezoelectric effect, as illustrated in Fig. 1.

Electrical excitation signal is applied across the thickness of the piezoelectric PLLA film. An in-plane strain in the piezoelectric film is induced by the electric field applied through the electrode layers (shearing motion around Direction 1 in Fig. 1), due to its piezoelectric coefficient d_{14}, to generate surface wave propagating along the same surface of the structure where the ultrasonic transducer is coupled to. The surface wave propagating along the surface of the structure causes in-plane expansion along the surface wave propagation direction and in-plane contraction along the direction perpendicular from the surface wave propagation direction, resulting in shear strain of the piezoelectric PLLA film with shear-mode piezoelectric effect, inducing electrical signal output from the electrode layers of the piezoelectric film to detect the surface wave.

III. MATERIALS AND METHODS

Experimental studies were conducted using commercial PLLA film (Sigma-Aldrich, Singapore) as a surface wave transmitter and receiver. The PLA films were mechanically stretched at a drawing ratio of 5 and at an elevated temperature from 80 °C to 120 °C. The performance of surface wave generation and detection is also compared with that of commercial PVDF film (PolyK, PA, USA). Silver-based top electrode layer was deposited on the piezoelectric films with the aid of sticker mask, as shown in Fig. 2(b). The bottom electrode layer with a thickness under 30 μm is made of conductive silver epoxy (Polytec PT EC244, Germany) that also served as a bonding agent to bond the piezoelectric films onto the surface of the structure, as shown in Fig. 2(a). Customized flexible printed circuit (FPC) with SubMiniature version A (SMA) connector was bonded onto the piezoelectric films using conductive silver epoxy, forming ultrasonic transducer, as shown in Fig. 2(c). During testing, coaxial cable with SMA connector could be used to connect the ultrasonic transducer to the testing equipment.

The displacements of the surface wave generated by PLLA and PVDF were measured by laser scanning vibrometer (LSV) testing using alternating current (ac) voltage excitation of 10 V in amplitude at 1 MHz. For the ultrasonic test, a signal generator (Tektronix, AFG 3103) was used to generate a modulated three-cycle sinusoidal wave with a frequency of 500 kHz and 1 MHz. The signal was then amplified to 100 Vpp by a power amplifier (NF, HSA 4101) and connected to the surface wave transmitter to generate surface wave. The surface wave receiver was connected to an oscilloscope (Tektronix, MDO 3102) to record the detected surface wave. Measurements were conducted with a sampling frequency of 100 MHz and with 512 waveform averages, effectively averaging out any noise interference. Subsequently, the ultrasonic signals were processed through a bandpass filter designed to filter frequency components outside the surface wave frequency range.

IV. RESULTS AND DISCUSSION

A. Directivity of the Ultrasonic Transducer Made of Piezoelectric PLLA Film

For the demonstration of surface wave detection, the flexible ultrasonic transducer made of the PLLA film was mechanically coupled to a 45-mm-thick aluminum alloy block with a rounded silver electrode deposited on top of the piezoelectric film. The rounded electrode allowed reduced sensitivity to the surface wave propagating from different angular directions. The bottom electrode layer was made of conductive epoxy, which also functioned as a bonding agent to couple the flexible ultrasonic transducer onto the surface of the structure. The PLLA film was a uniaxially oriented PLLA film stretched at a drawing ratio of 5 and annealed at 120 °C for 1 h. The piezoelectricity was induced from the mechanical stretching process without requiring electrical poling. The surface wave was generated with a sine-wave excitation signal of three cycles

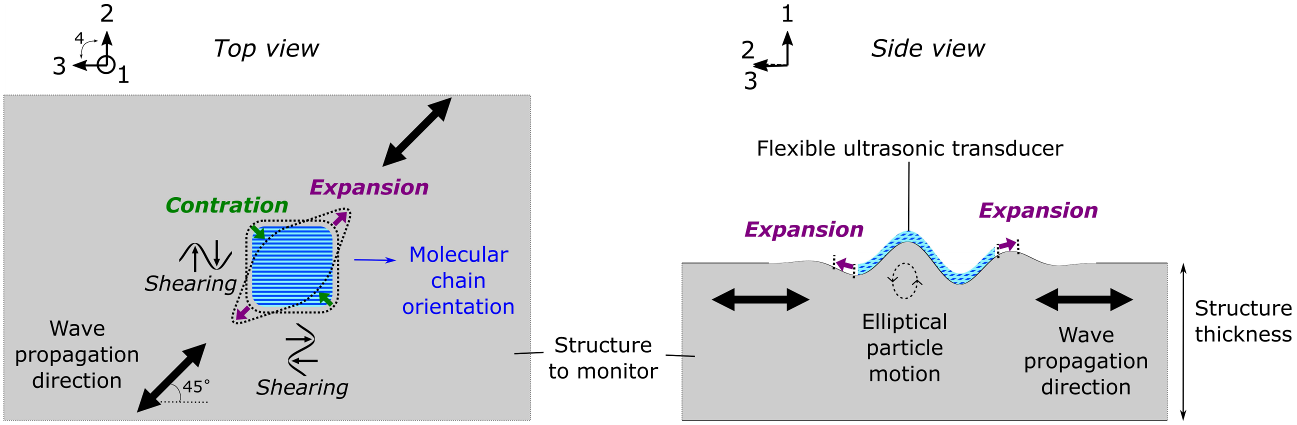

Fig. 1. Top view and side view of a structure to be monitored with a flexible ultrasonic transducer generating or detecting a surface wave. The wave propagation direction is about 45° from the molecular chain orientation of the PLLA film, causing in-plane expansion along the ultrasonic wave propagation direction and in-plane contraction along the direction perpendicular from the ultrasonic wave propagation direction. The expansion and contraction create shear strain of the PLLA film with shear-mode piezoelectric effect.

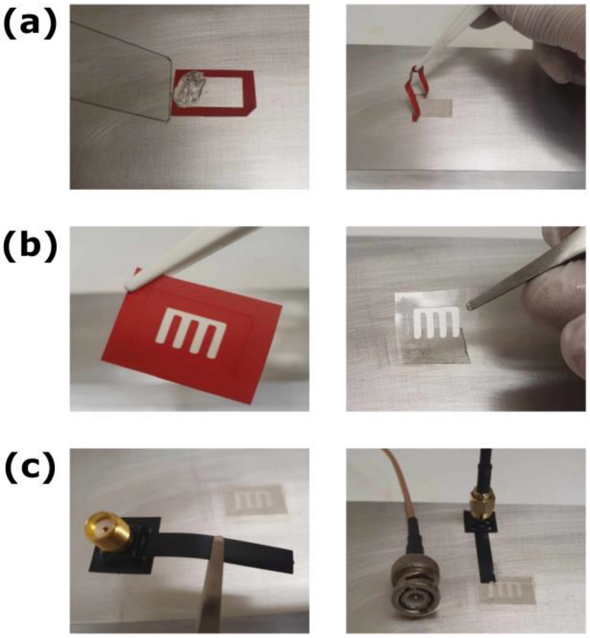

Fig. 2. Photographs of the fabrication of the flexible ultrasonic transducer on a structure with (a) bottom and (b) top electrodes of the piezoelectric transducer bonded with (c) customized FPC connected to the SMA connector.

at 1 MHz by a discrete ceramic-based ultrasonic transducer on an angle wedge at different angles with a constant distance from the PLLA receiver of 105 mm, as shown in Fig. 3.

By comparing the ultrasonic signals detected by the flexible ultrasonic transducer at different angular directions, it can be seen in Fig. 3 that the ultrasonic transducer was sensitive to the surface wave when the angle was about 45° (including 135°, 225°, and 315° as equivalent angles). This implies that the flexible ultrasonic transducer is sensitive to the surface wave when the molecular chain orientation of the PLLA film is about 45° from the propagation direction of the surface wave. This can be explained by the in-plane expansion of the shear-mode piezoelectric PLLA film along the ultrasonic wave propagation direction and the in-plane contraction along the direction perpendicular to the ultrasonic wave propagation direction, as shown in Fig. 1.

B. Performances of PLA as Surface Wave Transducers

The flexible ultrasonic transducer, as illustrated in Fig. 4, comprises the piezoelectric PLLA film sandwiched between the top and bottom electrodes, wherein the molecular chain orientation is about 45° from the surface wave propagation direction. The top electrode layer is patterned into comb shape, and the periodicity of the comb shape corresponds to the wavelength of the surface wave, according to the following equation:

$$\lambda = \frac{c}{f} \tag{1}$$

where λ is the wavelength of the surface wave, c is the velocity of the surface wave, and f is the frequency of the surface wave. The comb-shaped electrode allows to enhance surface wave selectivity.

The advantages of using the flexible ultrasonic transducer containing PLLA as a surface wave transmitter or receiver were studied by comparison with another conventional flexible ultrasonic transducer containing PVDF. A surface wave transmitter generates surface wave, whereas a surface wave receiver detects surface wave. The flexible ultrasonic transducers were mechanically coupled to a 45-mm-thick aluminum alloy block, aligned, and separated by 105 mm. As illustrated in Fig. 4 and according to (1), a top electrode on each of the ultrasonic transducers was patterned into a comb electrode with four fingers with a periodicity of 3 mm, corresponding to the wavelength of the surface wave at about 1 MHz. The frequency is selected considering high attenuation at higher frequencies. The length of the comb electrode is 7 mm, and the length direction is perpendicular to the surface wave propagation direction, as illustrated in Fig. 5.

Using ultrasonic transducers made from PVDF film as both surface wave transmitter and receiver, other unwanted wave modes were generated and detected, as shown in Fig. 5(b-i). However, when using the ultrasonic transducer made with PLLA film as a surface wave receiver [Fig. 5(b-ii)], the incident surface wave at about 37 μs is clearly observed with similar amplitude, while all the other unwanted wave modes

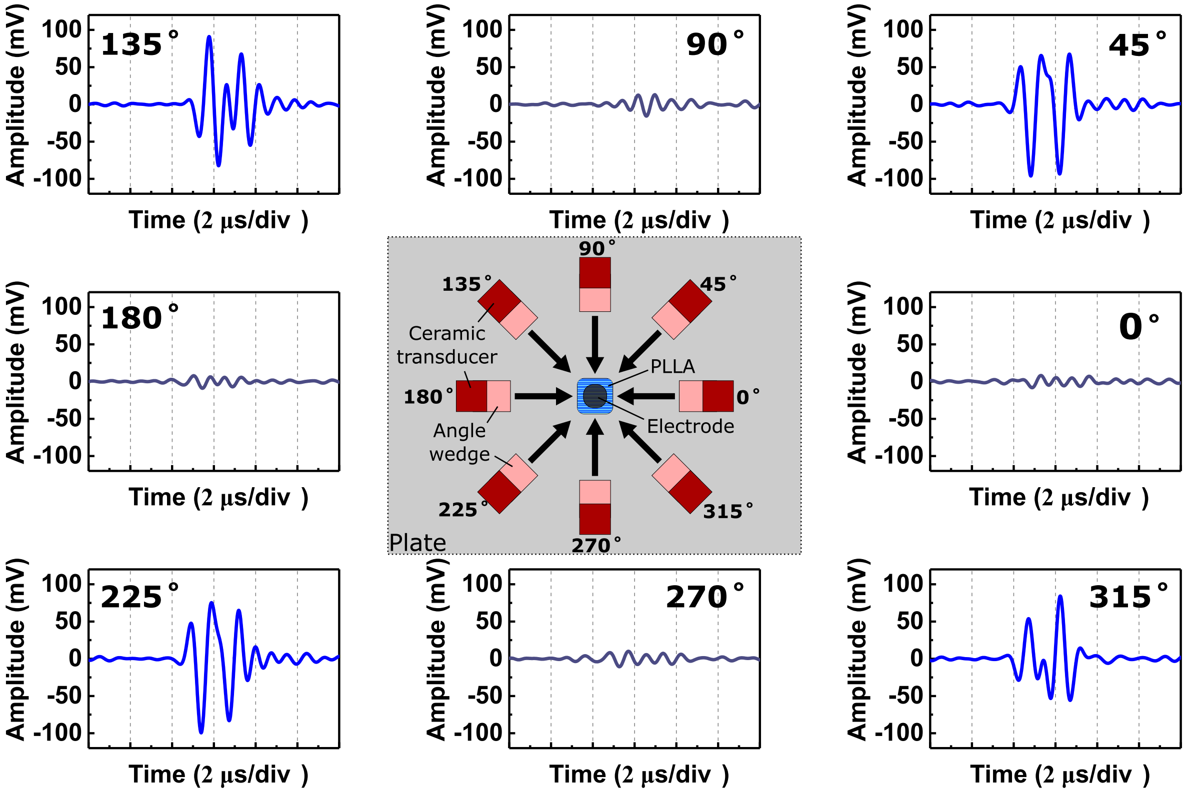

Fig. 3. Directivity of the ultrasonic transducer made of piezoelectric PLLA film mechanically coupled to a thick aluminum alloy block and used as a surface wave receiver. The molecular chains of the PLLA film were aligned at 0° in the drawing. The surface wave was generated by a discrete ceramic-based ultrasonic transducer at different angular directions and the corresponding signals detected by the PLLA ultrasonic transducer showing the arrival of the surface wave are compared.

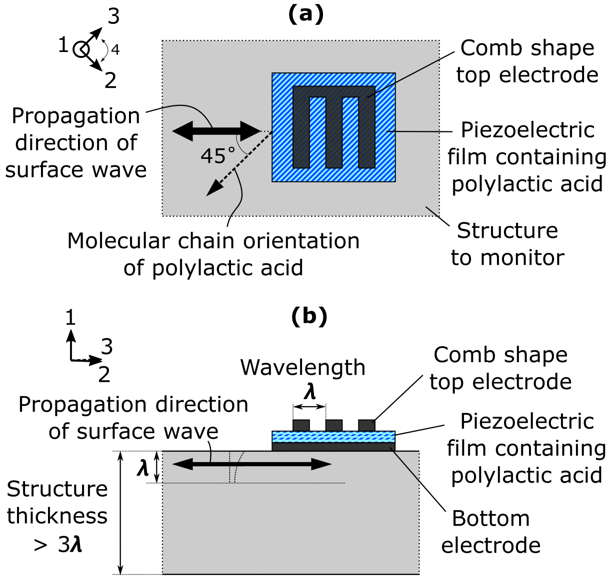

Fig. 4. Schematic illustration of the flexible ultrasonic transducer on a structure (a) top view and (b) side view.

are minimized, compared with the ultrasonic signal obtained using the PVDF transducer as a surface wave receiver. The unwanted modes generated by the PVDF are not detected by PLLA sensors because they are not coupled with the shear stress. However, using ultrasonic transducers made with PLLA film as a surface wave transmitter [Fig. 5(b-iii) and (b-iv)], the ultrasonic signal amplitude is about nine times lower than when using PVDF transducer as the surface wave transmitter. Therefore, the measurements showed that the ultrasonic transducers made with PLLA film can be used as both surface wave transmitter and receiver, with advantage in selectively generating and/or receiving surface wave compared to ultrasonic transducers made with PVDF film. Furthermore, the advantage is more significant when PLLA film is used as the receiver. Relatively small signal magnitude is observed when using PLLA as the transmitter to generate ultrasonic wave because of its low piezoelectric coefficient value and low elastic modulus. The design here leverages on the pure in-plane piezoelectric coefficient d_{14} of PLLA by dedicatedly aligning its chain orientation for enhancing surface wave mode selectivity. In contrast, due to multiple piezoelectric coefficients of PVDF, other wave modes are generated and/or detected.

The surface wave mode selectively generated by ultrasonic transducer made with PLLA film was clearly observed using LSV, as shown in Fig. 6. The surface wave was generated with enhanced propagation directionality due to the molecular chain orientation of PLLA about 45° from the propagation direction. In contrast, ultrasonic transducer made with PVDF showed unclear direction of wave propagation despite the use of comb electrode. Therefore, the ultrasonic transducers made with PLLA film exhibit high directivity and selectivity as surface wave transmitters and receivers.

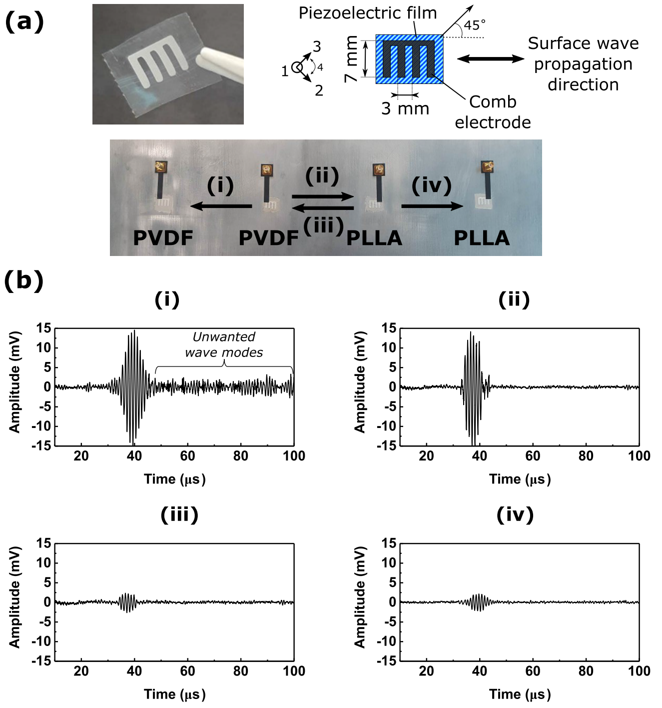

Fig. 5. (a) Schematic representation and photographs of one single and the four flexible ultrasonic transducers and comb electrode, on a 45-mm-thick aluminum alloy block with the representation of the surface wave propagation and (b) ultrasonic signals generated and detected by different combination of ultrasonic transducer pair: i) PVDF to PVDF; ii) PVDF to PLLA; iii) PLLA to PVDF; and iv) PLLA to PLLA.

C. Ultrasonic SHM Demonstration for a Shaft

Since relatively small signal magnitude is expected with PLLA transmitter, conventional piezoelectric ceramics-based ultrasonic transducers may be used to generate surface wave or high electrical voltage may be used when using flexible ultrasonic transducer made of PLLA film to generate surface wave. The surface wave can be detected using the flexible PLLA-based surface wave ultrasonic transducer mechanically coupled to the structure when generated by a different ultrasonic transducer: an ultrasonic transducer made of piezoelectric film containing PVDF, a discrete ultrasonic transducer, such as ceramic-based transducers, or a laser.

Ultrasonic SHM function with surface waves can be designed by leveraging on the higher piezoelectric coefficient of PVDF as the surface wave transmitter and the pure in-plane piezoelectric coefficient of PLLA as a surface wave receiver. This configuration enables ultrasonic signals containing clean surface waves with an improved signal-to-noise ratio, as depicted in Fig. 5(b). Moreover, adopting such a configuration with the transmitter positioned away from the receivers ensures that the electromagnetic interference (EMI) does not interfere with the first detected incident wave. The flexible nature of PVDF-based and PLLA-based surface wave ultrasonic transducer can be applied for ultrasonic SHM, wherein the structure can be of any complex geometry or size, such as plate, cylinder, tube, or elbow. The ultrasonic signals from the surface wave transducers are used as an indicator of structural health. Surface defects including a crack and corrosion commonly starting from a surface can be detected. For defect evaluation or assessment, the signals can be compared to a predetermined baseline signal from the structure in a previous condition, and a deviation from the baseline signal is used to indicate the change in the structure, such as presence or development of a defect in the structure. Alternatively, any reflection from structural irregularities observed in the signal output can be used to indicate the change in the structure, such as presence or development of a defect in the structure. Following the method as we used and demonstrated with PVDF transducers [16], the amplitudes of targeted wave mode arriving to the surface wave receiver are analyzed by processing the ultrasonic signals and obtaining its envelope. The reflection coefficients, C_r, are then obtained from the ratio of amplitudes of the reflected wave, R_r, to the incident wave, R_i, as the following equation:

$$C_r = \frac{R_r}{R_i}. \tag{2}$$

As a demonstration example, the flexible PLLA-based surface wave ultrasonic transducers were applied on a thick structure with complex geometry for generation and detection of a surface wave. They were installed on a stainless-steel shaft of 101.6 mm in diameter for surface defect monitoring, as shown in Fig. 7(a). The selected stainless-steel shaft structure is commonly used in maritime industry. For curved geometry, the flexible ultrasonic transducer can be installed around the circumference of the structure with the length of the comb electrode of the top electrode wrapping over the curved structure in the circumference direction, generating or detecting surface wave along the axial direction of the structure (long axis) that is also the perpendicular direction to the length direction of the comb electrode. An ultrasonic transducer made with piezoelectric PVDF film was installed around the circumference of the structure with the comb electrode forming rings with a periodicity of 7 mm. This ring-shaped PVDF ultrasonic transducer was used to generate surface wave at about 420 kHz. Four flexible ultrasonic transducers made from piezoelectric PLLA films with comb electrodes were installed around the shaft facing different defect depths, including one without defect representing the pristine condition. For detecting surface wave, the PLLA ultrasonic transducers were installed on the shaft with PLLA molecular chain orientation of about 45° from the axial direction of the shaft. The surface wave travels directly from the PVDF ultrasonic transducer to the PLLA ultrasonic transducer with a time of arrival of about 25 μs, corresponding to the incident wave (R_i) in Fig. 7(b). The surface wave is then reflected by the defect edge and arrives back at the PLLA ultrasonic transducer at about 70 μs. The surface wave also travels from the PVDF ultrasonic transducer to the groove edge, is reflected by the groove edge, and arrives at the PLLA ultrasonic transducer at about 45 μs. The defect is therefore detected by the PLLA ultrasonic transducer when a reflection of the surface wave appears in the ultrasonic signal.

After processing the ultrasonic signals to obtain its envelope [smoothed curve outlining absolute extremes as in Fig. 7(b)], the reflection coefficients for the different defect depths are calculated from (2) and shown in Fig. 7(c). This coefficient allows defect depth sizing. Defect as small as 1 mm can be detected with a wavelength of 3 mm. The advantages

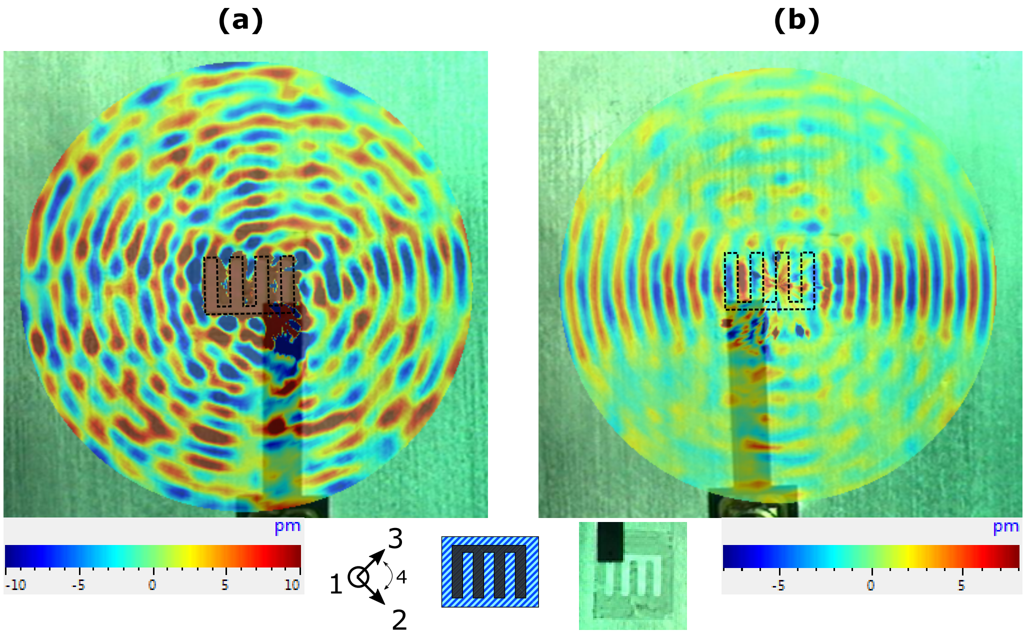

Fig. 6. Scanning images of out-of-plane displacement observed with laser vibrometer for a surface wave generated at about 1 MHz by ultrasonic transducer made from (a) PVDF and (b) PLLA. The insets in the bottom are the schematic illustration and photograph of the sample.

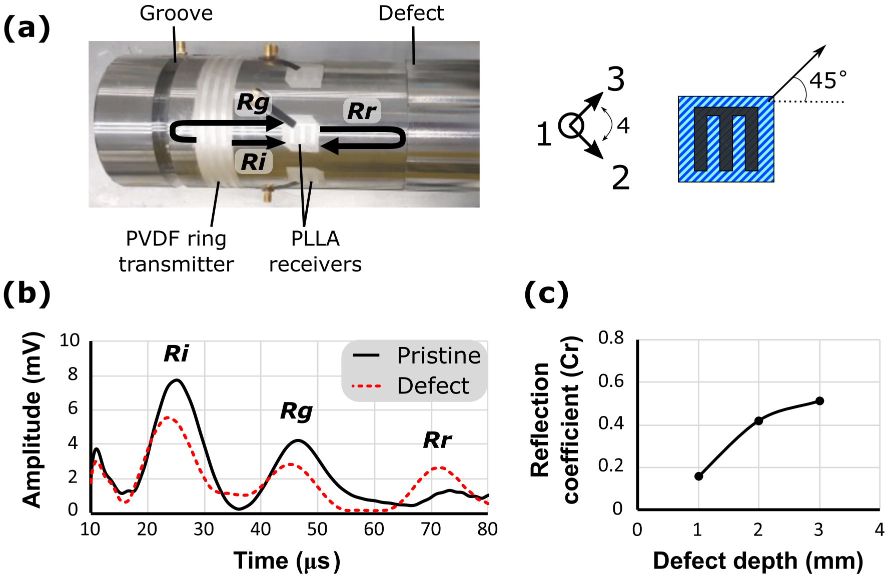

Fig. 7. (a) Photograph of the shaft structure with flexible ultrasonic transducers and corresponding schematic illustration of the flexible ultrasonic transducer made from PLLA, (b) processed ultrasonic signals for the pristine shaft and for the shaft with a defect of 3 mm in depth, and (c) reflection coefficient for different defect depths.

of this method for defect detection include the minimized loss of surface wave energy by the use of ring transmitter that minimizes wave spreading, the simple interpretation of ultrasonic signals with only surface wave present, and the flexibility of ultrasonic polymeric transducers that can be applied on curved surfaces with enhanced transfer of energy, in comparison with flat ceramic transducers with a limited contact area on curved surfaces.

V. CONCLUSION

Ultrasonic transducers made of piezoelectric PLLA film were designed and fabricated for generating and detecting surface waves useful for SHM of thick engineering structures. Although ultrasonic transducers made of piezoelectric PLLA have been reported in the prior art, none of them is related to a PLLA-based transducer for generation or detection of a surface wave. This is because of the well-known pure shear piezoelectric effect of PLLA that teaches away for using PLLA for generation and detection of surface wave. To overcome the challenge and achieve effective generation and detection of surface wave, the ultrasonic transducer made of piezoelectric PLLA film was dedicatedly designed with the molecular chain orientation at about 45° from the ultrasonic surface wave propagation direction to generate and detect expansion and contraction along the diagonal direction of the film caused by the surface wave. To further enhance the generation and detection of selected surface wave, the PLLA ultrasonic transducer has a comb-shaped top electrode with the periodicity corresponding to the wavelength of the targeted surface wave.

The flexible PLLA-based transducer is low cost, biodegradable, and conformable on curved surfaces with complex geometries. It is also lightweight and low profile (typically thinner than 100 μm) for minimized intrusion compared to bulky ceramic-based transducers and use of wedges, making it implementable under limited accessibility. This minimized intrusion results in minimized attenuation rate even when the surface wave travels across the transducer. In comparison with other conventional ultrasonic piezoelectric transducers, i.e., ceramics-based ultrasonic transducer with surface wave wedge and flexible polymers-based (PVDF) transducers, the present PLLA-based surface wave transducer offers the advantage of eliminating electrical poling and related depoling aging of the piezoelectric film. Most importantly, the main advantage of the developed PLLA-based transducer compared to conventional ultrasonic piezoelectric transducers used for surface wave generation or detection is the clean signal and simplified signal processing and analysis enabled by minimizing disturbance from other wave modes. The enhanced surface wave directivity and selectivity results in improved surface defect monitoring ability. With the flexible PLLA-based transducer mechanically coupled to a thick shaft structure, ultrasonic testing was performed at the frequency corresponding to the surface wavelength selected according to the transducer design and the ability of defect monitoring was successfully demonstrated.

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Marilyne Philibert (Member, IEEE) is currently a Research Scientist at IMRE, A*STAR, Singapore. Her research interests are ultrasonic-based structural health monitoring, composite materials, and piezoelectric transducers.

Yasmin Mohamed Yousry (Member, IEEE) is currently a Research Scientist at IMRE, A*STAR, Singapore. Her research interests include smart materials (dielectric, piezoelectric, and ferroelectric materials), sensors and actuators applications, and ultrasonic transducers for SHM.

Voon-Kean Wong (Member, IEEE) is currently a Senior Research Scientist at IMRE, A*STAR, Singapore. His research interests include the design of high-performance piezoelectric ultrasonic transducers, signal processing algorithms, and the development of ultrasonic systems tailored for SHM purposes.

Kui Yao (Fellow, IEEE) is currently a Senior Principal Scientist with the Institute of Materials Research and Engineering, Agency for Science, Technology and Research (A*STAR), Singapore. His research areas cover dielectric, piezoelectric, and ferroelectric materials and the sensors and transducers enabled by these materials, including their applications for structural and condition monitoring, healthcare, ultrasonic and photoacoustic detection and diagnosis, and noise and vibration mitigation.