

ULTRASONIC TRANSDUCER FOR STRUCTURAL HEALTH MONITORING, METHOD
FOR PRODUCING ULTRASONIC TRANSDUCER FOR STRUCTURAL HEALTH
MONITORING AND METHOD FOR STRUCTURAL HEALTH MONITORING

Field of the Invention

5 The present invention relates in general to structural health monitoring (SHM) and more particularly to an ultrasonic transducer for structural health monitoring, a method for producing an ultrasonic transducer for structural health monitoring and a method for structural health monitoring.

Background of the Invention

10 Structural health monitoring (SHM) is an emerging technology to directly assess the integrity of structures by using sensors integrated to a structure. SHM using ultrasonic guided waves is advantageous for inspecting large structures with a small number of ultrasonic transducers.

 Conventional shear mode piezoelectric transducers are however typically made
15 of bulky and fragile piezoelectric ceramics. The piezoelectric ceramics require complicated processing (dicing and electrical poling with high voltage along certain crystal direction) for fabrication into shear mode transducers.

 In view of the foregoing, it would be desirable to provide a low-cost ultrasonic
transducer for structural health monitoring and a simple method for producing such an
20 ultrasonic transducer.

Summary of the Invention

 Accordingly, in a first aspect, the present invention provides an ultrasonic
transducer for structural health monitoring. The ultrasonic transducer includes a
piezoelectric film, a first electrode on a first surface of the piezoelectric film, and a
25 second electrode on a second surface of the piezoelectric film. The piezoelectric film
includes polylactic acid having aligned molecular chain orientation.

 In a second aspect, the present invention provides a method for producing an
ultrasonic transducer for structural health monitoring. The method includes: dissolving

polylactic acid in a solvent to form a polylactic acid solution; forming a piezoelectric film from the polylactic acid solution, the polylactic acid in the piezoelectric film having aligned molecular chain orientation; forming a first electrode on a first surface of the piezoelectric film; and forming a second electrode on a second surface of the
5 piezoelectric film.

In a third aspect, the present invention provides a method for structural health monitoring. The method includes: mechanically coupling at least one ultrasonic transducer according to the first aspect to a structure; generating a guided shear wave propagating through the structure; detecting the guided shear wave; and comparing an
10 ultrasonic signal of the detected guided shear wave to a baseline signal of the structure in a reference condition to determine presence of a defect in the structure.

Other aspects and advantages of the invention will become apparent from the following detailed description, taken in conjunction with the accompanying drawings, illustrating by way of example the principles of the invention.

15 Brief Description of the Drawings

Embodiments of the invention will now be described, by way of example only, with reference to the accompanying drawings, in which:

FIG. 1 is a schematic diagram illustrating a first ultrasonic transducer and a second ultrasonic transducer for structural health monitoring in accordance with an
20 embodiment of the present invention;

FIG. 2 is a schematic flow diagram illustrating a method for producing an ultrasonic transducer for structural health monitoring in accordance with an embodiment of the present invention;

FIG. 3 is a schematic flow diagram illustrating a method for structural health
25 monitoring in accordance with an embodiment of the present invention;

FIG. 4A is a photograph of a poly(L-lactic acid) (PLLA) film prepared by mechanical stretching;

FIG. 4B are X-ray diffraction (XRD) patterns of a PLLA film without mechanical stretching and a PLLA film stretched to a draw ratio of 5;

FIG. 4C is a schematic diagram illustrating an experimental test setup for evaluating use of the stretched PLLA film to make an ultrasonic transducer in
5 accordance with an embodiment of the present invention;

FIG. 4D are dispersion curves of a 1.6 mm-thick aluminum plate used in the experimental test setup of FIG. 4C at different modes of ultrasonic waves;

FIG. 4E are time-frequency two-dimensional (2D) graphs of the ultrasonic signal detected by the ultrasonic transducer of FIG. 4C, overlapped with the dispersion curves
10 of the aluminum plate of FIG. 4D;

FIG. 4F is a graph illustrating changes in ultrasonic signals (SH0 mode shear horizontal wave) observed before and after creating a defect in the aluminum plate of FIG. 4C with different sizes;

FIGS. 5A and 5B are scanning electron microscope (SEM) images of a PLLA film
15 in the form of a fiber mat at different magnifications;

FIG. 5C is a schematic diagram illustrating use of an ultrasonic transducer made of a PLLA film in the form of a fiber mat in accordance with an embodiment of the present invention for generating or detecting a shear horizontal wave;

FIG. 5D is a graph of an ultrasonic signal in the case of using the ultrasonic
20 transducer made of the PLLA film of FIG. 5C for detecting the shear horizontal wave;

FIG. 5E is a graph of an ultrasonic signal in the case of using the ultrasonic transducer made of the PLLA film of FIG. 5C for generating the shear horizontal wave;

FIG. 5F is a graph comparing signals from the ultrasonic transducer of FIG. 5C as a receiver of a shear horizontal wave when the aluminum plate of FIG. 5C
25 mechanically coupled with the ultrasonic transducer was in air and immersed in water;

FIG. 5G is a graph comparing signals obtained from an ultrasonic transducer made of a piezoelectric poly(vinylidene fluoride) (PVDF) film and bonded to an aluminum plate in air and immersed in water;

FIGS. 5H through 5K are graphs of ultrasonic signals obtained from an ultrasonic
5 transducer made of a PLLA film in the form of fiber mat for detecting shear horizontal waves in an aluminum plate with defects of different sizes when the structure was in air and water;

FIG. 5L is a graph comparing DI values calculated based on ultrasonic wave signals obtained when the structure was in air and in water;

10 FIG. 5M is a schematic diagram illustrating a PLLA film in the form of fiber mat bonded on an aluminum plate with a square-shaped silver electrode deposited on the fiber mat to form an ultrasonic transducer in accordance with an embodiment of the present invention;

FIG. 6A is a schematic top plan view of a method of fabricating a PLLA film in
15 the form of fiber mat by centrifugal electro-spinning using a rotating collector;

FIG. 6B is a schematic top plan view of an ultrasonic transducer in accordance with an embodiment of the present invention made of the polylactic acid film of FIG. 6A for generating and detecting omni-directional guided shear wave in a structure; and

FIG. 7 is a schematic diagram illustrating a method of monitoring integrity of a
20 tubular structure by using ultrasonic transducers made of a PLLA film and electrodes for generating and/or detecting a torsional wave in the structure in accordance with an embodiment of the present invention.

Detailed Description of Exemplary Embodiments

The detailed description set forth below in connection with the appended
25 drawings is intended as a description of presently preferred embodiments of the invention, and is not intended to represent the only forms in which the present invention may be practiced. It is to be understood that the same or equivalent functions may be

accomplished by different embodiments that are intended to be encompassed within the scope of the invention.

The term "piezoelectric film" as used herein refers to a thin layer of a substance that is able to generate electricity when subjected to mechanical stress.

- 5 The term "aligned molecular chain orientation" as used herein refers to an arrangement of linear polymer molecules such that chains of molecules are aligned along a common direction or plane to obtain anisotropic properties, the anisotropic properties varying depending on a direction of measurement.

- 10 The term "shear wave" as used herein refers to a transverse wave that occurs in an elastic medium when the medium is subjected to a periodic shear strain produced by a force. Accordingly, the term "guided shear wave" as used herein refers to a shear wave propagating along a structure while guided by boundaries of the structure with particle motion direction being parallel to a surface of the structure and perpendicular to propagation direction of the shear wave.

- 15 The term "stretching" as used herein refers to making a material or substance longer or wider by pulling. Accordingly, the term "mechanically stretching" as used herein refers to a process in which a material is subjected to a tensile force, causing the material to elongate and align its molecular chain orientation in a direction of applied force.

- 20 The term "draw ratio" as used herein refers to a dimensional increase in the direction of the draw. For example, a draw ratio of two (2) refers to an increase in length of twice an original length and a draw ratio of five (5) means an increase in length of five (5) times the original length,

- 25 The term "coupling" as used herein refers to physically attaching one object to another. Accordingly, the term "mechanically coupling" as used herein refers to bonding of a material to a structure through adhesion and application of a mechanical force through strain at an interface between the material and the structure.

The term "about" as used herein refers to both numbers in a range of numerals and is also used to indicate that a value includes the standard deviation of error for the

device or method being employed to determine the value. The term "about" as used herein can allow for a degree of variability in a value or range, for example, within 10%, within 5%, or within 1 % of a stated value or of a stated limit of a range.

Referring now to FIG. 1, a first ultrasonic transducer 10 and a second ultrasonic
5 transducer 12 for structural health monitoring are shown. Each of the first and second ultrasonic transducers 10 and 12 includes a piezoelectric film 14, a first electrode 16 on a first surface of the piezoelectric film 14 and a second electrode (not shown) on a second surface of the piezoelectric film 14. The piezoelectric film 14 includes polylactic acid having aligned molecular chain orientation.

10 An isomer of the polylactic acid may be used to form the piezoelectric film 14 of the first and second ultrasonic transducers 10 and 12. Accordingly, the polylactic acid may be selected from a group consisting of poly(L-lactic acid) (PLLA) and poly(D-lactic acid) (PDLA).

The piezoelectric film 14 contains polylactic acid with aligned molecular chain
15 orientation. The aligned molecular chain orientation of the polylactic acid may be in parallel with or perpendicular to a propagation direction of a guided shear wave 18 to be generated or detected. In one or more alternative embodiments, the piezoelectric film 14 may be of a circular shape and the aligned molecular chain orientation of the polylactic acid may be in a circumferential direction of the piezoelectric film 14. When the
20 piezoelectric film 14 containing polylactic acid is circular in shape with molecular chain orientation in the circumferential direction of the the piezoelectric film 14, the ultrasonic transducer may generate or detect an omni-directional shear horizontal wave.

The second electrode is provided on the second surface of the piezoelectric film 14 at an opposite side of the piezoelectric film 14 from the first electrode 16. At least one
25 of the first electrode 16 and the second electrode may be a layer having a comb-shaped pattern. In the embodiment shown, the first electrodes 16 are comb-shaped. Fingers or teeth 20 of the comb-shaped electrode layer 16 may have a periodicity corresponding to a wavelength of the guided shear ultrasonic wave 18. The material of the first electrode 16 and the second electrode may be silver, carbon or gold. In one or more alternative
30 embodiments, the first electrode 16 and/or the second electrode may be of other shapes such as, for example, circular or square-shaped.

Having described elements of the first and second ultrasonic transducers 10 and 12, a method for producing the first and second ultrasonic transducers 10 and 12 for structural health monitoring will now be described below with reference to FIG. 2.

Referring now to FIG. 2, a method 200 for producing an ultrasonic transducer for structural health monitoring is shown. The method 200 begins at step 202 by dissolving polylactic acid in a solvent to form a polylactic acid solution. The solvent may be chloroform, tetrahydrofuran or dioxane and the polylactic acid solution may be prepared by dissolving the polylactic acid in the solvent.

At step 204, a piezoelectric film is formed from the polylactic acid solution, the polylactic acid in the piezoelectric film having aligned molecular chain orientation. The polylactic acid film with piezoelectricity may be fabricated by mechanically stretching a polylactic acid film fabricated from chemical solution. Alternatively, the polylactic acid film with piezoelectricity may be fabricated in the form of fiber mat by electro-spinning the polylactic acid solution with a rotating spinneret or rotating collector.

More particularly, in the mechanical stretching embodiment, the polylactic acid film may be fabricated from the polylactic acid solution by casting, spin-coating or spray coating. In such an embodiment, the step 204 of forming the piezoelectric film from the polylactic acid solution may include mechanically stretching the piezoelectric film to a predetermined number of times an original length of the piezoelectric film. The predetermined number of times the original length of the piezoelectric film may be between about 2 and about 7 times. The piezoelectric film may be mechanically stretched at a temperature of between about 120 degrees Celsius (°C) and about 155 °C. In one or more embodiments, the temperature at which the piezoelectric film is mechanically stretched may be between about 130 °C and about 155 °C. The polylactic acid film may be mechanically stretched at an elevated temperature of 120 °C or above (preferably between about 130 °C and about 155 °C) to a few times of its original length (preferably 2 to 6 times) with aligned molecular chain orientation.

In the electro-spinning embodiment, the step 204 of forming the piezoelectric film from the polylactic acid solution may include applying an electric field to a tip of a spinneret containing the polylactic acid solution, ejecting the polylactic acid solution from the spinneret, the ejected polylactic acid solution passing through the electric field, and

depositing the ejected polylactic acid solution on a collector to form a polylactic acid fibre. More particularly, fiber of polylactic acid may be fabricated by applying a strong electric field to the tip of the spinneret containing the polylactic acid solution. A continuous fine jet of the polylactic acid solution may be ejected from the spinneret and moved through
5 the electric field for deposition on the collector to form the fiber of polylactic acid. In such an embodiment, the step 204 of forming the piezoelectric film from the polylactic acid solution may further include spinning the polylactic acid fibre using the spinneret or the collector to form a polylactic acid fibre mat, the spinneret or the collector being rotatable. More particularly, the polylactic acid film in the form of fiber mat with aligned molecular
10 chain orientation may be formed by spinning the polylactic acid fiber using a rotating spinneret or collecting the fiber using a rotating collector, followed by annealing at an elevated temperature of 120 °C for 1 hour.

Accordingly, the piezoelectric film containing polylactic acid with molecular chain alignment may be induced by mechanical stretching of a polylactic acid film at elevated
15 temperature. Alternatively, the piezoelectric film containing polylactic acid with molecular chain alignment may be in the form of polylactic acid fiber mat through fabrication by electro-spinning in which either the spinneret or the collector is rotated.

At step 206, a first electrode is formed on a first surface of the piezoelectric film and at step 208, a second electrode is formed on a second surface of the piezoelectric
20 film. The first and second electrodes may be formed by depositing electrode layers on the piezoelectric film containing polylactic acid via spraying, printing or vacuum deposition. Accordingly, a first electrode layer may be provided on a first surface of the piezoelectric film and a second electrode layer may be provided on a second surface of the piezoelectric film at an opposite side from the first electrode layer.

25 Referring again to FIG. 1, use of the first and second ultrasonic transducers 10 and 12 for structural health monitoring is shown. In use as shown in FIG. 1, the first and second ultrasonic transducers 10 and 12 are mechanically coupled to a structure 22 to monitor the integrity of the structure 22, the first ultrasonic transducer 10 being operable to generate a guided shear wave 18 propagating in the structure 22 and the second
30 ultrasonic transducer 12 being operable to detect the guided shear wave 18 propagating in the structure 22. The piezoelectric film 14 generates and/or detects the guided shear wave 18 propagating in the structure 22, indicating a health condition of the structure 22.

The molecular chain orientation in the piezoelectric film 14 may be parallel with the plane of a surface of the structure 22, and perpendicular to or parallel with the propagation direction of the guided shear wave 18 to be generated and detected.

Each of the first and second ultrasonic transducers 10 and 12 may be
5 mechanically coupled to the structure 22 by bonding onto a surface of the structure 22 or embedding in the structure 22 using an adhesive (not shown). The structure 22 may be mechanically coupled with the piezoelectric film 14 by adhesive.

The ultrasonic guided shear wave 18 is a type of wave propagating along the structure 22 while guided by boundaries of the structure 22, with particle motion
10 direction being parallel to a surface of the structure and perpendicular to propagation direction of the guided shear wave 18. Although illustrated as being generated and detected by the first and second ultrasonic transducers 10 and 12 in the embodiment shown, the guided shear wave 18 may alternatively be generated or detected by other modalities such as, for example, a laser or a discrete transducer, in combination with an
15 ultrasonic transducer made of piezoelectric film containing polylactic acid and electrode layers in alternative embodiments.

A strain in the piezoelectric film 14 of the first ultrasonic transducer 10 may be induced by an electric field applied through the first electrode 16 and the second electrode to generate the guided shear wave 18 propagating in the structure 22. More
20 particularly, as electrical excitation signal may be applied across a thickness of the piezoelectric film 14 of the first ultrasonic transducer 10. The electric field applied through the first electrode 16 and the second electrode induces a strain in the piezoelectric film 14 to generate the guided shear wave 18 propagating in the structure 22.

The guided shear wave 18 in the structure 22 may be detected from an electrical
25 signal output from the first electrode 16 and the second electrode of the piezoelectric film 14 of the second ultrasonic transducer 12. The signal of receiving the guided shear wave 18 may be obtained by measuring charge generated from the first electrode 16 and the second electrode at top and bottom surfaces of the piezoelectric film 14 of the second ultrasonic transducer 12. The signal from the second ultrasonic transducer 12 is used as
30 an indicator of structural health. The signal may be compared to a predetermined baseline signal from the structure 22 in a previous condition and a deviation from the

baseline signal is used to indicate a change in the structure 22 such as, for example, presence or development of a defect in the structure 22.

The structure 22 to be monitored may be metallic, plastic or a composite. In the embodiment shown, the structure 22 is a flat, plate structure. When the structure 22 is flat, the guided shear wave 18 generated and detected in the plate structure 22 by the first and second ultrasonic transducers 10 and 12 may be a shear horizontal wave. In tubular structures, the guided shear wave 18 generated and detected in a tubular structure may be a torsional wave or in torsional wave mode.

Referring now to FIG. 3, a method 300 for structural health monitoring is shown. The method 300 begins at step 302 by mechanically coupling at least one ultrasonic transducer to a structure. The at least one ultrasonic transducer on the structure may be operable to generate or detect guided shear wave in the structure.

At step 304, a guided shear wave propagating through the structure is generated and the guided shear wave is detected at step 306. The at least one ultrasonic transducer may be operable to generate and/or detect a guided shear wave propagating in the structure. For example, the guided shear wave may be generated by a laser, a discrete transducer, or an ultrasonic transducer made of piezoelectric film containing polylactic acid and electrode layers mechanically coupled to the structure, and detected by another ultrasonic transducer made of piezoelectric film containing polylactic acid and electrode layers mechanically coupled to the structure. Alternatively, the guided shear wave may be generated by an ultrasonic transducer made of piezoelectric film containing polylactic acid and electrode layers mechanically coupled to the structure, and detected by a laser, a discrete transducer, or another ultrasonic transducer made of piezoelectric film containing polylactic acid and electrode layers mechanically coupled to the structure.

In one or more embodiments where the guided shear wave is generated by the at least one ultrasonic transducer, the step 304 of generating the guided shear wave propagating through the structure may include applying an electric field across the first and second electrodes of a first ultrasonic transducer to induce a strain in the piezoelectric film of the first ultrasonic transducer to generate the guided shear wave.

In one or more embodiments where the guided shear wave is generated by the at least one ultrasonic transducer, the step 306 of detecting the guided shear wave may include measuring an electrical signal output from the first and second electrodes of a second ultrasonic transducer.

- 5 At step 308, an ultrasonic signal of the detected guided shear wave is compared to a baseline signal of the structure in a reference condition to determine presence of a defect in the structure. In one or more embodiments, a signal output from the ultrasonic transducer may be compared to a predetermined baseline signal from the structure in a previous condition and a deviation from the baseline signal may be used to indicate a
10 change in the structure such as, for example, presence or development of a defect in the structure.

Examples

Example 1

- An example of the integrity of a structure being monitored using an ultrasonic
15 transducer comprising a piezoelectric film containing polylactic acid (PLLA) with molecular chain orientation obtained by mechanically stretching the PLLA film at an elevated temperature will now be described.

- A 10 wt% PLLA solution was prepared by dissolving PLLA in chloroform in a silicone oil bath at 50 °C. The solution was cast on a smooth glass substrate by using a
20 doctor blade. The glass substrate was then put on a hotplate at 50 °C to evaporate the solvent. The resulting PLLA film was peeled off the glass and cut into the desired size for the following stretching step. The films were cut into 3 cm x 5 cm rectangles. Two sides of the rectangular film were clamped, leaving a length of 3 cm to be stretched. A hot air gun was used to heat up the film for 10 seconds at 150 °C prior to stretching. The
25 films were stretched in different draw ratios of from 2 to 7. The hot air gun continuously heated up the film until 10 seconds after the required draw ratio was reached. The film was then removed from the clamps and cut into the desired size for characterization and transducer fabrication.

- Referring now to FIG. 4A, a photograph of a poly(L-lactic acid) (PLLA) film
30 prepared by mechanical stretching is shown.

Referring now to FIG. 4B, X-ray diffraction (XRD) patterns of a PLLA film without mechanical stretching and a PLLA film stretched to a draw ratio of 5 are shown. As can be seen from FIG. 4B, the PLLA film without stretching is in an amorphous phase, while the PLLA film at the draw ratio of 5 showed high crystallinity with crystalline orientation in the (200) and (110) directions. The XRD pattern of the stretched PLLA film shows that the stretched PLLA film is in a β -form (beta-form) crystal structure which is the piezoelectric phase of PLLA.

The stretched PLLA film was used to make ultrasonic transducers and the feasibility of using the ultrasonic transducers to detect a surface-breaking crack on a structure was evaluated.

Referring now to FIG. 4C, a schematic diagram illustrating an experimental test setup 400 for evaluating use of a stretched PLLA film 402 to make an ultrasonic transducer 404 in accordance with an embodiment of the present invention is shown. A 1.6 mm-thick aluminum plate 406 was used. The integrity of the aluminum plate 406 was monitored using ultrasonic transducers 404 made of the PLLA film 402 by mechanical stretching to detect shear horizontal waves 408 (a type of guided shear horizontal waves in plate structures).

Referring now to FIG. 4D, dispersion curves of the 1.6 mm-thick aluminum plate at different modes of the ultrasonic waves are shown. Zero mode shear horizontal wave (SH0) was selected as this mode is nondispersive — its group velocity does not change with frequency as can be seen from the corresponding dispersion curve SH0 in FIG. 4D. In addition, SH0 is more sensitive to defects that are oriented along its wave propagation direction due to its in-plane particle displacement motion.

Referring again to FIG. 4C, a piece of the PLLA film 402 with an electrode pattern 410 of 2.7 mm x 2.7 mm was bonded to the 1.6 mm-thick aluminum plate 406 by epoxy with the molecular chain aligned along the propagation direction of the SH0 mode wave to act as receiver of the ultrasonic wave 408. The signal for detecting the shear horizontal wave 408 was obtained by measuring the charge generated from electrodes 410 at top and bottom surfaces of the PLLA film 402. A discrete shear mode transducer probe 412 was used for generation of the ultrasonic wave 408 at a distance of 60 mm away from the receiver 404.

Referring now to FIG. 4E, time-frequency two-dimensional (2D) graphs of the ultrasonic signal detected by the ultrasonic transducer 404, overlapped with the dispersion curve of the aluminum plate 406, are shown. According to the spectrogram shown in FIG. 4E, the experimental results showed that SH0, SH1 and SH2 modes of
5 shear horizontal wave were able to be detected by the ultrasonic transducer 404 made of the PLLA film 402.

Referring again to FIG. 4C, a horizontal crack 414 was simulated with a thin notch with increasing depth, followed by a through-hole at the location of the notch.

Referring now to FIG. 4F, SH0 mode was monitored and ultrasonic signals were
10 collected at different defect states as shown. As can be seen from FIG. 4F, changes in the ultrasonic signal (SH0 mode shear horizontal wave) was observed before and after creating the defect 414 with different sizes. More particularly, signal amplitude was highest at pristine state, decreased with increasing defect depth, and finally disappeared as the shear horizontal wave 408 was blocked by the through-hole defect 414.

15 *Example 2*

In this example, the piezoelectric film containing PLLA is in the form of a fiber mat fabricated by electro-spinning a PLLA solution to a rotating collector. During the electrospinning process, a strong electric field was applied to the tip of a spinneret containing the PLLA solution. A continuous fine jet of solution was ejected from the
20 spinneret and moved through the electric field to be deposited on the collector. A constant feeding rate of 0.5 mL/h and an electric field strength of 1.5 kV/cm were used.

Referring now to FIGS. 5A and 5B, scanning electron microscope (SEM) images of the PLLA film in the form of fiber mat at different magnifications are shown. As can be seen from FIGS. 5A and 5B, the PLLA fibers with diameter of a few micrometers were
25 highly aligned and densely packed to form a mat.

Referring now to FIG. 5C, use of an ultrasonic transducer 500 made of a PLLA film 502 in the form of a fiber mat for generating or detecting a shear horizontal wave 504 is shown. To evaluate the performance of the ultrasonic transducer 500 made of the PLLA film 502 in the form of fiber mat in generating and detecting a guided shear
30 wave in a structure, the ultrasonic transducer 500 was bonded to an aluminum plate 506

and tested with a shear mode transducer probe 508. The ultrasonic transducer 500 was designed to specifically generate or detect the shear horizontal wave 504 (SH0 mode) at 500 kHz with a wavelength of 6.2 mm. An electrode 510 of the ultrasonic transducer 500 is of a comb-shaped pattern with the periodicity of the electrode comb fingers being
5 the same as the wavelength of the shear horizontal wave 504 (i.e. 6.2 mm). The molecular chain orientation direction was the same as the propagation direction of the SH0 mode wave 504.

Referring now to FIG. 5D, an ultrasonic signal in the case of using the ultrasonic transducer 500 made of the PLLA film 502 for detecting the shear horizontal wave 504
10 is shown. An electrical excitation signal (3 cycles of sine wave, 100 Vpp, 500 kHz) was applied on the shear mode transducer probe 508 and the SH0 mode wave 504 was detected by the ultrasonic transducer 500.

Referring now to FIG. 5E, an ultrasonic signal in the case of using the ultrasonic transducer 500 made of the PLLA film 502 for generating the shear horizontal wave
15 504 is shown. The same electrical excitation signal was applied in the thickness direction of the PLLA film 502 to generate the SH0 mode wave 504 and the wave was detected by the shear mode transducer probe 508.

Both the shaded areas in FIGS. 5D and 5E indicate the wave pack corresponding to the signal of the SH0 mode wave 504.

20 To demonstrate the performance of the ultrasonic transducer 500 for monitoring underwater structures, the aluminum plate 506 mechanically coupled to the ultrasonic transducer 500 as described above was immersed in water and the ultrasonic signal was compared to the signal when the aluminum plate 506 was in air.

Referring now to FIG. 5F, a comparison of the signals from the ultrasonic
25 transducer 500 as a receiver of the shear horizontal wave 504 when the aluminum plate 506 mechanically coupled with the ultrasonic transducer 500 was in air and immersed in water is shown. The ultrasonic transducer 500 was made of the PLLA film 502 in the form of fiber mat and was bonded to the aluminum plate 506. The wave packet of the signal corresponding to the selected mode of the guided shear wave 504 is shaded in
30 FIG. 5F. As can be seen from FIG. 5F, there was no change in the amplitude and time

of arrival of the signal corresponding to the SH0 mode wave 504 before and after the aluminum plate 506 was immersed in water.

Referring now to FIG. 5G, a comparison of signals obtained from an ultrasonic transducer made of a piezoelectric poly(vinylidene fluoride) (PVDF) film and bonded to an aluminum plate in air and immersed in water is shown. In this comparative example, the ultrasonic transducer is for generating and detecting a Lamb wave rather than a shear horizontal wave. As can be seen from FIG. 5G and in contrast to FIG. 5F, substantial changes in both amplitude and time of arrival were observed for the Lamb wave ultrasonic transducer made of the piezoelectric PVDF film before and after the aluminum plate was immersed in water.

To study the performance of the ultrasonic transducer made of the PLLA film in the form of fiber mat for structural health monitoring (SHM) of an underwater structure, an ultrasonic transducer was bonded to a 1.6 mm-thick aluminum plate and ultrasonic signals were obtained when the structure was in air and immersed in water. The ultrasonic transducer was designed with a comb-shaped electrode for specifically detecting SH0 mode of a shear horizontal wave at 500 kHz. A shear-mode piezoelectric ceramic at a distance of 100 mm from the ultrasonic transducer made of the PLLA film was used as a transmitter of the SH0 wave. Circular-shaped defects with a diameter of 3 mm was machined to different depths of from 0.3 mm to 1.6 mm (i.e. through hole), 50 mm away from the transmitter.

Referring now to FIGS. 5H through 5K, ultrasonic signals obtained from the ultrasonic transducer made of the PLLA film in the form of fiber mat for detecting shear horizontal waves in the aluminum plate with defects of different sizes when the structure was in air and water are shown. More particularly, FIG. 5H shows ultrasonic signals obtained from defects of different depths in air, FIG. 5I is a zoomed-in view of the ultrasonic signals in the circled portion shown in FIG. 5H, FIG. 5J shows ultrasonic signals obtained from defects of different depths in water, and FIG. 5K is a zoomed-in view of the ultrasonic signals in the circled portion shown in FIG. 5J.

Damage index (DI) was calculated in order to correlate the change in ultrasonic signals with the defects of different sizes. The DI values were calculated based on a comparison of signal amplitude obtained in a pristine stage and that obtained with a

defect of a particular size. The calculation of damage index DI was based on a residual signal energy method, which measures an energy ratio between different signals using the formula below:

$$DI = \frac{\int_{t1}^{t2} x^2 dt - \int_{t1}^{t2} y^2 dt}{\int_{t1}^{t2} x^2 dt}$$

- 5 where DI represents damage index; x represents signal amplitude in the pristine stage; y represents signal amplitude with a defect of a particular size; and $t1$ and $t2$ represent the start and end of a selected period.

- Referring now to FIG. 5L, a comparison of DI values calculated based on ultrasonic wave signals obtained when the structure was in air and in water is shown.
- 10 Signals were obtained from the ultrasonic transducer made of the PLLA film in the form of fiber mat for detecting shear horizontal wave in the aluminum plate with defects of different sizes. By comparing the DI values as shown in FIG. 5L, it can be seen that the sensitivity of detecting the defects when the structure was in water is comparable to that when the structure was in air. This demonstrates the advantages of the ultrasonic
- 15 transducer made of the PLLA film for underwater SHM.

- Referring now to FIG. 5M, a PLLA film 520 in the form of fiber mat was bonded on an aluminum plate 522 and a square-shaped silver electrode 524 (2.7 mm x 2.7 mm) was deposited on the fiber mat 520 to form an ultrasonic transducer 526 as shown to study the directivity of the ultrasonic transducer 526 as a receiver of guided shear wave
- 20 528. The guided shear wave or shear horizontal wave 528 was generated by a discrete shear mode probe 530 at different angles as shown in FIG. 5M. The signals from the ultrasonic transducer 526 with the guided shear wave 528 at different incident angles were compared. By comparing the signals from the ultrasonic transducer 526 with the shear horizontal wave 528 at different incident angles, it can be seen that the ultrasonic
- 25 transducer 526 is sensitive to the guided shear wave 528 when the incident angle is 0° , 90° , 180° and 270° (that is, when molecular chains are aligned either in parallel with or perpendicular to the propagation direction of the ultrasonic wave in the structure).

Example 3

Referring now to FIG. 6A, a method of fabricating a PLLA film 600 in the form of fiber mat by centrifugal electro-spinning using a rotating collector 602 is shown. In the centrifugal electro-spinning setup, either the collector 602 or a spinneret 604 is rotatable.

- 5 The resulting PLLA film 600 is circular in shape with molecular chain oriented in a circumferential direction of the PLLA film 600.

Referring now to FIG. 6B, a shear mode ultrasonic transducer 606 made of the polylactic acid film 600 obtained in FIG. 6A for generating and detecting omni-directional guided shear wave 608 in a structure 610 is shown. The PLLA film 600 with a circular-
10 shaped electrode 612 is bonded to the plate structure 610 by an adhesive to form the ultrasonic transducer 606 coupled to the structure 610. As can be seen from FIG. 6B, the ultrasonic transducer 606 may be used to generate or detect the omni-directional shear horizontal wave 608.

Example 4

- 15 Referring now to FIG. 7, a method of monitoring integrity of a tubular structure 700 by using ultrasonic transducers 702 and 704 made of a PLLA film 706 and electrodes 708 and 710 for generating and/or detecting torsional wave 712 (a type of guided shear wave in tubular structures) in the structure 700 is shown. The ultrasonic transducers 702 and 704 made of the PLLA containing piezoelectric film 704 and the
20 electrode layers 708 and 710 are mechanically coupled to the tubular structure 700. The ultrasonic transducers 702 and 704 are designed to effectively generate or detect the torsional wave 712. As shown in FIG. 7, the molecular chain orientation is along the circumferential direction or axial direction of the tubular structure 700 and the electrode layer 708 is in a circular pattern oriented along the circumferential direction of the tubular
25 structure 700. The electrode layer 708 of the ultrasonic transducer 702 for generating the torsional wave 712 may be circular in shape for effectively generating the torsional wave 712, while the electrode layer 710 of the ultrasonic transducer 704 for detecting the torsional wave 712 may be in the form of an array along the circumferential direction of the tubular structure 700. By using these transducers 702 and 704 in a pitch-catch
30 mode, both severity and location of a defect in the tubular structure 700 can be detected.

The experimental results demonstrate that piezoelectricity-induced deformation arising from the piezoelectric effect of certain isomers of polylactic acid can be effectively coupled to a structure to generate guided shear wave, detect the guided shear wave in the structure and indicate structural integrity of the structure.

- 5 The experimental results also demonstrate significant advantages of using guided shear waves generated and/or detected by ultrasonic transducers in accordance with embodiments of the present invention comprising a piezoelectric film containing polylactic acid for structural health monitoring (SHM) without substantial influence by liquid presence. As demonstrated by the experimental results, when the structure to be
10 monitored is in a surrounding media such as a liquid, the guided shear wave propagating in the structure and indication of the health condition of the structure are not substantially affected by the surrounding media.

As is evident from the foregoing discussion, the present invention provides an ultrasonic transducer for structural health monitoring, a method for producing the
15 ultrasonic transducer and a method for structural health monitoring with guided shear wave by integrating at least one ultrasonic transducer made of piezoelectric film containing polylactic acid and electrode layers to a structure to be monitored. Advantageously, the ultrasonic transducer of the present invention may be made of low-cost piezoelectric polymer and the method for producing the ultrasonic transducer is
20 scalable for large scale production. Further advantageously, the ultrasonic transducer of the present invention has piezoelectricity properties without requiring electrical poling processing. The flexible and low-profile ultrasonic transducers of the present invention may also be advantageously applied to structures with complex shapes. The method for structural health monitoring of the present invention advantageously requires simpler
25 signal interpretation by using non-dispersive, zero-mode guided shear wave, experiences inherently low attenuation and minimizes environmental effects for structures in contact with liquid or solid.

The ultrasonic transducer for structural health monitoring and the method for structural health monitoring may be applied to monitor integrity of pipes for transporting
30 chemicals, underground structures, etc.

While preferred embodiments of the invention have been described, it will be clear that the invention is not limited to the described embodiments only. Numerous modifications, changes, variations, substitutions and equivalents will be apparent to those skilled in the art without departing from the scope of the invention as described in
5 the claims.

Further, unless the context clearly requires otherwise, throughout the description and the claims, the words "comprise", "comprising" and the like are to be construed in an inclusive as opposed to an exclusive or exhaustive sense; that is to say, in the sense of "including, but not limited to".

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CLAIMS

1. An ultrasonic transducer for structural health monitoring, comprising:
a piezoelectric film comprising polylactic acid having aligned molecular chain
5 orientation;
a first electrode on a first surface of the piezoelectric film; and
a second electrode on a second surface of the piezoelectric film.
2. The ultrasonic transducer of claim 1, wherein the polylactic acid is selected from
10 a group consisting of poly(L-lactic acid) (PLLA) and poly(D-lactic acid) (PDLA).
3. The ultrasonic transducer of claim 1 or 2, wherein the aligned molecular chain
orientation of the polylactic acid is in parallel with or perpendicular to a propagation
direction of a guided shear wave to be generated or detected.
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4. The ultrasonic transducer of claim 1 or 2, wherein the piezoelectric film is of a
circular shape and the aligned molecular chain orientation of the polylactic acid is in a
circumferential direction of the piezoelectric film.
- 20 5. The ultrasonic transducer of any one of the preceding claims, wherein at least
one of the first and second electrodes is a layer having a comb-shaped pattern.
6. The ultrasonic transducer of claim 5, wherein fingers of the comb-shaped
electrode layer have a periodicity corresponding to a wavelength of the guided shear
25 wave.
7. A method for producing an ultrasonic transducer for structural health monitoring,
comprising:
dissolving polylactic acid in a solvent to form a polylactic acid solution;
30 forming a piezoelectric film from the polylactic acid solution, the polylactic acid in
the piezoelectric film having aligned molecular chain orientation;
forming a first electrode on a first surface of the piezoelectric film; and
forming a second electrode on a second surface of the piezoelectric film.

8. The method for producing the ultrasonic transducer for structural health monitoring according to claim 7, wherein the step of forming the piezoelectric film from the polylactic acid solution comprises:

mechanically stretching the piezoelectric film to a predetermined number of times
5 an original length of the piezoelectric film.

9. The method for producing the ultrasonic transducer for structural health monitoring according to claim 8, wherein the predetermined number of times the original length of the piezoelectric film is between about 2 and about 7 times.

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10. The method for producing the ultrasonic transducer for structural health monitoring according to claim 8 or 9, wherein the piezoelectric film is mechanically stretched at a temperature of between about 120 degrees Celsius (°C) and about 155 °C.

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11. The method for producing the ultrasonic transducer for structural health monitoring according to claim 10, wherein the temperature at which the piezoelectric film is mechanically stretched is between about 130 °C and about 155 °C.

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12. The method for producing the ultrasonic transducer for structural health monitoring according to claim 7, wherein the step of forming the piezoelectric film from the polylactic acid solution comprises:

applying an electric field to a tip of a spinneret containing the polylactic acid solution;

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ejecting the polylactic acid solution from the spinneret, the ejected polylactic acid solution passing through the electric field; and

depositing the ejected polylactic acid solution on a collector to form a polylactic acid fibre.

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13. The method for producing the ultrasonic transducer for structural health monitoring according to claim 12, wherein the step of forming the piezoelectric film from the polylactic acid solution further comprises:

spinning the polylactic acid fibre using the spinneret or the collector to form a polylactic acid fibre mat, wherein the spinneret or the collector is rotatable.

14. A method for structural health monitoring, comprising:
mechanically coupling at least one ultrasonic transducer of any one of claims 1 to
6 to a structure;
- 5 generating a guided shear wave propagating through the structure;
detecting the guided shear wave; and
comparing an ultrasonic signal of the detected guided shear wave to a baseline
signal of the structure in a reference condition to determine presence of a defect in the
structure.
- 10
15. The method for structural health monitoring according to claim 14, wherein the
step of generating the guided shear wave propagating through the structure comprises:
applying an electric field across the first and second electrodes of a first
ultrasonic transducer to induce a strain in the piezoelectric film of the first ultrasonic
15 transducer to generate the guided shear wave.
16. The method for structural health monitoring according to claim 14 or 15, wherein
the step of detecting the guided shear wave comprises:
measuring an electrical signal output from the first and second electrodes of a
20 second ultrasonic transducer.