

ACOUSTIC TRANSDUCERS FOR STRUCTURAL HEALTH MONITORING AND METHODS OF FABRICATION

TECHNICAL FIELD

[0001] This invention is related to transducers and a method of fabricating the transducers. More specifically, this invention is related to direct-write acoustic transducers and the method of direct-writing piezoelectric materials and electrodes in the fabrication of the acoustic transducers for structural health monitoring.

BACKGROUND

[0002] Direct-writing (DW) often denotes a group of processes comprising precise deposition and patterning of functional and/or structural materials directly on structural parts or structural assemblies in prior defined locations. These materials are deposited and processed in-situ on the structure surface, and are directly patterned to a shape used in the final components. Based on the mechanisms of material handling and transfer, the direct-write technologies can be categorized into six major groups: spray-based method, laser-based method, ink dispensing-based method, tip-based writing methods and screen printing/dip-coating-based method. Aerosol spray is a popular direct-write method for industry applications. Commercially, aerosol spray techniques are extensively used in painting industry such as surface finishing of automotive and architecture parts. However, the application of aerosol-spray in the deposition of functional coatings for forming electronic devices has not yet been given much attention. Inkjet printing on the other hand is a droplet-based direct-write technique, involving the formation of a sequence of pico-litre volume of liquid material droplets deposited in well-defined patterns. The liquid materials are called inks, which can be made from solutions or suspensions of functional materials. After deposition, the ink becomes solidified by the evaporation of solvent, by chemical changes in the ink or by cooling. Subsequent processing steps such as high temperature treatment or sintering may also be involved.

[0003] Producing sensors from direct-write process is a promising method for forming sensors and sensor networks on a structure, and the as-fabricated sensor network can be used for structural health monitoring (SHM). SHM comprises damage detection and structural integrity characterization of engineering structures, allowing examination of structures in such a

manner that the integrity of the structure can be determined without disturbing a present condition. SHM can be realized based on different physical principles, among them, ultrasonic SHM is a fast growing area as it has the advantages of being a low cost and fast testing process as well as being able to test various materials such as metals, ceramics, polymers, and composites, as compared to SHM methods based on magnetic testing, eddy current testing, and radiographic testing. As such, ultrasonic SHM with lowered cost and improved reliability has been sought after for many different applications.

[0004] One recent trend in ultrasonic SHM is in utilizing embedded sensor networks to monitor a structural integrity condition. In particular, this technique or technology is used in structural health monitoring of aeronautic structures and civil structures to maintain a high degree of safety and reliability in these structures. Traditionally, sensor networks used in these areas are constructed by assembling discrete sensors on the structure. The installation of this network often involves a large number of sensors, and as a result, the weight of the sensors, cable connections, and associated equipment used in a traditional sensor network pose significant problems such as high global cost, poor reliability, and interference with the working condition of the structure under monitoring.

[0005] One possible way to achieve desired low cost, improved reliability and reduced interference are through the integration of low-profile direct-write sensors in the manufacturing process of the structural parts and structural assemblies. Despite the promise of direct-write techniques in SHM, state of the art direct-write sensors for SHM are mainly based on passive operation, such as piezoresistive materials and thermal couples. These sensors can only sense changes of environmental parameters such as strain and temperature through responsive parameter changes at locations of the sensors.

[0006] Moreover, even for transducers which are fabricated with direct-write techniques, only the electrodes are patterned by the direct-write techniques; the piezoelectric materials used, such as piezoelectric ceramic plates or piezoelectric polymer films, in these devices are incorporated separately. As a result, these as-fabricated transducers require subsequent bonding or assembling of the piezoelectric ceramic plates or piezoelectric polymer films on the structures to be monitored.

[0007] In addition, the bonding of such transducers which have been fabricated on flat substrates is challenging to conform to the curved surface of structures to be monitored. Furthermore, adhesive used to install or bond the transducers often has a damping effect such that the coupling between the acoustic transducer and the structure is not effective. Additionally, bonding of a large number of transducers causes many serious concerns in practical implementations, such as quality inconsistency, degraded reliability, and unacceptable high cost. In particular, aeronautic applications are weight-sensitive, and are often exposed to fluid flow. High profile and large weight of bonded and installed devices for structural health monitoring can profoundly affect air flow around them, resulting in diminished efficiency, longevity and economy.

[0008] Therefore, there is a need for a method of fabricating light-weight transducers by directly depositing and patterning acoustic active materials and electrodes on prior defined locations on the surface of structural parts or structural assemblies without the extra step of bonding, and incorporating said transducers in-situ in the manufacturing process of engineering structures for structural health monitoring.

[0009] Furthermore, other desirable features and characteristics will become apparent from the subsequent detailed description and the appended claims, taken in conjunction with the accompanying drawings and this background of the disclosure.

SUMMARY

[0010] According to a first aspect of the invention, a method of fabricating an acoustic transducer for generation and/or detection of acoustic waves for structural health monitoring is described, the method comprising in-situ direct-writing of a piezoelectric material to create a piezoelectric layer on a structure to be monitored, wherein the structure is conductive and the structure functions as a bottom electrode; and in-situ direct-writing of a conductive electrode on top of the piezoelectric layer to act as a top electrode.

[0011] According to a second aspect of the invention, a system with acoustic transducer for structural health monitoring is described, the system comprising a structure to be monitored having one or more of a flat surface and a curved surface thereon, wherein the structure is conductive and the structure functions as a bottom electrode; a layer of piezoelectric material

on top of a portion of the structure; and a layer of electrode on top of the piezoelectric material layer, wherein the layer of electrode is patterned, and wherein the layer of piezoelectric material and the layer of electrode form an acoustic transducer for generating and detecting acoustic waves in the structure to be monitored for identifying defects in the structure to be monitored.

[0012] According to a third aspect of the invention, a method for structural health monitoring is described, the method comprising the step of forming a plurality of acoustic transducers on a structure to be monitored, wherein the structure is conductive and the structure functions as a bottom electrode, wherein each of the plurality of acoustic transducers comprises a layer of piezoelectric material direct-written on top of the structure, and a layer of electrode direct-written on top of the piezoelectric material layer wherein at least a first one and a second one of the plurality of acoustic transducers are formed across a portion of the structure, and wherein the first one and the second one of the plurality of acoustic transducers are configured to generate and detect an acoustic wave in the portion of the structure to obtain structural health information.

BRIEF DESCRIPTION OF THE DRAWINGS

[0013] The accompanying figures, where like reference numerals refer to identical or functionally similar elements throughout the separate views and which together with the detailed description below are incorporated in and form part of the specification, serve to illustrate various embodiments, by way of example only, and to explain various principles and advantages in accordance with a present embodiment.

[0014] FIG. 1 depicts a flow chart of a method of fabricating transducers with direct-write techniques in accordance with a present embodiment.

[0015] FIG. 2 depicts a cross-sectional planar view of a plate structure bearing direct-write acoustic transducers in accordance with the present embodiment.

[0016] FIG. 3, comprising FIGs. 3A and 3B, depicts top planar views of various shadow masks used for patterning by aerosol spray in accordance with the present embodiment, wherein FIG. 3A depicts the top planar view of the shadow mask for deposition of

piezoelectric material and FIG. 3B depicts the top planar view of the shadow mask for deposition of annular array comb electrodes.

[0017] FIG. 4 illustrates a direct-write piezoelectric polymer transducer array on an aluminum plate completed by the aerosol spray technique in accordance with the present embodiment.

[0018] FIG. 5 illustrates four direct-write piezoelectric acoustic transducers on a metal plate completed by the inkjet printing technique in accordance with the present embodiment.

[0019] FIG. 6 depicts a cross sectional planar view of a direct-write acoustic transducer with a bottom electrode in accordance with the present embodiment.

[0020] FIG. 7 depicts a cross sectional planar view of a direct-write acoustic transducer with a protective layer in accordance with the present embodiment.

[0021] FIG. 8 depicts a cross sectional planar view of two direct-write acoustic transducers on a curved structure to be monitored in accordance with the present embodiment.

[0022] FIG. 9, comprising FIGs. 9A and 9B, depicts direct-write acoustic transducers on a surface of a structure to be monitored with a defect in the middle of the structure in accordance with the present embodiment, wherein FIG. 9A depicts a top planar view of the direct-write transducers on the structure and FIG. 9B depicts a cross-sectional planar view of the two direct-write acoustic transducers along the dotted line AA' of FIG. 9A with acoustic waves being emitted from the transducer acting as an actuator and detected by the other transducer acting as a sensor.

[0023] FIG. 10, comprising FIGs. 10A and 10B, depicts graphs of dispersion curves of Lamb waves for an aluminum plate with a thickness of 1.27 mm in accordance with the present embodiment, wherein FIG. 10A depicts the graph of the dispersion curve of phase velocities versus frequency and FIG. 10B depicts the graph of the dispersion curve of group velocities versus frequency.

[0024] FIG. 11, comprising FIGs. 11A and 11B, depicts illustrations of finite element simulation for a model of direct-write acoustic transducers on a surface of a structure to be monitored with a defect in the middle of the structure in accordance with the present embodiment, wherein FIG. 11A depicts a top planar view of the model and FIG. 11B depicts a graph of a result of the simulation for the model.

[0025] FIG. 12 depicts a graph of an input electrical signal to an actuator of a 13-cycle Hanning windowed tone burst signal with a central frequency of 1.3 MHz and an amplitude of 10 V in accordance with the present embodiment.

[0026] FIG. 13, comprising FIGs. 13A to 13C, depicts graphs of simulated results from a sensor under different crack depths or damage conditions in accordance with the present embodiment, wherein FIG. 13A depicts a graph of electrical signals from a sensor, FIG. 13B depicts a graph of a Fast Fourier Transformation (FFT) of a first wave packet in time domain for the results in FIG. 13A, and FIG. 13C depicts a graph of voltage amplitudes of the 1.3 MHz component of the electrical signals from a sensor for the different crack depths.

[0027] FIG. 14, comprising FIGs. 14A to 14C, depicts graphs of simulated results from a sensor under different defect conditions with added mass in accordance with the present embodiment, wherein FIG. 14A depicts a graph of electrical signals from a sensor, FIG. 14B depicts a graph of a Fast Fourier Transformation (FFT) of a first wave packet in time domain for the results in FIG. 14A, and FIG. 14C depicts a graph of voltage amplitudes of the 1.3 MHz component of the electrical signals from a sensor for the different defect conditions with added mass.

[0028] FIG. 15 depicts a graph of simulated electrical signals from a sensor for defects of different nature (i.e. a crack or an added mass) for comparison in accordance with the present embodiment.

[0029] FIG. 16, comprising FIGs. 16A and 16B, depicts graphs of material properties of a piezoelectric P(VDF/TrFE) polymer layer deposited by the aerosol spray method used in direct-write transducers fabricated on an aluminum plate in accordance with the present embodiment, wherein FIG. 16A depicts a graph of dielectric constant versus frequency and FIG. 16B depicts a graph of a polarization-voltage hysteresis loop of the piezoelectric P(VDF/TrFE) polymer layer.

[0030] FIG. 17, illustrates a section of a patterned annular array comb top electrode with an area analyzed using a laser scanning vibrometer (LSV) with an excitation alternating current (AC) signal in accordance with the present embodiment.

[0031] FIG. 18, comprising FIGs. 18A to 18C, depicts graphs of surface displacement of the area analyzed with the LSV as shown in FIG. 17 in accordance with the present embodiment, wherein FIG. 18A corresponds to a three-dimensional representation of a displacement profile, FIG. 18B corresponds to a two-dimensional representation of the displacement profile, and FIG. 18C corresponds to a three-dimensional representation of the displacement profile when the piezoelectric material is excited with an excitation AC signal of an opposite sign as compared to FIG. 18A.

[0032] FIG. 19, comprising FIGs. 19A and 19B, depicts illustrations of an experimental set-up for defect testing with four direct-write acoustic transducers on a surface of a structure under monitoring in accordance with the present embodiment, wherein FIG. 19A depicts a top planar view of the set-up and FIG. 19B illustrates the set-up with a metal bar/mass attached to the centre of a surface of the structure under monitoring.

[0033] And FIG. 20, comprising FIG. 20A and FIG. 20B, depicts graphs of experimental results for a defect of added mass in accordance with the present embodiment, wherein FIG. 20A depicts a graph of a detected bandpass filtered electrical signal, consisting of three wave packets, at a sensor for the defect of added mass with a thickness of 1.0 mm, and FIG. 20B depicts a graph of amplitudes for the 1.3 MHz component of second wave packets of the detected signals for different defects of added mass.

[0034] Skilled artisans will appreciate that elements in the figures are illustrated for simplicity and clarity and have not necessarily been depicted to scale. For example, the dimensions of some of the elements in the block diagrams or steps in the flowcharts may be exaggerated in respect to other elements to help improve understanding of the present embodiment.

DETAILED DESCRIPTION

[0035] The following detailed description is merely exemplary in nature and is not intended to limit the invention or the application and uses of the invention. Furthermore, there is no intention to be bound by any theory presented in the preceding background of the invention or the following detailed description. It is the intent of the preferred embodiments to disclose a method for fabricating light-weight transducers by directly depositing and patterning acoustic

active materials and electrodes on prior defined locations on surfaces of structural parts or structural assemblies without the extra step of bonding, and incorporating said transducers in-situ in the manufacturing process of engineering structures for structural health monitoring. The method in accordance with a present embodiment advantageously implements direct-write acoustic transducers thereby completely eliminating any glue used to bond the transducers on the structure to be monitored, thus enhancing acoustic coupling between the transducers and the structure. Similarly, the direct-write technique allows the transducers to be produced on curved structures with better conformity, thereby providing for an improved interface between the transducers and the structures, improved signal to noise ratio, reduced interference as well as enhanced adherence of the transducers to the surface of the structure under monitoring.

[0036] The method in accordance with the present embodiment provides improved scalability as compared to those in the prior art. The individual installation process for implementing a large number of discrete transducers is replaced by an in-situ batch fabrication of low-profile direct-write transducers for integration in manufacturing processes of structural parts and structural assemblies, thereby improving consistency and reliability while reducing the global cost of the structural parts and structural assemblies. In addition, the reduced weight and profile of the direct-write transducers over prior art installed discrete transducers are highly valued in aeronautic applications which are weight-sensitive and often involve extensive exposure to fluid flow.

[0037] Referring to FIG. 1, a flow chart of the method of fabricating transducers with a direct-write technique in accordance with the present embodiment is depicted. Direct-write refers to a process of directly depositing and patterning materials at prior defined locations on structural parts or structural assemblies. Initially at step 101, precursor ink solution for a piezoelectric layer and ink solution for a conductive electrode layers are prepared. Preferably, the precursor ink solution for the piezoelectric layer comprises a polymer. Preferably, the polymer comprises P(VDF/TrFE). Preferably, P(VDF/TrFE) solutions for the precursor ink were prepared by dissolving P(VDF/TrFE) pellets or powder in a solvent composed of dimethylformamide (DMF) and acetone. At step 102, preferably the surface of a structure to be monitored is treated. Preferably, the structure to be monitored comprises a plate structure, on which the piezoelectric ultrasonic transducers will be direct-written. Preferably, the plate structure is made of metal such as aluminum, titanium or steel. Preferably the surface of the

plate structure is treated if the surface roughness is too high before deposition of the piezoelectric layer and the electrode layer. This is done to ensure that there is no contamination between the surface of the structure and the direct-write layers in order to achieve satisfactory adhesion of the direct-write transducers on the structures to be monitored. At step 103, the piezoelectric layer is deposited on the surface of the structure to be monitored by direct-writing. Different aspects of direct-writing in accordance with the present embodiment will become apparent in the following examples. For example, in-situ direct-writing of the piezoelectric material may include in-situ spraying of the precursor solution of the piezoelectric material. At step 104, the electrode layer is deposited on the piezoelectric layer by direct-writing as a top electrode. Preferably the material for the top electrode is a metal. As an example, the top electrode deposited and patterned is of an annular array comb shape such that concentric arcs are formed with one common trace connecting all the arcs. Preferably the electrodes are located at the periphery of a defined area on the plate structure to be monitored. At step 105, preferably a protective layer is deposited on the electrode layer. In the present embodiment, the structure to be monitored is conductive and the structure functions as a bottom electrode.

[0038] The method depicted in FIG. 1 with the implementation of direct-write acoustic transducers completely eliminates any glue used to bond the transducers on the structure to be monitored since both the piezoelectric layer and the electrode layer can be deposited and patterned directly on the surface of the structure. This enhances the acoustic coupling between the transducers and the structure. Moreover, the method is also compatible with in-situ integration of manufacturing processes for structural parts and structural assemblies to be monitored, thereby improving consistency and reliability while reducing the global cost of the structural parts and structural assemblies. In addition, the direct-write transducers fabricated by this method with polymer piezoelectric materials are highly valuable in aeronautic and other applications due to their reduced weight and profile over the traditionally installed discrete transducers.

[0039] Referring to FIG.2, a cross-sectional planar view of a plate structure bearing direct-write acoustic transducers in accordance with the present embodiment is depicted. The present embodiment of the acoustic transducer comprises patterned electrodes 203a-f deposited on top of a patterned piezoelectric layer 202, which in turn is deposited on the surface of a structure to be monitored 201. When the structure to be monitored 201 is conductive, it can act as a

bottom electrode for the transducer. Preferably, the piezoelectric layer 202 can be electrically poled to exhibit piezoelectric properties.

Example 1

[0040] Referring to FIG. 3, top planar views of various shadow masks used for patterning by aerosol spray in accordance with the present embodiment are depicted. In accordance with the present embodiment, an aerosol spray technique for direct-writing of transducers was used. P(VDF/TrFE) precursor solutions with concentrations of 1 to 15 wt%, and more preferably 3 to 5 wt% were prepared for the aerosol spray in accordance with step 101. The solutions were then transferred to the container of an airbrush for aerosol spray coating on aluminum plates. To achieve the desired direct-written pattern for the piezoelectric layer, the piezoelectric precursor ink solution was aerosol sprayed onto structures to be monitored directly with the use of steel shadow/patterned masks 301 in accordance with step 103. FIG. 3A depicts a top planar view of a shadow mask 301 for deposition of patterned piezoelectric films by aerosol spray. The shadow mask contains empty or hole regions 302a-d for the deposition of the P(VDF/TrFE) piezoelectric layer. Preferably, the aerosol-sprayed P(VDF/TrFE) films on the aluminum plate are smooth, dense, and uniform. Preferably, the thickness of the films can be controlled from a few micrometers (μm) to tens of micrometers by varying the deposition time. Preferably, the P(VDF/TrFE) films have a thickness of about 20 μm . The electrode layer was then deposited by evaporation such as electron-beam (E-beam) evaporation with the aid of a shadow mask 303 in accordance with step 104. FIG. 3B depicts a top planar view of the shadow mask 303 for deposition of the electrode by E-beam evaporation. In accordance with the present embodiment, the shadow mask is made of stainless steel and contains empty or hole regions for deposition of the electrodes. Preferably, the shape of the empty or hole regions 304 is in the pattern of an annular array comb. Preferably, the electrode material is Al or gold. Preferably, the Al or gold electrode layer has a thickness of 200 nm or more. Those skilled in the art would appreciate that while Al or gold is mentioned, other conductive materials can be used.

[0041] Referring to FIG. 4, an illustration of a direct-write transducer array on a surface of a structure to be monitored 401 completed by the aerosol spray technique in accordance with the present embodiment is depicted. Preferably, the structure to be monitored is an aluminum

plate. The piezoelectric material 402a-d deposited is P(VDF/TrFE), and the electrodes 403a-d are made up of gold.

Example 2

[0042] Referring to FIG. 5, an illustration of four direct-write acoustic transducers on a surface of a structure to be monitored 501 completed by the inkjet printing technique in accordance with the present embodiment is depicted. Both piezoelectric layers 502a-d and electrode layers 503a-d were prepared by the inkjet printing process. The precursor ink for forming the patterned piezoelectric layer and the conductive ink for forming the patterned conductive electrode layers were deposited onto the structure to be monitored with an inkjet printer without the use of any mask. The piezoelectric precursor ink used in this case was similar to the P(VDF/TrFE) solution utilized in Example 1, while the conductive inks used may comprise silver-containing solution, colloidal suspension of silver nanoparticles, organometallic compounds in solution, and conductive polymers. Various sintering techniques such as thermal sintering, electrical sintering, photonic sintering, and microwave sintering inks may be used for solidification of the conductive ink after deposition. Limited by the thermal stability of the piezoelectric polymer P(VDF/TrFE) used in accordance with the present embodiment, the conductive ink used was a silver nanoparticle colloidal suspension conductive ink which can be thermally sintered at 120 °C. The piezoelectric film pattern and the electrode pattern were generated by software such as AutoCAD, which were subsequently saved in a bitmap file. An aluminum plate was loaded in the inkjet printer and fan-shaped piezoelectric layers 502a-d were direct-written substantially at corners of the plate according to the prior defined bitmap file. The plate with the deposited P(VDF/TrFE) layers was then baked at 120 °C to solidify the polymer layer before loading it into the inkjet printer again to write the top electrodes 503a-d with the silver nanoparticle colloidal suspension conductive ink on top of the piezoelectric layer. The top electrodes 503a-d were direct-written with the prior defined annular array comb pattern and were placed substantially at the plate corners with a spanning angle substantially at 90 degrees. Subsequently, the plate with the direct-write piezoelectric acoustic transducers was again baked at 120 °C for 1 hour to solidify the deposited silver nanoparticles to form the top electrodes. During the whole inkjet printing process, resolution of dots per inch (DPI) was set at 20/cm, with a drop spacing of 40 μm.

Example 3

[0043] Referring to FIG. 6, a cross sectional planar view of a direct-write acoustic transducer 601 with a bottom electrode 602 in accordance with the present embodiment is depicted. In the situation where the structure to be monitored 605 is made of non-conductive materials (for example ceramics such as alumina or zirconia, or polymers) or if there is an insulation coating on a conductive structure under monitoring, the bottom electrode 602 is needed. The bottom electrode 602 can be deposited by direct writing through the evaporation or the inkjet printing process, as described in Example 1 and Example 2 respectively, prior to the deposition of a piezoelectric layer 603 and top electrodes 604a-c. According to the present embodiment, the direct-written bottom electrode is deposited intermediate between the structure to be monitored and the piezoelectric layer. Alternately, it can be deposited by a screen printing, a painting, or a spraying process.

Example 4

[0044] Referring to FIG. 7, a cross sectional planar view of a direct-write acoustic transducer 701 with a protective layer 702 is depicted. Preferably, the protective layer 702 is an insulating material. Preferably the insulation material is polyimide (PI) or poly(methyl methacrylate) (PMMA). Preferably, the protective layer deposited over the top electrode protects the transducers from contamination and moisture to avoid electrical shorting and to improve operational stability and reliability.

Example 5

[0045] Referring to FIG. 8, a cross sectional view 801 of two direct-write acoustic transducers 803a-b on a curved structure to be monitored 802 in accordance with the present embodiment is depicted. Lamb wave 804 can propagate in curved plates. Aerosol spray or inkjet printing techniques have the ability to deposit solutions or suspensions to form coatings with conformity to the curved structure to be monitored 802. In accordance with the present embodiment, direct-write acoustic transducers described in Examples 1 to 4 can be direct-written on the curved structure to be monitored 802. This ensures that the piezoelectric layer of the acoustic transducers deposited on the surface of the structure conforms to the contour of the structure. This has the advantage of providing for a better interface between the

transducers and the structures, improved signal to noise ratio, reduced interference, as well as enhanced adherence of the transducers to the surface of the structure to be monitored.

[0046] FIG. 9A depicts a top planar view 901 of four direct-write acoustic transducers on the surface of a structure to be monitored with a defect 904 in the middle of the structure in accordance with the present embodiment. Each of the four annular array comb electrodes 903a-d of the transducers deposited on patterned piezoelectric layers 902a-d is deployed or positioned substantially at a corner of a portion of the structure to be monitored with a spanning angle facing away from the corner. Preferably, the spanning angle is substantially at 90 degrees. The electrodes 903a-d at each corner are composed of six concentric arcs, with one common electrode trace connecting all the arcs. The electrodes may be further connected to electrical testing equipment. FIG. 9B depicts a cross sectional planar view of two direct-write acoustic transducers along the dotted line AA' as shown in FIG. 9A, with acoustic waves 908a-b emitting from an actuator 906a and being detected at a sensor 906b in the structure to be monitored 907. When the transducer is operating as an actuator, a voltage is applied between its top electrode and its bottom electrode to stress the piezoelectric film and thereby generate ultrasonic waves in the structure to be monitored through the converse piezoelectric effect. Preferably, a narrow bandwidth windowed tone burst voltage is applied as the diagnostic exciting signal to prevent wave dispersion. In another mode where the transducer is operating as a sensor, its piezoelectric layer generates electrical output in response to an ultrasonic wave passing through it by the piezoelectric effect. The generation and detection of acoustic waves by acoustic transducers on the structure to be monitored realize the function of monitoring in structural health monitoring (SHM) applications.

[0047] Among different types of ultrasonic waves, Lamb waves have improved applicability for SHM. Lamb waves are a type of guided waves, which exist in a structure with parallel free boundaries and can be regarded as a combination of longitudinal waves and shear vertical waves. Lamb waves have the advantages of being able to travel long distances, being able to investigate the entire thickness of the plate they travel in, and being able to inspect large coated structures. Lamb waves also have the advantage of low energy consumption and, as a result, great cost-effectiveness. For a given plate with a thickness h , there exists a finite number of propagation Lamb modes specified by their phase velocities at an ultrasonic frequency f . A complete description of Lamb wave propagation characteristics in structures is normally given in the form of a set of dispersion curves. Each curve represents a specific

mode, illustrating the mode's phase velocity as a function of its frequency. Generally, the Lamb waves can be divided into two categories: **A** mode (antisymmetric modes) and **S** mode (symmetric modes). For **S** modes, the Lamb waves across the thickness of a structure are symmetric for displacement u , while for **A** modes, the Lamb waves across the thickness of the structure are antisymmetric for u . The theoretical expression of the dispersion curves for **S** modes is:

$$\frac{\tan(qh)}{\tan(ph)} = -\frac{4k^2pq}{(q^2-k^2)^2} \quad (1)$$

while that for **A** modes is:

$$\frac{\tan(qh)}{\tan(ph)} = -\frac{(q^2-k^2)^2}{4k^2pq} \quad (2)$$

in which $p^2 = \frac{\omega^2}{c_L^2} - k^2$, $q^2 = \frac{\omega^2}{c_T^2} - k^2$, $k = \frac{\omega}{c_p}$; k is the wave number; c_L is the velocity of longitudinal mode; c_T is the velocity of transverse mode; c_p is the phase velocity; and ω is the angular frequency of the Lamb wave. The relationships of c_p and ω as shown in the above equations give the dispersion curves.

[0048] In accordance with the present embodiment, the structure to be monitored is an aluminum plate with a dimension of $100 \times 100 \times 1.27 \text{ mm}^3$. Referring to FIG. 10, comprising FIGs. 10A and 10B, graphs of dispersion curves of Lamb waves for the aluminum plate with a thickness of 1.27 mm in accordance with the present embodiment are depicted, wherein FIG. 10A depicts the graph of the dispersion curve of phase velocities versus frequency and FIG. 10B depicts the graph of the dispersion curve of group velocities versus frequency. Generally, a suitable Lamb mode for a specific SHM task can be identified from the dispersion curves. In particular, a suitable Lamb mode for SHM should have the characteristics of low-dispersion, low attenuation, high sensitivity, easy excitability, and good detectability. The basic modes S_0 and A_0 are normally used in practice. The selection of a certain Lamb mode can be achieved through the design of an electrode. For example, annular array comb electrodes with a period equal to the wavelength of the desired Lamb mode are adopted to achieve the desired guided wave mode in structures. Here, the period is a distance between each arc of the annular array comb electrodes, and it corresponds to an excitation frequency of a mode of the Lamb mode ultrasonic wave in the piezoelectric material. Particularly, the annular array comb electrodes in accordance with the present embodiment can effectively select A_0 mode and can generate omni-directional waves in the structure to be monitored. By comparison, the mode selection

performance for an annular array comb electrode is much better than a circular electrode or a comb electrode, as this pattern allows the overall networking and wirings to be thinner and thus less intrusive in the host structure. For example, in accordance with the present embodiment of the dispersion curves as shown in FIG. 10A, the A_0 mode has a phase velocity $c_p = 2.6$ km/s and a wavelength of 2.0 mm when an excitation frequency is $f = 1.3$ MHz. As a result, annular array comb electrodes with an electrode period of 2.0 mm were used to selectively excite the A_0 mode in the structure to be monitored. In general, the periodic distance of the annular array comb electrode is designed to correspond to the wavelength of the desired Lamb mode which in turn is determined by the dimension and properties of the structure to be monitored.

[0049] Thus, here a system for acoustic transducer structural health monitoring is described. The system for acoustic transducer structural health monitoring comprises a structure to be monitored having one or more of a flat surface and a curved surface thereon; a layer of piezoelectric material on top of a portion of the structure; and a layer of electrode on top of the piezoelectric material layer, where the layer of electrode is patterned, for example, in the form of an annular array comb such that the concentric arcs are formed with one common trace connecting all the arcs, and where the layer of piezoelectric material and the layer of electrode form an acoustic transducer for generating and detecting acoustic waves in the structure to be monitored, the acoustic waves, for example, comprising a Lamb mode ultrasonic wave for identifying defects in the structure to be monitored.

[0050] Referring to FIG. 11, comprising FIGs. 11A and 11B, illustrations of finite element simulation for a model of direct-write acoustic transducers on a surface of a structure under monitoring with a defect in the middle of the structure in accordance with the present embodiment are depicted, wherein FIG. 11A depicts a top planar view of the model and FIG. 11B depicts a graph of a result of the simulation for the model. Finite element simulations using commercial available ANSYS software (version 15.0) were conducted to evaluate the performance of the ultrasonic transducers for detection of damage or defects on the plate structure with a transducer array similar to that shown in FIGs. 9A and 9B. In operation, one transducer is used as an actuator to generate a Lamb wave in the plate while the transducer located at the other end in a diagonal direction is used as a sensor to receive the Lamb wave. The electrical signals from the sensor, also known as sensor signals, are then compared and evaluated under different defect conditions. In the current example, simulations were carried

out with a two-dimensional model. The model included an actuator located at one end with a sensor located at the other end. When ultrasonic waves generated by the actuator propagate towards the sensor, the ultrasonic waves interacted with the defect located at the center of the plate. The interaction of the ultrasonic waves with the defects caused changes in the sensor signals. By comparing the sensor signals under different defect conditions (including undamaged or pristine condition of the structure), the presence of a damage or defect, and the severity and location of the damages or defects in the portion of the structure can be determined.

[0051] A typical electrical signal used to excite an actuator in the simulation is shown in FIG. 12. FIG. 12 depicts a graph of an input electrical signal to an actuator of a 13-cycle Hanning windowed tone burst signal with a central frequency of 1.3 MHz and an amplitude of 10 V in accordance with the present embodiment. Ultrasonic waves generated by the excited actuator in the simulation can propagate through the structure and the sensor signals can then be calculated.

[0052] In accordance with the present embodiment, a crack is simulated as the defect in the simulation described. FIG. 13A depicts a graph of simulated sensor signals under different crack damage or depth conditions. As an example, the thickness of the structure under monitoring is 1.27 mm and the width of the crack is 3 mm. From FIG. 13A, it is clear that a crack with a depth of approximately 20% of the plate thickness, i.e., 0.254 mm can be easily distinguished from its undamaged or pristine signal in the time domain data. FIG. 13B depicts a Fast Fourier Transformation (FFT) of the first packet of the sensor signals in FIG. 13A in time domain. Since the transducer array was designed to generate and receive acoustic waves at 1.3 MHz for the A_0 mode of the Lamb waves, the voltage amplitudes of the 1.3 MHz component of the FFT sensor signals are of interest. In particular, it can be observed that the FFT plot 1302 for a structure with a crack at a depth of approximately 40% of the plate thickness has an amplitude of approximately 0.08 mV at 1.3 MHz, which is lower than the amplitude of 0.13 mV for the FFT plot 1301 of an undamaged or pristine structure without a crack. This trend is explained in greater detail in FIG. 13C. FIG. 13C depicts a graph of the voltage amplitudes of the 1.3 MHz component of the sensor signals for the different crack depths extracted. Referring to FIG. 13C, it can be observed that the voltage amplitude of the 1.3 MHz component of the sensor signal decreases in value as the crack depth increases. For example, a data point 1303 representing the amplitude of the 1.3 MHz component of the FFT

sensor signal for the undamaged structure is approximately at 0.13 mV which is higher than the value of 0.08 mV of the data point 1304 for the structure with a crack at a depth of 40% of the plate thickness. Moreover, the change of voltage amplitude for a crack with 10 % structure thickness depth is distinguishable from the undamaged condition which means that this form of monitoring is sensitive even for cracks with small crack depths of up to 10 % of the plate thickness. These results show that the designed transducer array can be used for effective monitoring of crack damages.

[0053] Additionally, in accordance with the present embodiment, an addition of mass is simulated as the defect in the simulation described. Referring to FIG. 14, comprising FIGs. 14A to 14C, graphs of simulated results from a sensor under different defect conditions with added mass in accordance with the present embodiment are depicted, wherein FIG. 14A depicts a graph of electrical signals from a sensor, FIG. 14B depicts a graph of a Fast Fourier Transformation (FFT) of a first wave packet in time domain for the result in FIG. 14A, and FIG. 14C depicts a graph of voltage amplitudes of the 1.3 MHz component of the electrical signals from a sensor for the different defect conditions with added mass. Preferably, in simulating the additive defect, brass metals with a width of 3 mm and thicknesses of 0.5 mm and 1 mm were modeled as attached to the center of the plate. In particular, as shown in FIG. 14B, it can be observed that the FFT plot 1402 for a structure with an added mass of a thickness of 1 mm has an amplitude of approximately 0.095 mV at 1.3 MHz, which is lower than that of the FFT plot 1401 for an undamaged or pristine structure without an added mass. This trend is explained in greater detail in FIG. 14C. Referring to FIG. 14C, it can be observed that the voltage amplitude of the 1.3 MHz component of the sensor signal decreases in value as the thickness of the added mass increases. For example, a data point 1403 representing the amplitude of the 1.3 MHz component of the FFT sensor signal for the undamaged structure is approximately at 0.13 mV which is higher than the amplitude of 0.095 mV of the data point 1404 for the structure with an added mass of a thickness of 1 mm. It is thus evident from the trend in FIG. 14C that the designed transducer array is also able to detect the additive mass defect effectively.

[0054] While both the crack and addition of mass cause drops in the voltage amplitudes of the sensor signals, the effect of crack damage and the addition of mass can be distinguished from the shift of the respective sensor signals in time domain. FIG. 15 depicts a graph for the comparison of electrical signals from the sensor for the undamaged condition, the condition

with an addition of a 1 mm thick mass (with a width of approximately 3 mm) and the condition with a 1 mm depth of crack (with a width of approximately 3 mm). From FIG. 15, it can be observed that the first wave packet of the sensor signal corresponding to the condition with the additive mass defect, is shifted to the right as compared to that of the sensor signal for the undamaged or pristine condition; while the first wave packet of the sensor signal corresponding to the condition of the crack defect is shifted to the left as compared to that of the sensor signal for the undamaged condition. The shifts in time correspond to changes in the acoustic velocities. When a mass is added on the plate, the acoustic velocity of Lamb wave is reduced at the location of the mass, and results in a time delay of the first wave packet. On the contrary, if the defect consists of a crack, there will be a reduction in the plate thickness at the location of the crack, causing the acoustic velocity to increase at the crack and leads to an early appearance of the wave packet compared to that of the undamaged condition. The results obtained are thus useful for determining the types of damages or defects present in the propagation path of the acoustic waves. More generally, the combination of the magnitudes of the voltage amplitudes of the sensor signals as well as their corresponding shifts in the time domain for structures with different defect conditions elucidate information about the type, size, and severity of the defects in the structures under monitoring. This method of analyzing the acoustic waves propagated in the structures under monitoring is therefore useful for structural health monitoring, especially when it is done in conjunction with the method of direct-writing transducers on said structures which provides the improved signal to noise ratio required.

[0055] Experimentally, in order to ensure that the experimental results are of value and that the direct-write acoustic transducers fabricated are in good working conditions, at least two conditions should be satisfied: firstly, the direct-write piezoelectric material layer is of good quality and secondly, the piezoelectric properties of this piezoelectric material must be sizeable. In light of the first condition, in accordance with the present embodiment, the properties of aerosol sprayed piezoelectric material layer P(VDF/TrFE) was tested and compared against a similar material prepared by a conventional technique like spin coating. FIG. 16A depicts a graph of dielectric properties of the piezoelectric P(VDF/TrFE) polymer deposited by the aerosol spray method used in direct-write transducers fabricated on an aluminum plate in accordance with the present embodiment. The P(VDF/TrFE) piezoelectric layer in the direct-write transducer array exhibited a dielectric constant of 13 and a dielectric loss of 0.05 at 1 kHz at room temperature, which are comparable to spin-coated P(VDF/TrFE)

layers. In addition, FIG. 16B depicts a graph of a polarization-voltage hysteresis loop of the piezoelectric P(VDF/TrFE) polymer layer in the direct-write acoustic transducers fabricated on the aluminum plate. The polarization-voltage hysteresis loops of the P(VDF/TrFE) piezoelectric layer measured is well-defined with a remnant polarization of $\sim 65 \text{ mC/m}^2$, which is also comparable to that of spin-coated P(VDF/TrFE) layers. Thus, the aerosol sprayed P(VDF/TrFE) layers were concluded to be of good quality.

[0056] To ensure that the piezoelectric material has sizable piezoelectric properties and is comparable to a similar material deposited conventionally by spin coating, fabricated transducers are tested with a laser scanning vibrometer (LSV). FIG. 17 is an illustration of a section of a patterned annular array comb top electrode 1701 being analyzed with the LSV in accordance with the present embodiment. Preferably, the annular comb-shaped gold electrode 1702 is used as a top electrode with all the comb fingers connected, and the piezoelectric P(VDF-TrFE) film 1703 under the comb fingers is polarized in the direction perpendicular to the surface of the piezoelectric layer, under an external electric field. Accordingly, the piezoelectric constant d_{33} of the film was measured with the LSV. During testing, a unipolar alternating current (AC) signal of 30 V at a frequency of 1.5 kHz was applied to the sample.

[0057] Referring to FIG. 18, comprising FIGs. 18A to 18C, graphs of surface displacement of the area 1704 analyzed with the LSV in accordance with the present embodiment are depicted, wherein FIG. 18A corresponds to a three-dimensional representation of the displacement profile, FIG. 18B corresponds to a two-dimensional representation of the displacement profile, and FIG. 18C corresponds to a three-dimensional representation of the displacement profile when the piezoelectric material is excited with an excitation AC signal of an opposite sign as compared to FIG. 18A. The effective measured piezoelectric coefficient d_{33} value of the P(VDF-TrFE) film is -18 pm/V under the clamping effect of the aluminum plate, and is comparable to the values obtained with spin-coated PVDF-based layers under substrate clamping.

[0058] Referring to FIG. 19, comprising FIGs. 19A and 19B, an experimental set-up for defect testing with four direct-write acoustic transducers on a surface of a structure under monitoring in accordance with the present embodiment was depicted, wherein FIG. 19A depicts a top planar view of the set-up and FIG. 19B illustrates the set-up with a metal bar/mass 1908 as an example of the defect 1905 in FIG. 19A attached to the centre of a surface of the structure under monitoring. After the initial testing conditions were satisfied, an

experiment for defect testing 1901 was carried out. In the setup, an acoustic transducer acting as an actuator 1907 to generate Lamb wave 1906 is connected to a signal generator 1902 while another transducer acting as a sensor 1904 is connected to an oscilloscope 1903. The signal generator 1902 channel is also directly connected to the oscilloscope 1903 to monitor the input signal at the actuator 1907. Preferably, the metal bar/mass 1908 attached to the centre is a brass or copper mass of 0.5 to 1.0 mm thick.

[0059] The received signal by the oscilloscope 1903 was then recorded as shown in FIG. 20A. FIG. 20A depicts a graph of a detected bandpass filtered electrical signal, consisting of three wave packets, at a sensor for the defect of an added mass with a thickness of 1.0 mm in accordance with the present embodiment. The received signal in FIG. 20A was filtered with a selected bandpass to give clear wave packets. The first wave packet is due to electromagnetic interference, while the second and the third wave packets are signals due to the propagation of the Lamb wave. In particular, the second wave packet constitutes the Lamb wave directly transmitted from the actuator to the sensor while the third wave packet is due to the Lamb wave reflected from the plate boundary near the actuator. In this experiment, a copper bar with the side lengths of 5.0 mm $\times$ 3.0 mm was glued at the center of the aluminum plate as a defect. Preferably, the copper bar has a thickness of 0.5 or 1.0 mm.

[0060] The wave packet of interest is thus the second wave packet signals corresponding to different defect thicknesses. FIG. 20B depicts a graph of amplitudes for the 1.3 MHz component of second wave packets of the detected signals for the different defects of added mass in accordance with the present embodiment. It shows that the amplitude of the 1.3 MHz component decreases as the defect of added mass increases in thickness, in agreement with the trend of the theoretical prediction as shown in FIG. 14C. In accordance with the present embodiment, for more reliable measurements to locate a defect position and to determine the severity of the defect, four acoustic transducers placed substantially at the periphery or at each corner of a defined area or portion of a substrate or structure under monitoring with a spanning angle may be actuated individually. Preferably, the spanning angle faces away from the corner. Preferably, at least a pair of the acoustic transducers is formed substantially aligned across a portion of the structure. In this method, when one transducer served as an actuator, the other three transducers served as ultrasonic sensors to detect the generated acoustic wave in the structure. As a result, there are twelve transmit-catch spectra for all the possible transducer pairs. Accordingly, for SHM of a structure under monitoring, these twelve

spectra are recorded as reference signals before any defect is formed on the structure, and are recorded again after the introduction of a defect. Differentiated spectra can then be obtained by comparing the spectra before and after the introduction of the defect. For example, scattering spectra, a type of differentiated spectra, may be obtained by subtracting the spectra measured with the defect from the spectra measured before the introduction of said defect. The scattering spectra then contain the ultrasonic signal attributed to the appearance of the defect. Consequently, analyses on the ultrasonic signals, including the time-of-flights and amplitudes of scattered waves in the differentiated spectra, can be done to get useful information such as the location, size and/or severity of the defect in the structure under monitoring.

[0061] Possible applications of the present invention include aeronautic structural health monitoring and non-destructive testing methods using acoustic transducers. It should however be appreciated that the use of the present invention for the method of fabricating transducers and the use of said transducers in a method for structural defect monitoring and analysis is not limited to the applications mentioned therein.

[0062] Not all the piezoelectric materials are suitable for producing devices on all structures to be monitored by a direct-write process. For example, the piezoelectric layer as demonstrated in accordance with the present embodiment is a PVDF-based piezoelectric polymer with a low processing temperature. The piezoelectric polymer can withstand a temperature of up to 120 °C, thereby limiting the operation temperature of ultrasonic transducers to below 120 °C. For monitoring structures at higher temperatures, piezoelectric ceramic may be used.

[0063] In addition, piezoelectric polymers have piezoelectric coefficients significantly lower than those of piezoelectric ceramics. In another word, piezoelectric ceramic-based ultrasonic transducers have larger actuation force to excite a more powerful acoustic wave. However, producing piezoelectric ceramic transducers by direct-write technology often requires high processing temperatures which some structures cannot withstand, and so piezoelectric polymers are still favoured in those applications.

[0064] In the application, unless specified otherwise, the terms "comprising", "comprise", and grammatical variants thereof, intended to represent "open" or "inclusive" language such that they include recited elements but also permit inclusion of additional, non-explicitly recited elements.

[0065] It will be apparent that various other modifications and adaptations of the application will be apparent to the person skilled in the art after reading the foregoing disclosure without departing from the spirit and scope of the application and it is intended that all such modifications and adaptations come within the scope of the appended claims.

CLAIMS

What is claimed is:

1. A method of fabricating an acoustic transducer for generation and/or detection of acoustic waves for structural health monitoring, the method comprising:

in-situ direct-writing of a piezoelectric material to create a piezoelectric layer on a structure to be monitored, wherein the structure is conductive and the structure functions as a bottom electrode; and

in-situ direct-writing of a conductive electrode on top of the piezoelectric layer to act as a top electrode.

2. The method of claim 1 wherein the piezoelectric material is a polymer and wherein the step of in-situ direct-writing of the piezoelectric material comprises in-situ spraying of a precursor solution of the polymer.

3. The method of claim 1 wherein the step of direct-writing of the piezoelectric material comprises one of depositing the piezoelectric layer on a surface of the structure conforming to a contour of the surface of the structure to be monitored or aerosol spraying of the piezoelectric material through a patterned mask directly onto the structure to be monitored.

4. The method of claim 1 further comprising the step of patterning the top electrode to form an annular array comb electrode such that concentric arcs are formed with one common trace connecting all the arcs.

5. The method of claim 4 wherein the step of patterning the top electrode to form an annular array comb electrode comprises forming the annular array comb electrode with a period, wherein the period is a distance between each arc, and wherein the period corresponds to an excitation frequency of a mode of a Lamb mode ultrasonic wave in the piezoelectric material.

6. The method of claim 4 wherein the step of patterning the top electrode to form an annular array comb electrode comprises forming the annular array comb electrode substantially at a corner of a portion of the structure with a spanning angle facing away from the corner.
7. The method of claim 1 wherein the step of in-situ direct-writing of the piezoelectric material comprises inkjet printing of the piezoelectric material directly onto the structure to be monitored.
8. The method of claim 1 further comprising the step of depositing a protective layer over the top electrode.
9. A system with an acoustic transducer for structural health monitoring, comprising:
a structure to be monitored having one or more of a flat surface and a curved surface thereon, wherein the structure is conductive and the structure functions as a bottom electrode;
a layer of piezoelectric material on top of a portion of the structure; and
a layer of electrode on top of the piezoelectric material layer, wherein the layer of electrode is patterned, and wherein the layer of piezoelectric material and the layer of electrode form an acoustic transducer for generating and detecting acoustic waves in the structure to be monitored for identifying defects in the structure to be monitored.
10. The system of claim 9, wherein the acoustic waves comprise a Lamb mode ultrasonic wave for identifying defects in the structure to be monitored, wherein the layer of electrode is in the form of an annular array comb such that the concentric arcs are formed with one common trace connecting all the arcs, and the annular array comb electrode is patterned with a period, the period being a distance between each arc, and wherein the period corresponds to an excitation frequency of the Lamb mode ultrasonic wave.
11. The system of claim 10 further comprising a plurality of the acoustic transducers wherein each of the plurality of the acoustic transducers has annular array comb electrodes positioned substantially at a corner of a portion of the structure with a spanning angle facing away from the corner.

12. A method for structural health monitoring comprising the step of forming a plurality of acoustic transducers on a structure to be monitored, wherein the structure is conductive and the structure functions as a bottom electrode, wherein each of the plurality of acoustic transducers comprises a layer of piezoelectric material direct-written on top of the structure and a layer of electrode direct-written on top of the piezoelectric material layer, wherein at least a first one and a second one of the plurality of acoustic transducers are formed across a portion of the structure, and wherein the first one and the second one of the plurality of acoustic transducers are configured to generate and detect an acoustic wave in the portion of the structure to obtain structural health information.

13. The method of claim 12 wherein a subset of the plurality of acoustic transducers including the first one and the second one of the plurality of acoustic transducers are arranged around a periphery of the portion of the structure, the method further comprising the steps of:

the first one of the plurality of acoustic transducers generating the acoustic wave in the portion of the structure;

the second one of the plurality of acoustic transducers detecting the acoustic wave in the portion of the structure; and

comparing a first electrical signal of the acoustic wave detected by the second one of the plurality of acoustic transducers on the portion of the structure when the portion of the structure is in a pristine condition with a second electrical signal of the acoustic wave detected by the second one of the plurality of acoustic transducers on the structure at a structural health monitoring time to determine if the obtained structural health information indicates formation of a defect in the portion of the structure

14. The method of claim 13 wherein the step of comparing the first and second electrical signals of the acoustic wave detected by the second one of the plurality of acoustic transducers comprises comparing a shift in time of the first and second electrical signals in a time domain to determine a type of defect in the structure.

15. The method of claim 13 wherein the step of comparing the first and second electrical signals of the acoustic wave detected by the second one of the plurality of acoustic transducers comprises comparing amplitudes of the first and second electrical signals to determine a location, a size or a severity of the defect in the structure.

16. The method of claim 13 further comprising the step of actuating each of the plurality of the plurality of acoustic transducers arranged around the periphery of the portion of the structure individually to generate an acoustic wave in the portion of the structure in such a way that when one of the plurality of acoustic transducers is actuated to generate the acoustic wave in the structure, the remaining ones of the plurality of acoustic transducers detect the acoustic wave in the structure.