

ULTRASONIC TRANSDUCER AND METHOD OF STRUCTURAL HEALTH MONITORING**Technical Field**

[0001] The present invention generally relates to an ultrasonic transducer and method for monitoring structure defects.

Background

[0001] Ultrasonic-based structural health monitoring (SHM) technologies aim to inspect and assess the integrity of a structure by using ultrasonic transducers on the structure, particularly in industries such as aerospace, civil engineering, and mechanical systems. Surface waves, including Rayleigh waves, Stoneley waves, and Scholte waves, are sensitive to surface and subsurface defects such as cracks and corrosion. Ultrasonic transducers thus generate surface waves in the structure being monitored and detect how the surface waves propagate along the surface of the structure in order to monitor defects in the structure.

[0002] Traditional ultrasonic transducers are typically made of fragile piezoelectric ceramics. They are consequently bulky, require electrical poling, and suffer from degradation over time due to de-poling. They also struggle with complex geometries as conventional designs of such ultrasonic transducers cannot be used on curved surfaces. Accurate use of ultrasonic transducers for SHM is also prone to human factors, facing accessibility and safety issues. Furthermore, their handling and setup for inspections can be laborious, with limited real-time monitoring capabilities.

[0003] Hence, there exists a need for an ultrasonic transducer that is durable, efficient, lightweight and has a low profile, that is capable of monitoring defects for structures having complex geometries.

Summary

[0004] The present invention relates to an ultrasonic transducer designed to be mechanically coupled to a surface of a structure for the purpose of generating and detecting surface waves for structural health monitoring (SHM). The ultrasonic transducer is flexible, comprising a piezoelectric film made of polylactic acid (PLA), an inexpensive and widely available polymer, provided between two electrodes during use. The molecular chains of the PLA film are oriented preferably approximately 45 degrees from the direction of surface wave propagation, a

configuration that enhances sensitivity of the film to shear mode piezoelectric effect. The surface wave is an ultrasonic wave that propagates along the surface of the structure, interacting with any surface or subsurface irregularities such as cracks, corrosion, or other defects. This interaction modifies characteristics of the wave, which can be detected by the ultrasonic transducer. By detecting any reflected or altered waves caused by defects, the ultrasonic transducer is able to provide real-time data on the structural integrity. The piezoelectric polymeric-based ultrasonic transducer is flexible, has a low profile, and is lightweight, allowing it to be readily applied to curved surfaces or any complex geometries with limited accessibility and allows minimized intrusion in the structure to be monitored.

[0005] According to a first exemplary aspect, there is provided flexible ultrasonic transducer part comprising:

- a flexible piezoelectric film made from polylactic acid and having a shear mode piezoelectric effect; and

- a first electrode provided on a first surface of the piezoelectric film;

- wherein in use for monitoring structural health of a structure, a second electrode is provided on a second surface of the piezoelectric film to form an ultrasonic transducer that is attached to the structure such that a molecular chain orientation of the piezoelectric film is at 35 to 55 degrees relative to a propagation direction of a surface wave generated on the structure.

[0006] In use, propagation of the surface wave may cause in-plane expansion of the structure along the propagation direction and in-plane contraction of the structure in a direction perpendicular to the propagation direction, thereby resulting in shear strain of the piezoelectric film that induces an electrical signal output from the first and second electrodes for processing to monitor the structural health of the structure.

[0007] When an electric field is applied to the piezoelectric film through the first and second electrodes, an in-plane strain may be induced in the piezoelectric film, thereby generating the surface wave.

[0008] The first electrode may comprise a comb-shaped electrode layer having a plurality of electrode fingers and periodicity of the electrode fingers may correspond to a wavelength of the surface wave.

[0009] Length of each electrode finger may be provided at 35 to 55 degrees to the molecular chain orientation of the piezoelectric film.

[0010] The comb-shaped electrode layer may comprise at least three electrode fingers, wherein length of each electrode finger is at least twice a wavelength of the surface wave.

[0011] In use, each electrode finger may be provided perpendicular to the propagation direction of the surface wave.

[0012] When the surface of the structure has a curvature, in use, the ultrasonic transducer may be attached to the surface such that length of each electrode finger is aligned with a circumferential direction of the curvature.

[0013] The polylactic acid may be one of: poly(L-lactic acid) and poly(D-lactic acid).

[0014] The second electrode may be made of a layer of a conductive epoxy that serves as an electrode and as a bonding agent to bond the ultrasonic transducer onto the surface of the structure.

[0015] In use, the surface wave may interact with any defect within a depth of one wavelength of the surface wave from the surface of the structure.

[0016] In use, the molecular chain orientation of the piezoelectric film may be at 45 degrees relative to the propagation direction of the surface wave generated on the structure.

[0017] According to a second aspect, there is provided a flexible ultrasonic transducer comprising:

- the ultrasonic transducer part of the first aspect; and
- the second electrode provided on the second surface of the piezoelectric film.

[0018] According to third aspect, there is provided a method of structural health monitoring of a structure, the method comprising the steps of:

- (a) attaching a flexible ultrasonic transducer to a surface of the structure, the flexible ultrasonic transducer comprising: a flexible piezoelectric film made from polylactic acid and having a shear mode piezoelectric effect, the piezoelectric film having a molecular chain orientation at 35 to 55 degrees relative to a propagation direction of a surface wave to be generated on the structure, a first electrode provided on a first surface of the piezoelectric film, and a second electrode provided on a second surface of the piezoelectric film;
- (b) generating the surface wave on the structure, wherein propagation of the surface wave causes in-plane expansion of the structure along the propagation direction and in-plane contraction of the structure in a direction perpendicular to the propagation

direction, thereby resulting in shear strain of the piezoelectric film that induces an electrical signal output from the first and second electrodes; and
(c) processing the electrical signal to monitor the structural health of the structure.

[0019] Step (b) may comprise applying an electric field to the piezoelectric film through the first and second electrodes to induce an in-plane strain in the piezoelectric film, thereby generating the surface wave.

[0020] Step (b) may be performed using one of: the flexible ultrasonic transducer, an ultrasonic transducer having a piezoelectric film made of polyvinylidene fluoride provided between two electrodes, a discrete ultrasonic transducer, and a laser.

[0021] Step (c) may comprise comparing the electrical signal with a baseline signal obtained from the structure in a previous condition, wherein deviation of the electrical signal from the baseline signal indicates at least one of: presence of a defect in the structure and development of a defect in the structure.

[0022] The electrical signal may be indicative of a structural irregularity in the structure that gave rise to a reflected surface wave detected by the ultrasonic transducer.

[0023] The piezoelectric film may have a molecular chain orientation at 45 degrees relative to the propagation direction of the surface wave to be generated on the structure

[0024] For both aspects, wavelength of the surface wave is one-third or less of a thickness of the structure.

[0025] According to a fourth aspect, there is provided method of manufacturing the ultrasonic transducer part of the first aspect, comprising the steps of:

- (a) stretching a polylactic acid film at a drawing ratio ranging from 3 to 7 at a temperature ranging from 80 °C to 120 °C to form the flexible piezoelectric film; and
- (b) depositing the first electrode on the flexible piezoelectric film.

Brief Description of the Drawings

[0026] In order that the invention may be fully understood and readily put into practical effect there shall now be described by way of non-limitative example only exemplary embodiments of the present invention, the description being with reference to the accompanying illustrative drawings listed below.

FIG. 1a is a schematic illustration of a top view of a flexible ultrasonic transducer attached to a structure.

FIG. 1b is a schematic illustration of side view of the arrangement of FIG. 1a.

FIG. 2a is a schematic illustration of a top view of a structure to be monitored having a flexible ultrasonic transducer attached thereto and generating and/or detecting a surface wave.

FIG. 2b is a schematic illustration of a side view of the arrangement of FIG. 2a.

FIG. 3a is a schematic illustration of a top view of a flexible ultrasonic transducer attached to a structure.

FIGS. 3b to 3d are graphs of ultrasonic signals output by the flexible ultrasonic transducer in the arrangement of FIG. 3a upon receiving a surface generated at different angular directions relative to a molecular chain orientation of a poly(L-lactic acid) (PLLA) piezoelectric film of the flexible ultrasonic transducer.

FIG. 4a is a photograph of four flexible ultrasonic transducers attached to an aluminium alloy block.

FIG. 4b is a schematic illustration of a comb-shaped electrode layer provided on each of the four flexible ultrasonic transducers of FIG. 1a.

FIGS. 5a to 5d are graphs of ultrasonic signals output by each of the four flexible ultrasonic transducers of FIG. 4a.

FIG. 6a is a scanning image of displacement observed with a laser vibrometer for a surface wave generated at about 1 MHz by an ultrasonic transducer having a polyvinylidene fluoride (PVDF) piezoelectric layer.

FIG. 6b is a scanning image of displacement observed with a laser vibrometer for a surface wave generated at about 1 MHz by an ultrasonic transducer having a PLLA piezoelectric layer.

FIG. 7a is a schematic illustration of flexible ultrasonic transducers installed on plate.

FIG. 7b is a schematic illustration of flexible ultrasonic transducers installed on cylinder.

FIG. 7c is a schematic illustration of flexible ultrasonic transducers installed on tube.

FIG. 7d is a schematic illustration of flexible ultrasonic transducers installed on an elbow structure.

FIG. 8a is a photograph of flexible ultrasonic transducers attached to a shaft structure and a schematic illustration of one of the attached flexible ultrasonic transducers having a PLLA piezoelectric film.

FIG. 8b is a graph of ultrasonic signals obtained by the flexible ultrasonic transducer having the PLLA piezoelectric film in the arrangement of FIG. 8a.

FIG. 8c is a graph of reflection coefficients at different defect depths obtained from the ultrasonic signals in FIG. 8b.

FIG. 9a is a schematic illustration of a flexible ultrasonic transducer having a polylactic acid (PLA) piezoelectric film attached to a structure to generate surface waves that are detected by another flexible ultrasonic transducer attached to the structure and having a PLA piezoelectric film.

FIG. 9b is a schematic illustration of a flexible ultrasonic transducer having a PVDF piezoelectric film attached to a structure to generate surface waves that are detected by a flexible ultrasonic transducer attached to the structure and having a PLA piezoelectric film.

FIG. 9c is a schematic illustration of a discrete ultrasonic transducer having a ceramic piezoelectric film attached to a structure to generate surface waves that are detected by a flexible ultrasonic transducer attached to the structure and having a PLA piezoelectric film.

FIG. 9d is a schematic illustration of an ultrasonic ceramic transducer on an angle wedge attached to a structure to generate surface waves that are detected by a flexible ultrasonic transducer attached to the structure and having a PLA piezoelectric film.

FIG. 9e is a schematic illustration of a laser generating on a structure surface waves that are detected by a flexible ultrasonic transducer attached to the structure and having a PLA piezoelectric film.

FIG. 10a is a schematic illustration of two flexible ultrasonic transducer attached to a structure and each having a PLA piezoelectric film for monitoring structural health of the structure.

FIG. 10b is a schematic illustration of one flexible ultrasonic transducer attached to a structure and having a PLA piezoelectric film for monitoring structural health of the structure.

FIG. 11 is a flowchart of an exemplary method of manufacturing an ultrasonic transducer part.

FIG. 12 is a flowchart of an exemplary method of structural health monitoring.

Detailed Description

[0027] Exemplary embodiments of an ultrasonic transducer 10, a method of manufacturing an ultrasonic transducer part 100, and a method of structural health monitoring 200 will be described below with reference to FIGS. 1a to 12, in which the same reference numerals are used across the figures to refer to the same or similar parts.

[0028] The presently disclosed ultrasonic transducer 10 is configured to be mechanically coupled or attached to a surface 91 of a structure 90 for monitoring structural health of the structure 90, for example, in the detection of surface and subsurface defects such as cracks or corrosion. The ultrasonic transducer 10 comprises a flexible piezoelectric film 20 made from polylactic acid (PLA), a biopolymer having piezoelectric properties (shear mode piezoelectric effect) when mechanically stretched. In use, the ultrasonic transducer 10 is preferably position on the structure 90 such that molecular chains of the PLA are aligned and oriented at about 35 to 55 degrees, preferably 45 degrees, relative to a propagation direction 80 of a surface wave that is generated on the structure 90, as shown in FIG. 1. The molecular chain orientation 70 of the PLA enhances the shear mode piezoelectric effect of the film 20, allowing it to more effectively generate and detect surface waves. PLA is advantageously used to make the film 20 due to its low cost, light weight, ease of manufacturing and processability for large scale production, and the absence of a requirement for electrical poling in order to exhibit piezoelectric properties when mechanically stretched. The PLA film 20 with piezoelectricity can be fabricated by mechanically stretching polylactic acid film at various drawing ratios from 3 to 7 at elevated temperatures ranging from 80 °C to 120 °C. The PLA used to form the piezoelectric film 20 may be either one of the isomers of PLA, i.e., either poly(L-lactic acid) (PLLA) or poly(D-lactic acid) (PDLA).

[0029] The ultrasonic transducer 10 also comprises a top or first electrode 30 provided on a first or top surface of the piezoelectric film 20. The first electrode 30 comprises a comb-shaped electrode layer 30 having a plurality of electrode fingers 31. The electrode fingers 31 have a periodicity λ corresponding to a wavelength λ of the surface wave, as shown in FIG. 1b. The periodicity of the electrode fingers 31 is a displacement comprising a width of each electrode finger 31 and a space between adjacent electrode fingers 31. The comb-shaped electrode layer 30 allows selectivity of the surface wave to be enhanced. Materials such as silver, gold, or carbon may be used for the first electrode 30 and can be deposited on the piezoelectric film 20 using methods such as spraying, printing, or vacuum deposition. In a preferred embodiment, the comb-shaped electrode layer 30 comprises at least three electrode fingers 31. A length L of each electrode finger 31 (as shown in FIG. 4b) is preferably twice the wavelength λ of the surface wave. Each electrode finger 31 (i.e. its length direction) is preferably perpendicular to the propagation direction 80 of the surface wave. Accordingly, the length of each electrode finger 31 of the comb-shaped first electrode 30 is provided at 35 to 55 degrees (preferably 45 degrees) to the molecular chain orientation of the piezoelectric film 20.

[0030] In use, a bottom or second electrode 40 is provided on a second or bottom surface of the PLA film 20, the second surface being opposite the first surface. In a preferred embodiment, the second electrode 40 is made of a layer of a conductive epoxy. The conductive epoxy may be applied to the flexible PLA piezoelectric film 20 only when the ultrasonic transducer 10 is to be attached to the structure 90 to be monitored. Using conductive epoxy, the second electrode 40 not only serves as an electrical contact but also acts as a bonding agent, ensuring that the ultrasonic transducer 10 remains permanently bonded to the surface 91 of the structure 90 being monitored.

[0031] Notably, the ultrasonic transducer 10 may be partially supplied as an ultrasonic transducer part comprising only the flexible PLA piezoelectric film 20 and the first electrode 30 provided on the first surface of the PLA piezoelectric film 20, such that the second electrode 40 is provided on the second surface of the PLA piezoelectric film 20 only during use of the ultrasonic transducer 10. As shown in FIG. 11, an exemplary method of manufacturing the ultrasonic transducer part 100 (that can be used to form the flexible ultrasonic transducer 10 during use) may comprise the steps of:

(a) stretching a polylactic acid film at a drawing ratio ranging from 3 to 7 at a temperature ranging from 80 °C to 120 °C to form the flexible piezoelectric film 20 (110); and

- (b) depositing the first electrode 30 on the flexible piezoelectric film 20 (120).

Working Mechanism

[0032] The ultrasonic transducer 10 operates based on the piezoelectric effect of PLA. With reference to FIGS. 2a and 2b, when the surface wave propagates on the surface 91 of the structure 90, the surface wave motion pushes particles of the structure 90 along the propagation direction 80, with an elliptical particle motion 82, both perpendicular to the surface 91 of the structure 90 (out-of-plane in direction 1 as indicated by the coordinate icons in FIGS. 2a and 2b) and parallel to the propagation direction 80 (in-plane). This causes in-plane expansion 51 of the structure 90 along the propagation direction 80 and in-plane contraction 52 of the structure 90 in a direction perpendicular to the propagation direction 80. This results in shear strain of the piezoelectric film 30 with shear mode piezoelectric effect that induces an electrical signal output from the first and second electrodes 30, 40 for detection of the surface wave.

[0033] As the surface wave propagates, it interacts with any defects or irregularities within the structure 90, which modify characteristics of the surface wave. The modified waves are detected by the ultrasonic transducer 10, which converts mechanical strain into electrical signals. The electrical signal output is obtained by measuring the charge generated from the first and second electrodes 30, 40, and can be processed and analysed to detect the presence of defects or irregularities in the structure 90. For example, the electrical signal output may be compared to a predetermined baseline signal obtained in a same way from the same structure 90 in a previous condition (e.g., a pristine state), and a deviation from the baseline signal may be used to indicate a change in the structure 90, such as presence or development of a defect in the structure 90. Alternatively or additionally, any reflection from structural irregularities in the electrical signal output may be used to indicate the change in the structure 90, providing further information on the location and size of the defect.

[0034] Notably, when an electric field is applied to the piezoelectric film 20 across its thickness through the first and second electrodes 30, 40, an in-plane strain is induced in the piezoelectric film 20 due to its shear piezoelectric coefficient d_{14} which originates from its crystal structure that does not require electrical poling to render piezoelectricity. The in-plane strain gives rise to a shearing motion 61 in an angular shear direction 4 parallel to the surface 91 of the structure 90. The shearing motion 61 in turn generates the surface wave that propagates on the surface 91 of the structure 90, for example Rayleigh wave at a free surface of a solid, Stoneley waves at an interface of two solids, or Scholte wave at the interface of a fluid and a solid. The surface

wave is a type of ultrasonic wave that propagates or travels on the surface 91 while being guided by the surface 91 itself. Such guided waves can be used for monitoring of engineering structure such as plates, pipelines, shafts, or other structures with complex geometries., as described above.

[0035] For optimal performance, thickness T of the structure 90 should be at least three times the wavelength λ of the surface wave. In other words, wavelength λ of the surface wave is preferably one-third or less than the thickness T of the structure 90. The surface wave that travels on the surface 91 of the structure has a penetration depth of approximately one wavelength λ of the surface wave. In this way, the surface wave interacts with any defect within a depth of one wavelength λ of the surface wave from the surface 91 of the structure 90. For defect monitoring, the ultrasonic testing is preferably performed at a frequency corresponding to the wavelength λ of the surface wave.

[0036] The ultrasonic transducer 10 can thus not only detect surface waves for detecting presence of defects or irregularities in the structure 90, it can also be used to generate the surface wave needed for defect detection to take place using the ultrasonic transducer 10. Other known means can also be used to generate the surface wave, such as a discrete ultrasonic transducer containing lead zirconate titanate (PZT), a laser, or a flexible ultrasonic transducer comprising a piezoelectric film made of polyvinylidene fluoride (PVDF) provided between electrode layers.

[0037] In use, the ultrasonic transducer 10 can be applied to structures having a wide range of geometries, including flat surfaces, cylinders, tubes, and more complex shapes like elbows. This flexibility is a major advantage, as it allows for effective monitoring of structures with varying designs.

Example 1

[0038] FIG. 3a shows an exemplary embodiment of an ultrasonic transducer 10 used for surface wave detection. The ultrasonic transducer 10 comprised a piezoelectric film 20 containing or made of PLA, wherein the molecular chain orientation 70 of the PLA is about 45 degrees from the ultrasonic wave propagation direction 80. The flexible ultrasonic transducer 10 was mechanically coupled or attached to a surface 91 of a 45 mm-thick aluminium alloy block 90. A first electrode 30 of the ultrasonic transducer 10 comprised a rounded silver electrode layer of 3 mm diameter deposited on the piezoelectric film 20. A rounded silver electrode layer 30 reduces sensitivity of the ultrasonic transducer 10 to a surface wave

propagating from different angular directions. A second electrode layer (not shown) of the ultrasonic transducer 10 was made of a conductive epoxy that served as a bottom electrode and also as a bonding agent to bond the flexible ultrasonic transducer 10 onto the surface 91 of the structure 90. The piezoelectric film 20 was a uniaxially oriented poly(L-lactic acid) (PLLA) film 20 mechanically stretched at a drawing ratio of 5 and annealed at 120 °C for 1 hour. Piezoelectricity in the PLLA film 20 was induced from the mechanical stretching process without requiring electrical poling. A surface wave was generated with a sine-wave excitation signal of 3 cycles at 1 MHz by a discrete ceramic-based ultrasonic transducer (not shown) on an angle wedge at different angles (relative to the molecular chain orientation 70) with a constant distance of 105 mm from the ultrasonic transducer 10 acting as a receiver. A wavelength of the surface wave at 1 MHz matched the electrode diameter of 3 mm the ultrasonic transducer 10 and a time of arrival of the surface wave to the receiver (i.e., the ultrasonic transducer 10) was about 36 μ s with a velocity of 2960 m/s.

[0039] By comparing the ultrasonic signals detected by the flexible ultrasonic transducer 10 at different angular directions of the surface wave propagation relative to the molecular chain orientation 70 as shown in FIGS. 3b to 3i, it can be seen that the ultrasonic transducer 10 was most sensitive to the surface wave when the angle between propagation direction and the molecular chain orientation 70 was about 45 degrees (this includes the angular directions at 135 degrees, 225 degrees and 315 degrees). This implies that the flexible ultrasonic transducer 10 is most sensitive to the surface wave when the molecular chain orientation 70 of the PLLA film is about 45 degrees from the propagation direction of the surface wave. This can be explained by the in-plane expansion 51 of the shear mode piezoelectric PLLA film 20 along the ultrasonic wave propagation direction 80 and the in-plane contraction 52 along the direction perpendicular to the ultrasonic wave propagation direction 80, as shown in FIG. 2a.

Example 2

[0040] This example demonstrates the advantages of using the flexible ultrasonic transducer 10 containing PLA as a surface wave transmitter or receiver in comparison with other ultrasonic transducers, i.e., a flexible ultrasonic transducer containing PVDF. A surface wave transmitter generates surface waves, while a surface wave receiver detects surface waves. In this example, as shown in FIG. 4a, two flexible ultrasonic transducers 10 each having a piezoelectric film 20 made of PLLA were mechanically coupled or attached to a 45 mm-thick aluminium alloy block 90 beside two ultrasonic transducers each having a piezoelectric film made of PVDF that were similarly attached to the block 90, in order to compare performance of the piezoelectric film containing or made of PLLA 20 with the performance of piezoelectric

films made of PVDF. The PLLA piezoelectric film 20 in the ultrasonic transducers 10 was stretched at a drawing ratio of 5 and annealed at 120 °C for 1 hour. The ultrasonic transducers 10, 200 were aligned and separated by a distance of 105 mm between adjacent ultrasonic transducers 10, 200. As illustrated in FIG. 4b, a top electrode 30 of each of the ultrasonic transducers 10, 200 was patterned into a comb-shaped electrode layer with four electrode fingers 31 having a periodicity of 3 mm, corresponding to a wavelength λ of the surface wave at about 1 MHz, according to the following equation:

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

where, λ is the wavelength of the surface wave, c is a velocity of the surface wave, and f is a frequency of the surface wave. Similar to the set-up illustrated in FIG. 1b, the block 90 is at least three times thicker (45 mm) than the wavelength λ of the surface wave (3 mm). The length L of each electrode finger of the comb electrode 30 was 7 mm, which is at least twice as long as the wavelength λ of 3 mm. Each ultrasonic transducer 10, 200 was oriented on the block 90 with the length direction of its electrode fingers 31 perpendicular to the surface wave propagation direction 80, as shown in FIG. 4b.

[0041] In this example, the time for a surface wave to propagate from one ultrasonic transducer 10, 200 to another 10, 200 was about 36 μ s. Using ultrasonic transducers 200 having PVDF piezoelectric films as both surface wave transmitter and receiver (FIG. 4a(a)), other unwanted wave modes were generated and detected as can be seen in FIG. 5a. In comparison, when using an ultrasonic transducer 200 having a PVDF piezoelectric film as a surface wave transmitter and an ultrasonic transducer 10 having a PLLA piezoelectric film 20 as a surface wave receiver (FIG. 4a(b)), the incident surface wave at about 36 μ s was clearly observed with similar amplitude while other unwanted wave modes are minimised (as can be seen in FIG. 5b). However, when ultrasonic transducers 10 having PLLA piezoelectric films 20 are used as the surface wave transmitter (FIGS. 4a(c) and 4a(d)), the ultrasonic signal amplitude is about 9 times lower (as can be seen in FIGS. 5c and 5d) compared to when ultrasonic transducers 200 having PVDF piezoelectric films are used as the surface wave transmitter (FIGS. 5a and 5b).

[0042] In conclusion, the ultrasonic transducers 10 having PLLA piezoelectric films 20 can be used as both surface wave transmitter and receiver and showed better performance in selectively generating and/or receiving surface wave compared to ultrasonic transducers 200 having PVDF piezoelectric films. The presently disclosed ultrasonic transducer 10 thus leverages on the pure shear mode 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 (unwanted) wave modes are generated and/or detected.

[0043] , The surface wave mode selectively generated by the ultrasonic transducer 10 having a PLLA piezoelectric film was clearly observed using a laser scanning vibrometer, as shown in FIG. 6b. The surface wave was generated with enhanced propagation directionality due to the molecular chain orientation 70 of the PLLA piezoelectric film at about 45 degrees from the propagation direction 80. In contrast, an ultrasonic transducer 200 having a PVDF piezoelectric film showed unclear direction of wave propagation despite use of a comb-shaped top or first electrode, as shown in FIG. 6a. Hence, the ultrasonic transducer 10 having a PLLA piezoelectric film 20 exhibits high directivity and selectivity as a surface wave transmitter and receiver, with its most significant advantage demonstrated when used as a surface wave receiver.

Example 3

[0044] This example demonstrates surface wave generation and detection using the flexible ultrasonic transducer 10 having a PLA piezoelectric film 20 on structures with simple and complex geometries, as shown in FIGS. 7a to 7d. The flexible ultrasonic transducer 10 generates and/or detects a surface wave propagating along the same surface of the structure to which the ultrasonic transducer is attached. For curved geometries, the flexible ultrasonic transducer 10 can be installed around the circumference of the structure with the length of the comb-shaped first electrode wrapping over the curved structure in the radial direction R, i.e., with the plurality of electrode fingers 31 aligned with a circumferential direction of the curvature, generating or detecting surface wave along an axial direction A of the structure that is perpendicular to the length direction L of the comb-shaped first electrode 30.

[0045] FIG. 8a shows an example where flexible ultrasonic transducers 10 were installed on a structure 90 comprising a 101.6 mm diameter stainless steel shaft for surface defect monitoring. An ultrasonic transducer 200 having a PVDF piezoelectric film was installed around a circumference of the structure 90 with the length of the comb electrode wrapping over the curved structure 90 in a radial direction to form rings with periodicity of 7 mm. This ring-shaped PVDF ultrasonic transducer 200 was used to generate surface waves at about 420 kHz along an axial direction of the shaft structure 90 that is perpendicular to the length direction of the comb electrode. This generated surface waves that travelled along the axial direction (long axis) of the shaft 90. Four flexible ultrasonic transducers 10 each having a PLLA piezoelectric film with comb electrodes 30 were installed around the shaft 90 facing different depths of

defects 93. For detecting surface waves, the PLLA ultrasonic transducers 10 were installed on the shaft 90 with PLLA molecular chain orientation 70 of about 45 degrees from the axial direction of the shaft 90. The generated surface waves R_i travelled directly from the PVDF ultrasonic transducer 200 to the PLLA ultrasonic transducer 10 with a time of arrival of about $25\mu s$, corresponding to the incident wave R_i shown in FIG. 8b. The generated surface waves were also reflected by an edge of the defect 93 as a defect-reflected wave R_r and arrived back at the PLLA ultrasonic transducer at about $70\mu s$. The generated surface wave also travelled from the PVDF ultrasonic transducer 200 to an edge of a groove 94 provided around the structure 90 and was reflected by the groove edge as a groove-reflected wave R_g to arrive at the PLLA ultrasonic transducer 10 at about $45\mu s$. The defect 93 was therefore detected by the PLLA ultrasonic transducer 10 when a reflection of the surface wave appeared in the ultrasonic signal output by the PLLA ultrasonic transducer 10.

[0046] Any reflection from structural irregularities in the signal output from the flexible ultrasonic transducer 10 is used to indicate the presence or development of a defect in the structure 90. An exemplary method is to analyse amplitudes of wave mode arriving at the surface wave receiver 10 by processing its output ultrasonic signals and obtaining its envelope (smooth curve outlining absolute extremes as in FIG. 8b). Reflection coefficients, C_r , were obtained from a ratio of amplitudes of the reflected wave, R_r , to amplitudes of the incident wave R_i as shown in the following equation:

$$C_r = \frac{R_r}{R_i}$$

[0047] The reflection coefficients C_r for different defect depths are shown in FIG. 8c. This coefficient allows for defect depth sizing. The advantages of this method for defect detection in the minimised loss of surface wave energy by use of ring transmitter that minimise wave spreading, and the flexibility of ultrasonic polymeric ultrasonic transducers that can be applied on curved surfaces with enhanced transfer of energy compared to flat ceramic ultrasonic transducers with limited contact area on curved surfaces.

Example 4

[0048] This example demonstrates surface wave detection on structures 90 using the flexible ultrasonic transducer 10 containing polylactic acid piezoelectric film 20 with comb-shaped electrode 30, wherein the surface wave is generated by different ultrasonic transducers. The surface wave can be generated by: an ultrasonic transducer 10 of the present invention having a piezoelectric film 20 containing polylactic acid and electrode layers 30, 40 (FIG. 9a), an ultrasonic transducer 200 having a piezoelectric film containing PVDF 220 and electrode layers

230 (FIG. 9b), a discrete ultrasonic transducer C10 having a ceramic piezoelectric layer C20 and an electrode C30 (FIG. 9c), an ultrasonic ceramic transducer C100 on an angle wedge WA (FIG. 9d), or a laser L10 (Figure 9e), and detected by another flexible ultrasonic transducer 10 of the present invention having a PLA piezoelectric film 20 and electrode layers 30, 40 mechanically coupled to the structure.

[0049] The electrical signals output from the ultrasonic transducers 10 acting as surface wave receivers may be used as an indicator of structural health. In some embodiments, this may be done by comparing the electrical signals to a predetermined baseline signal obtained from the structure 90 in a previous (e.g. pristine) condition, using a first ultrasonic transducer 10 as a surface wave generator and a second ultrasonic transducer 10 as a surface wave receiver, as shown in FIG. 10a, wherein a deviation from the baseline signal is used to indicate a change in the structure 90, such as presence or development of a defect D in the structure 90. In other embodiments, a single ultrasonic transducer 10 may be provided to generate and also detect the surface wave as shown in FIG. 10b, wherein any reflection 80R from structural irregularities observed in the electrical signals output by ultrasonic transducer 10 can be used to indicate the change in the structure 90, such as presence or development of a defect D in the structure 90.

[0050] From the above, it can be seen that an exemplary method (200) of structural health monitoring of a structure may comprise:

- (a) attaching a flexible ultrasonic transducer to a surface of the structure, the flexible ultrasonic transducer comprising: a flexible piezoelectric film made from polylactic acid and having a shear mode piezoelectric effect, the piezoelectric film having a molecular chain orientation at 35 to 55 degrees relative to a propagation direction of a surface wave to be generated on the structure, a first electrode provided on a first surface of the piezoelectric film, and a second electrode provided on a second surface of the piezoelectric film (210);
- (b) generating the surface wave on the structure, wherein propagation of the surface wave causes in-plane expansion of the structure along the propagation direction and in-plane contraction of the structure in a direction perpendicular to the propagation direction, thereby resulting in shear strain of the piezoelectric film that induces an electrical signal output from the first and second electrodes (120); and
- (c) processing the electrical signal to monitor the structural health of the structure (230).

[0051] The presently disclosed invention offers several advantages over conventional ultrasonic transducers made from piezoelectric ceramics or PVDF films:

- Improved selectivity and sensitivity: The 45-degree molecular chain orientation in the PLA film 20 enhances the detection and generation of surface waves, improving sensitivity of the ultrasonic transducer 10 to defects.
- No electrical poling: Unlike traditional piezoelectric ceramics, the PLA film 20 does not require electrical poling, eliminating the risk of performance degradation due to de-poling over time.
- Lightweight and flexible: The lightweight and flexible nature of the ultrasonic transducer allows it to conform to complex surfaces, making it highly versatile for use in a variety of applications.
- Cost-effective production: PLA is a low-cost material with excellent scalability for large-scale production, making this ultrasonic transducer 10 economically viable for widespread SHM applications.

[0052] While there has been described in the foregoing description exemplary embodiments of the present invention, it will be understood by those skilled in the technology concerned that many variations in details of design, construction and/or operation may be made without departing from the present invention. It will be appreciated that many further alterations, modifications and permutations of various aspects of the described embodiments are possible that fall within the spirit and scope of the claims.

Claims

1. A flexible ultrasonic transducer part comprising:
 - a flexible piezoelectric film made from polylactic acid and having a shear mode piezoelectric effect; and
 - a first electrode provided on a first surface of the piezoelectric film;wherein in use for monitoring structural health of a structure, a second electrode is provided on a second surface of the piezoelectric film to form an ultrasonic transducer that is attached to the structure such that a molecular chain orientation of the piezoelectric film is at 35 to 55 degrees relative to a propagation direction of a surface wave generated on the structure.
2. The flexible ultrasonic transducer part of claim 1, wherein in use, propagation of the surface wave causes in-plane expansion of the structure along the propagation direction and in-plane contraction of the structure in a direction perpendicular to the propagation direction, thereby resulting in shear strain of the piezoelectric film that induces an electrical signal output from the first and second electrodes for processing to monitor the structural health of the structure.
3. The flexible ultrasonic transducer part of claim 1 or claim 2, wherein when an electric field is applied to the piezoelectric film through the first and second electrodes, an in-plane strain is induced in the piezoelectric film, thereby generating the surface wave.
4. The flexible ultrasonic transducer part of any one of the preceding claims, wherein the first electrode comprises a comb-shaped electrode layer having a plurality of electrode fingers and wherein periodicity of the electrode fingers corresponds to a wavelength of the surface wave.
5. The flexible ultrasonic transducer part of claim 4, wherein length of each electrode finger is provided at 35 to 55 degrees to the molecular chain orientation of the piezoelectric film.
6. The flexible ultrasonic transducer part of claim 4 or claim 5, wherein the comb-shaped electrode layer comprises at least three electrode fingers, wherein length of each electrode finger is at least twice a wavelength of the surface wave.
7. The flexible ultrasonic transducer part of any one of claims 4 to 6, wherein in use, each electrode finger is provided perpendicular to the propagation direction of the surface wave.

8. The flexible ultrasonic transducer of any one of claims 4 to 7, wherein when the surface of the structure has a curvature, in use, the ultrasonic transducer is attached to the surface such that length of each electrode finger is aligned with a circumferential direction of the curvature.
9. The flexible ultrasonic transducer part of any one of the preceding claims, wherein the polylactic acid is one of: poly(L-lactic acid) and poly(D-lactic acid).
10. The flexible ultrasonic transducer part of any one of the preceding claims, wherein the second electrode is made of a layer of a conductive epoxy that serves as an electrode and as a bonding agent to bond the ultrasonic transducer onto the surface of the structure.
11. The flexible ultrasonic transducer of any one of the preceding claims, wherein wavelength of the surface wave is one-third or less of a thickness of the structure.
12. The flexible ultrasonic transducer part of any one of the preceding claims, wherein in use, the surface wave interacts with any defect within a depth of one wavelength of the surface wave from the surface of the structure.
13. The flexible ultrasonic transducer part of any one of the preceding claims, wherein in use, the molecular chain orientation of the piezoelectric film is at 45 degrees relative to the propagation direction of the surface wave generated on the structure.
14. A flexible ultrasonic transducer comprising:
the ultrasonic transducer part of any one of claims 1 to 13; and
the second electrode provided on the second surface of the piezoelectric film.
15. A method of structural health monitoring of a structure, the method comprising the steps of:
 - (a) attaching a flexible ultrasonic transducer to a surface of the structure, the flexible ultrasonic transducer comprising: a flexible piezoelectric film made from polylactic acid and having a shear mode piezoelectric effect, the piezoelectric film having a molecular chain orientation at 35 to 55 degrees relative to a propagation direction of a surface wave to be generated on the structure, a first electrode provided on a first surface of the piezoelectric film, and a second electrode provided on a second surface of the piezoelectric film;
 - (b) generating the surface wave on the structure, wherein propagation of the surface

wave causes in-plane expansion of the structure along the propagation direction and in-plane contraction of the structure in a direction perpendicular to the propagation direction, thereby resulting in shear strain of the piezoelectric film that induces an electrical signal output from the first and second electrodes; and

(c) processing the electrical signal to monitor the structural health of the structure.

16. The method of claim 15, wherein step (b) comprises applying an electric field to the piezoelectric film through the first and second electrodes to induce an in-plane strain in the piezoelectric film, thereby generating the surface wave.

17. The method of claim 15, wherein step (b) is performed using one of: the flexible ultrasonic transducer, an ultrasonic transducer having a piezoelectric film made of polyvinylidene fluoride provided between two electrodes, a discrete ultrasonic transducer, and a laser.

18. The method of any one of claims 15 to 17, wherein step (c) comprises comparing the electrical signal with a baseline signal obtained from the structure in a previous condition, wherein deviation of the electrical signal from the baseline signal indicates at least one of: presence of a defect in the structure and development of a defect in the structure.

19. The method of any one of claims 15 to 17, wherein the electrical signal is indicative of a structural irregularity in the structure that gave rise to a reflected surface wave detected by the ultrasonic transducer.

20. The method of any one of claims 15 to 19, wherein wavelength of the surface wave is one-third or less of a thickness of the structure.

21. The method of any one of claims 15 to 20, wherein the piezoelectric film has a molecular chain orientation at 45 degrees relative to the propagation direction of the surface wave to be generated on the structure

22. A method of manufacturing the ultrasonic transducer part of any one of claims 1 to 13, comprising the steps of:

- (a) stretching a polylactic acid film at a drawing ratio ranging from 3 to 7 at a temperature ranging from 80 °C to 120 °C to form the flexible piezoelectric film; and
- (b) depositing the first electrode on the flexible piezoelectric film.