

STRUCTURAL HEALTH MONITORING METHOD AND SYSTEM

FIELD OF INVENTION

[0001] The present invention relates broadly, but not exclusively, to structural health monitoring methods and systems, and particularly ones utilizing bulk acoustic waves.

BACKGROUND

[0002] Pipeline structures are widely used in various industrial sectors, such as oil and gas industry, marine & offshore industry, chemical and refinery industry, and in general utility infrastructure, in which effective structural health monitoring (SHM) of the pipeline structures is highly demanded for safe and continuous operation.

[0003] Various conventional techniques have been applied for the inspection of the pipeline structures, such as visual inspection, ultrasonic techniques, radiography, electromagnetic techniques, and vibration-based methods. Visual inspection can typically only detect damage on the external surfaces of the pipeline structures. Radiography is expensive and is subject to complex safety regulations. The electromagnetic method is effective for detecting damage in metallic pipeline structures, while it is not applicable for composite structures. The vibration-based method is a simple and effective method for evaluating the overall status of the structure, but it is not effective for identifying the location or the types of the damage. The ultrasonic technique is effective for detecting internal damage, but usually ultrasonic inspection is manually conducted using bulky ultrasonic probes, and requires effective and consistent acoustic coupling between the ultrasonic probes and pipeline materials. The results of ultrasonic testing often depend on the skills and experience of individual operators.

[0004] Efforts have been made for realizing *in-situ* monitoring of pipeline structures with minimized manual use of bulky external equipment. For example, research and development work has been reported to integrate optical fibers in pipeline structures for *in-situ* SHM. However, the fiber optics cannot effectively evaluate the

internal damage in the pipeline structures. There are also reported works employing discrete sensors, e.g., piezoelectric ceramic patches or discrete ultrasonic probes bonded or fixed on the pipeline structures for damage detection. The bonding or coupling of the ultrasonic sensors on pipeline structures has issues of consistency and reliability due to manual installation, and results in high cost with the implementation of a large number of sensors.

[0005] Therefore, a need exists to provide a SHM method and system that can address at least some of the above problems, in particular, a SHM method and system that may be reliable and preferably low-cost and with a capability of monitoring both surface and internal defects over a long pipeline structure.

SUMMARY

[0006] An aspect of the present disclosure provides a structural health monitoring method including forming *in-situ* a plurality of acoustic transducers on a surface of a structure to be monitored. Forming *in situ* the plurality of acoustic transducers includes directly coating and patterning a piezoelectric layer and electrode layers of the acoustic transducers on the surface of the structure such that the piezoelectric layer is crystallized *in situ* and polarizing the piezoelectric layer, wherein the piezoelectric layer is polarized in a polarization direction along the surface of the structure. The method also includes generating, from a first position on the structure, bulk acoustic wave signals for propagation in the structure; detecting, at a second position on the structure, the bulk acoustic wave signals propagating in the structure; and analyzing the detected bulk acoustic wave signals to determine structural health of the structure, wherein at least one of generating and detecting the bulk acoustic wave signals is performed by one or more of the acoustic transducers.

[0007] Another aspect of the present disclosure provides a structural health monitoring system including a plurality of acoustic transducers formed *in situ* on a surface of a structure to be monitored, wherein one or more of the acoustic transducers are configured to perform at least one of generating, from a first position on the structure, bulk acoustic wave signals for propagation in the structure, and detecting, at a second position on the structure, the bulk acoustic wave signals propagating in the structure; and a processor configured to analyze the detected bulk acoustic wave signals to determine structural health of the

structure. The plurality of acoustic transducers includes a piezoelectric layer and electrode layers directly coated and patterned on the surface of the structure, wherein the piezoelectric layer comprises a crystallized structure. The piezoelectric layer is polarized in a polarization direction along the surface of the structure.

BRIEF DESCRIPTION OF THE DRAWINGS

[0008] Embodiments of the invention will be better understood and readily apparent to one of ordinary skill in the art from the following written description, by way of example only, and in conjunction with the drawings, in which:

[0009] Figure 1 shows a flow chart illustrating a structural health monitoring method according to an example embodiment.

[0010] Figure 2 shows a schematic diagram of an implementation of a structural health monitoring of a pipeline structure according to an example embodiment.

[0011] Figure 3 shows graphs of dispersion curves for an example stainless steel pipeline.

[0012] Figure 4 shows a photograph of a pipeline structure with SHM using the acoustic transducers according to an example embodiment.

[0013] Figure 5 shows graphs of time-domain acoustic signals received by Transducer C in the set-up of Figure 4 under different conditions.

[0014] Figure 6 shows graphs of frequency-domain acoustic signals in the set-up of Figure 4 under different conditions.

[0015] Figure 7 shows a photograph of another implementation of a structural health monitoring of a pipeline structure according to an alternate embodiment.

[0016] Figure 8, comprising 8(a) and 8(b), shows representations of vibration data using the set-up shown in Figure 7.

[0017] Figure 9, comprising 9(a) and 9(b), shows schematic diagrams illustrating in-plane polarization according to an example embodiment.

[0018] Figure 10, comprising 10(a) and 10(b), shows schematic diagrams illustrating in-plane polarization according to an alternate embodiment.

[0019] Figure 11 shows a model for simulation of in-plane polarized piezoelectric coating acoustic transducers for defect detection based on the configuration of Figure 9(b).

[0020] Figure 12, comprising 12(a), 12(b) and 12(c), shows simulation results of the model of Figure 11.

[0021] Figure 13 shows a photograph of another implementation of structural health monitoring where the piezoelectric acoustic transducers act as actuators.

[0022] Figure 14 shows a photograph of another implementation of structural health monitoring where the piezoelectric acoustic transducers act as sensors.

DETAILED DESCRIPTION

[0023] The present disclosure provides a method and a system for structural health monitoring of structures using piezoelectric acoustic transducers. As described in further details below, the piezoelectric acoustic transducers are made of a piezoelectric coating *in-situ* crystalized and patterned on the structures (hereinafter also referred to as piezoelectric coating acoustic transducers) for structural health monitoring (SHM) purpose. The piezoelectric coating acoustic transducers are capable of generating and detecting bulk acoustic waves propagating in a structure, e.g. in the axial (i.e. longitudinal) or circumferential direction of a pipeline structure. Thus, both surface and internal defects within the structure are detectable based on the technology disclosed herein.

[0024] Figure 1 shows a flow chart 100 illustrating a structural health monitoring method according to an example embodiment. At step 102, a plurality of acoustic transducers are formed *in-situ* on a surface of a structure to be monitored. At step 104, bulk acoustic wave signals are generated from a first position on the structure for propagation in the structure. At step 106, the bulk acoustic wave signals propagating in the structure are detected at a second position on the structure. At step 108, the detected bulk acoustic wave signals are analyzed to determine structural health of the structure. At least one of generating and detecting the bulk acoustic wave signals is performed by one or more of the acoustic transducers.

[0025] In the examples that follow, the SHM method and system are described with reference to a pipeline structure; however, it would be appreciated that the present method and system can be applied to other structures, e.g. storage tanks, silos, etc. with suitable modifications.

[0026] In one implementation, the method comprises 1) *in-situ* forming piezoelectric coating acoustic transducers on a pipeline structure by directly crystallizing and patterning a piezoelectric layer and electrode layers; 2) generating and detecting a bulk acoustic wave propagating in an axial or circumferential direction of the pipeline structure using the *in-situ* formed piezoelectric coating acoustic transducers; 3) evaluating the structural health status of the pipeline structure by analyzing the acoustic signals obtained from the piezoelectric coating acoustic transducers.

[0027] The piezoelectric coating acoustic transducers preferably comprise an environmentally-friendly piezoelectric coating layer and electrode layers *in-situ* crystalized and patterned on a pipeline structure. For example, the piezoelectric coating layer can be made of a lead-free piezoelectric ceramic coating or piezoelectric polymer coating, without substantial lead composition, including but not limited to sodium potassium niobate (KNN) or bismuth sodium titanate (BNT) based piezoelectric ceramic materials, polyvinylidene fluoride (PVDF) homo-polymers, and poly(vinylidene fluoride-co-trifluoroethylene) P(VDF-TrFE) copolymers.

[0028] To form the piezoelectric acoustic transducers, a bottom electrode layer may be deposited on the pipeline structure, below the piezoelectric coating layer, particularly when the exterior surface of the pipeline structure is electrically non-conductive. The bottom electrode layer can be made of any metallic materials or non-metallic materials which have good electrical conductivity. For pipeline structures which are conductive at the exterior surface, the bottom electrode layer is optional because the exterior surface of the pipeline structure can serve as the bottom electrode.

[0029] Top electrodes having e.g. a comb pattern may be deposited and patterned on top of the piezoelectric coating layer and the period of the comb electrodes may be selected to match substantially with the wavelength of the bulk acoustic wave modes to be excited in the pipeline.

[0030] The piezoelectric coating layer may be polarized in the thickness direction (i.e. normal to the surface of the structure) or an in-plane direction (i.e. along or parallel to the surface of the structure). The electrodes and the piezoelectric materials may be deposited by direct-write techniques such as aerosol spray, inkjet-printing, thermal or cold spray, screen printing, and physical vapor deposition, with or without a shadow mask.

[0031] The acoustic transducers that are formed *in-situ* on the structure can generate from a first position on the structure, bulk acoustic wave signals for propagation in the structure and/or detect, at a second position on the structure, the bulk acoustic wave signals propagating in the structure. Although not specifically shown in the drawings, the present embodiments use a processor (e.g. a personal computer, laptop or tablet device) to analyze the detected bulk acoustic wave signals to determine structural health of the structure.

[0032] Several non-limiting examples are described below to provide further details of the present method and system.

Example 1

[0033] Figure 2 shows a schematic diagram of an implementation of a structural health monitoring of a pipeline structure according to an example embodiment. As illustrated in Figure 2, the piezoelectric coating acoustic transducers for monitoring a pipeline structure 102 may be made of two set of transducers 104a, 104b, where one or more of transducers 104a serves as an actuator 106, and one or more of transducers 104b serves as a sensor 108. The pipeline structure 102 is made of stainless steel 316, with an outer diameter of 168 mm, a thickness of 11 mm, and a length of 1 meter, and is used for demonstrating the pipeline SHM function with the piezoelectric coating acoustic transducers. A layer of P(VDF/TrFE) piezoelectric coating 110 is *in-situ* deposited, crystallized and patterned on selected areas on the pipeline structure 102. The P(VDF/TrFE) coating 110 is deposited by spraying P(VDF/TrFE) solution (5 wt% in a mixed solvent of dimethylformamide and acetone) using an aerosol spray gun. During spray, the coating area of the pipeline structure 102 may be heated to around 90 °C, and the P(VDF/TrFE) coating 110 is directly patterned on the pipeline structure 102 with the aid of shadow masks. After the spraying process, the P(VDF/TrFE) coating 102 may be annealed at 135 °C. The thickness of the P(VDF/TrFE) films is around 30 μm. To fabricate the top electrode 112a, 112b with comb pattern, silver paste patterns are brushed on the surface of P(VDF/TrFE) coating 110 with the aid of another shadow mask. As the pipeline structure 102 is electrically conductive, it is used as the bottom electrode. The P(VDF/TrFE) coating 110 is polarized in the thickness direction (i.e. substantially normal to the surface of the pipeline structure 102) via a direct current (DC) voltage at electric field of 50 MV/m at 100 °C, or by corona discharge at 20 kV.

[0034] In the example shown in Figure 2, the period of the comb electrode pattern substantially matches with the wavelength of the bulk acoustic wave mode to be excited. Bulk acoustic waves which propagate in the whole volume of the pipeline structure 102, such as longitudinal modes, flexural modes, and torsional modes or shear modes, can be generated by applying an alternating electric potential in a direction substantially parallel to the polarization direction. Typical dispersion curves (phase and group velocities) for a stainless steel pipeline with an outer diameter of 168 mm and a wall thickness of 11 mm (such as the pipeline structure 102 in Figure 2) are shown in Figure 3. The left graph in Figure 3 shows phase velocities versus frequency, while the right graph in Figure 3 shows the group velocities versus frequency.

[0035] For a selected wave mode $L(0,1)$ at frequency $f=260$ kHz as marked in Figure 3, the corresponding wavelength calculated via the equation $\lambda=v_p/f$ is around 12.1 mm, where v_p is the phase velocity of the selected mode. Thus, the top electrodes 112a, 112b of the piezoelectric coating acoustic transducer can be formed with a comb pattern, where both the width of electrode and the gap between electrodes are $\lambda/2$. Two sets of piezoelectric coating acoustic transducers may be fabricated on the pipeline structure, where one or more transducers of the first set can serve as an actuator for generating bulk acoustic waves propagating along the axial direction, and one or more transducers of the other set can serve as a sensor for receiving the bulk acoustic waves. Any defects in the propagation path between the actuator and the sensor may affect the signals of the bulk acoustic waves. Thus, the structural health status of the pipeline structure between the two transducers can be monitored. Such a bulk longitudinal wave may propagate over a long distance in metallic pipeline, at least over tens of meters. In a long pipeline, a plural number of such transducer pairs may be used to monitor the entire pipeline structure. As the $L(0,1)$ mode waves are longitudinal wave mode across the thickness of pipeline structure, both defects on the exterior or interior surfaces of the pipeline can be detected by the transducers, even though the transducers are fabricated on the exterior surface of the pipeline structure.

[0036] The comb electrode pattern as shown in Figure 2 may be designed to partially cover the pipeline structure in the circumferential direction. Thus, each segment of electrodes can serve as one independent acoustic transducer.

[0037] Figure 4 shows a photograph of a pipeline structure 400 with SHM using the acoustic transducers according to an example embodiment. The set-up in Figure 4 has three sets of piezoelectric coating acoustic transducers, each made of the

P(VDF/TrFE) coating *in-situ* formed on the stainless steel pipeline structure 400 and each having one of the three segments of the electrodes in the circumferential direction, with a defect 402 located between Transducers B and C. The defect 402 in this example is in the form of a notch with lateral dimensions of 40 mm by 40 mm and varied depths. By using Transducers A and C designed at 260 kHz as an actuator, and Transducer B as the sensor, the presence of the notch and the change of notch depths can be observed as below.

[0038] During testing, Transducer A or C are excited by a 260 kHz tone burst signal with 5 cycles at amplitude of 100 V_{p-p}. The acoustic signal received by Transducer B is collected with an oscilloscope. It has been observed that the presence of the notch can lead to a reduction of the amplitude of the detected acoustic signals as shown in Figure 5. The amplitude of the acoustic signal is substantially reduced by 39% for the 11 mm-thick pipeline structure with a notch of 1 mm in depth (see boxed section of graph 502), and further reduced by 84% with a notch of 4 mm in depth (see boxed section of graph 504). The time-domain signals are analyzed in the frequency-domain, as shown in Figure 6, and similar results are observed. In Figure 6, curve 602 shows the acoustic signal when there is no defect, curve 604 shows the acoustic signal when there is a notch of 1 mm in depth, and curve 606 shows the acoustic signal when there is a notch of 4 mm in depth.

Example 2

[0039] The piezoelectric coating acoustic transducers in Example 1 can alternatively be made of a lead-free piezoelectric ceramic coating by a thermal spray method. In this example, the pipeline structure is a stainless steel (316L grade) pipe, with an outer diameter of 33.1 mm, a thickness of 3.5 mm, and a length of 189 mm. Prior to deposition of the lead-free piezoelectric ceramic coating, two intermediate layers and a bottom electrode layer are deposited on the pipeline structure. The first intermediate layer is made of NiCrAlY alloy with a thickness of 100 μm, and the second intermediate layer made of YSZ (ZrO₂ with 8 mol% Y₂O₃) with a thickness of around 300 μm, both of which are to enhance the mechanical robustness of the structure during the subsequent thermal treatment process. The bottom electrode layer is made of Pd/Ag (30/70) with a thickness of around 10 μm.

[0040] The composition of (K_{0.44}Na_{0.52}Li_{0.04})(Nb_{0.84}Ta_{0.10}Sb_{0.06})O₃ ((K,Na,Li)(Nb,Ta,Sb)O₃) may be selected for fabrication of the lead-free piezoelectric

ceramic layer. K_2CO_3 , Na_2CO_3 , Li_2CO_3 , Nb_2O_5 , Ta_2O_5 , and Sb_2O_5 powders are used as the starting materials with the selected stoichiometric composition with 10 mol% excess K and Na. The weighed materials may be mixed by planetary ball milling process, followed by ceramic calcination at 850 °C, and further heat treatment at 1000 °C for 5 hours in an alumina crucible, in order to achieve the desired particle size for subsequent plasma spray deposition process. The resulting powder may be introduced into an atmospheric plasma spraying system, molten and deposited on the pipeline structure at ambient pressure using Ar plasma with plasma power of 17 kW. $(K,Na,Li)(Nb,Ta,Sb)O_3$ perovskite phase is crystallized in the thermal sprayed coating on the pipeline structure, with a thickness of approximately 120 μm . In order to improve the crystallinity of the as-sprayed $(K,Na,Li)(Nb,Ta,Sb)O_3$ coating, a post-spray heat treatment may be conducted in an furnace or by flame from a torch, at approximately 950 °C. Finally, Ag upper electrodes are patterned on the $(K,Na,Li)(Nb,Ta,Sb)O_3$ layer by painting using a brush with the aid of a shadow mask, followed with firing at 520 °C. The thermal sprayed $(K,Na,Li)(Nb,Ta,Sb)O_3$ coating can then be poled at room temperature under an electric field of 35 kV/cm.

[0041] Figure 7 shows a photograph of a set-up to perform SHM on a pipeline structure 702 using the *in-situ* formed $(K,Na,Li)(Nb,Ta,Sb)O_3$ lead-free piezoelectric ceramic coating acoustic transducers 704a, 704b as described in the preceding paragraph.

[0042] The piezoelectric strain coefficient d_{33} for the $(K,Na,Li)(Nb,Ta,Sb)O_3$ lead-free piezoelectric ceramic coating can be measured using a laser scanning vibrometer. Figure 8 presents, in the form of measurement of surface displacement, the instantaneous vibration data of the $(K,Na,Li)(Nb,Ta,Sb)O_3$ ceramic layer produced on the stainless steel pipeline structure 702 under a sine-shaped electric driving wave, with a 19 V amplitude at 1 kHz. The effective piezoelectric coefficient d_{33} is determined to be approximately 50 pm/V, under the mechanical clamping condition with the pipeline structure 702.

[0043] In this example, the comb electrode width and electrode gap are set as 6.1 mm, which is the half wavelength of the bulk acoustic wave mode of $L(0,2)$ mode at 416 kHz, propagating along the axial direction. A notch defect 706 with lateral dimensions of 7 mm by 7 mm and depth of 2.5 mm may be made on the pipeline structure 702 as shown in Figure 7. Similar to Example 1, the defect 706 on the pipeline structure 702

can be detected with the bulk acoustic wave by the lead-free piezoelectric ceramic coating acoustic transducers 704a, 704b.

Example 3

[0044] The piezoelectric acoustic transducers made of lead-free piezoelectric ceramic coating by thermal spray method as described in Example 2 can be polarized in an in-plane direction (e.g. along the surface of the structure) and electrically driven in another in-plane direction perpendicular to the polarization direction so that in-plane dominant bulk acoustic waves can be generated. To fabricate the lead-free piezoelectric ceramic coating acoustic transducers with in-plane polarization, different poling and working electrodes are used in an example implementation.

[0045] In the configuration shown in Figure 9(a), a pair of poling electrodes are first deposited on the lead-free piezoelectric coating layer, such as $(\text{K,Na,Li})(\text{Nb,Ta,Sb})\text{O}_3$ layer, as produced according to Example 2. Because the polarization is in-plane, an electrically non-conductive layer is disposed below the piezoelectric ceramic coating layer. The electrically non-conductive layer may be the second intermediate layer made of YSZ (ZrO_2 with 8 mol% Y_2O_3) as described in Example 2. The thickness of the intermediate layer may be as thick as 1 mm. A direct current (DC) electric field of 15 kV/cm is applied through the poling electrodes, so that the polarization of the piezoelectric ceramic coating material is aligned in the circumferential direction, denoted as θ -axis in Figure 9.

[0046] After the poling process, the poling electrodes are removed, such as by chemical etching, and working electrodes 902a, 902b as shown in Figure 9(a) are deposited in the axial (i.e. longitudinal) in-plane direction, denoted as z-axis, which is perpendicular to the circumferential polarization direction of the piezoelectric coating material. When an electric potential is applied to the working electrodes 902a, 902b, the piezoelectric ceramic materials may largely distort in the in-plane direction. When a high-frequency alternating electrical excitation is applied to the electrodes, bulk acoustic waves with dominant in-plane deformation can be generated. The in-plane bulk acoustic waves have minimized acoustic energy loss in liquid to extend acoustic propagation distance and thus monitoring range, which is an advantage for use in liquid or with liquid inside the pipeline structure.

[0047] Figure 9(b) shows another configuration of in-plane polarized piezoelectric coating acoustic transducers on a pipeline structure, in which the piezoelectric coating layer is poled along the pipeline axial (i.e. longitudinal) direction, and the electric field during operation is applied in the circumferential in-plane direction normal to the polarization direction. In other words, the working electrodes 904a, 904b in Figure 9(b) are deposited in the circumferential in-plane direction. In Figures 9(a) and 9(b), an alternating electric potential is applied in a direction substantially perpendicular to the polarization direction of the piezoelectric layer.

[0048] Figure 10 shows schematic diagrams illustrating in-plane polarization according to an alternate embodiment. The transducer structures in Figure 10 can be fabricated using substantially the same method as described above with reference to Figure 9, except that the acoustic transducers 1002, 1004 in Figure 10 have different orientations from those in Figure 9. For example, the in-plane polarized piezoelectric coating acoustic transducers 1002, 1004 can be arranged in a tilted direction in the θ -z plane as shown in Figure 10, such that the in-plane dominated bulk acoustic waves may propagate in a helical direction along both the circumferential and length directions of a pipeline structure. The embodiment shown in Figure 10 can help to realise bulk acoustic wave modes which are not parallel to major axes of the pipeline structure.

[0049] Figure 11 shows a model for simulation of in-plane polarized piezoelectric coating acoustic transducers for defect detection based on the configuration of Figure 9(b). A stainless steel 316L pipeline 1100 with an outer diameter of 33.1 mm, a thickness of 3.5 mm, and a length of 189 mm is deposited with a piezoelectric $(\text{K,Na,Li})(\text{Nb,Ta,Sb})\text{O}_3$ layer and electrode layers to form the piezoelectric coating acoustic transducers on the pipeline structure. The thickness of the piezoelectric ceramic layer is 150 μm . Top electrode width and gap are set to be 6.1 mm and the operating frequency is selected to be 255 kHz. A notch defect 1102 of 7 mm by 14 mm with depth of 2.5 mm is located at the middle of the pipeline structure 1100 on the surface. The defect 1102 simulates the occurrence of corrosion on the pipeline surface, which is a type of common defects in marine and offshore industry. The piezoelectric coating acoustic transducers are polarized in the axial direction of the pipeline structure 1100 as indicated by the black solid arrows. Working electrodes are in the circumferential direction. By applying a 5.5-cycle Hanning window signal with frequency of 255 kHz and amplitude of 150 V to the working electrodes of the actuator 1104, in-plane dominated acoustic waves are generated, and detected by the sensor 1106.

[0050] Figures 12(a) and 12(b) present the simulation results of acoustic signals received by the sensor 1106 of Figure 11 on the pipeline structure 1100 with and without the corrosion defect 1102. A clear drop in the amplitude of acoustic signal is observed in both time-domain (Figure 12(a)) and frequency domain (Figure 12(b)) when the defect 1102 is presented. For the time-domain result shown in Figure 12(a), where curve 1202 shows the response when there is no defect and curve 1204 shows the response when there is a defect, a time delay is also observed when the defect is present. The simulation results indicate that the in-plane polarized piezoelectric coating acoustic transducers can be used for detecting defects in the pipeline structure.

[0051] Figure 12(c) shows the displacement amplitude at the sensor area in the circumferential direction, radial direction and axial direction, respectively. It is evident that the displacement amplitude in circumferential direction (curve 1206) is largest, followed by the displacement amplitude in the axial direction (curve 1208). The displacement amplitude in the radial direction (curve 1210), which is in the out-of-plane direction of the pipeline structure, is negligible compared to the two in-plane directions, i.e., circumferential direction and axial direction. The result indicates that the bulk acoustic wave generated by piezoelectric coating acoustic transducer is dominated by the in-plane components. This can be particularly useful for SHM of pipeline structures immersed in liquid or with liquid inside the pipeline structure because of the minimized acoustic energy loss.

Example 4

[0052] The piezoelectric coating acoustic transducers as described in Examples 1-3 can be used as either sensors or actuators when used together with other discrete acoustic probes or transducers, as shown in Figures 13 and 14. Figure 13 shows the use of piezoelectric coating acoustic transducers 1302 made of P(VDF/TrFE) coating *in-situ* formed on a pipeline structure 1300 as actuators for generating bulk acoustic waves, and the use of a surface-mounted piezoelectric ceramic transducer 1304 as a sensor. In Figure 13, the direction of propagation of the bulk acoustic wave is from right to left. Figure 14 shows the use of a surface-mounted piezoelectric ceramic transducer 1402 as an actuator and piezoelectric coating acoustic transducers 1404 made of P(VDF/TrFE) coating *in-situ* formed on a pipeline structure 1400 as sensors. In Figure 14, the direction of propagation of the bulk acoustic wave is from left to right. Both

configurations can be used for SHM of the pipeline structures as alternatives to the configurations shown in Examples 1-3.

Example 5

[0053] The piezoelectric coating acoustic transducers as described in Examples 1-3 may be configured such that the transducers work at the resonant frequency of the transducer structure. For example, for a piezoelectric coating acoustic transducers operating in the thickness mode (i.e. the polarization is along the thickness direction normal to the surface of the structure), the thickness of the transducer, t_p , may be chosen to be $t_p = v/2f$, where v is the longitudinal sound velocity of the transducer material and the f is the desired working frequency of the transducer. In such a design, the transducer's capability for generating and detecting acoustic waves may be significantly enhanced.

[0054] As described above, the structural health monitoring method and system in the present disclosure make use of piezoelectric acoustic transducers which are *in-situ* crystallized and patterned on the structure to be monitored, for generating and detecting bulk acoustic wave propagating in the in-plane direction (e.g. longitudinal or circumferential direction). The method and system as disclosed have several advantages including *in-situ* monitoring with improved reliability and consistency, and reduced labor and cost for replacing manual installation and transducer operation. Capabilities such as monitoring both surface and internal defects, inspection of long pipeline structure, and compatibility with limited space access, can be provided. Furthermore, the piezoelectric materials used in the present examples are lead-free, thus providing an environmentally-friendly solution.

[0055] It will be appreciated by a person skilled in the art that numerous variations and/or modifications may be made to the present invention as shown in the specific embodiments without departing from the scope of the invention as broadly described. For example, the number and placement of the acoustic transducers may be varied, and a different piezoelectric material may be selected for the piezoelectric layer. The present embodiments are, therefore, to be considered in all respects to be illustrative and not restrictive.

CLAIMS

1. A structural health monitoring method comprising:
forming *in-situ* a plurality of acoustic transducers on a surface of a structure to be monitored, wherein forming *in situ* the plurality of acoustic transducers comprises:
directly coating and patterning a piezoelectric layer and electrode layers of the acoustic transducers on the surface of the structure such that the piezoelectric layer is crystallized *in situ*; and
polarizing the piezoelectric layer,
wherein the piezoelectric layer is polarized in a polarization direction along the surface of the structure;
generating, from a first position on the structure, bulk acoustic wave signals for propagation in the structure;
detecting, at a second position on the structure, the bulk acoustic wave signals propagating in the structure; and
analyzing the detected bulk acoustic wave signals to determine structural health of the structure,
wherein at least one of generating and detecting the bulk acoustic wave signals is performed by one or more of the acoustic transducers.
2. The method as claimed in claim 1, wherein the structure comprises an elongated pipe, and wherein the piezoelectric layer is polarized in a longitudinal direction of the pipe.
3. The method as claimed in claim 1, wherein the structure comprises an elongated pipe, and wherein the piezoelectric layer is polarized in a circumferential direction of the pipe.
4. The method as claimed in any one of claims 1 to 3, wherein generating the bulk acoustic wave signals comprises applying an alternating electric potential in a direction substantially perpendicular to the polarization direction of the piezoelectric layer.
5. The method as claimed in any one of claims 1 to 4, wherein the piezoelectric layer comprises a polymer.
6. The method as claimed in any one of claims 1 to 4, wherein the piezoelectric layer comprises a ceramic, and wherein the ceramic is substantially lead-free.

7. The method as claimed in any one of claims 1 to 6, wherein forming *in situ* the plurality of acoustic transducers comprises forming two groups of acoustic transducers at the first and second positions respectively, and wherein the bulk acoustic wave signals are generated by one or more acoustic transducers of the first group and detected by one or more acoustic transducers of the second group.

8. The method as claimed in any one of claims 1 to 6, wherein forming *in situ* the plurality of acoustic transducers comprises forming one group of acoustic transducers at the first position, and wherein the bulk acoustic wave signals are generated by the *in-situ* formed acoustic transducers and detected by one or more discrete acoustic transducers.

9. The method as claimed in any one of claims 1 to 6, wherein forming *in situ* the plurality of acoustic transducers comprises forming one group of acoustic transducers at the second position, and wherein the bulk acoustic wave signals are generated by one or more discrete acoustic transducers and detected by the *in-situ* formed acoustic transducers.

10. The method as claimed in any one of claims 1 to 9, wherein at least one of generating and detecting the bulk acoustic wave signals comprises operating the acoustic transducers substantially at a resonant frequency.

11. The method as claimed in any one of the claims 1 to 10, wherein the bulk acoustic wave signals are generated for propagation based on at least one of a longitudinal mode, a torsional mode, a shear mode and a flexural mode.

12. A structural health monitoring system comprising:

a plurality of acoustic transducers formed *in situ* on a surface of a structure to be monitored, wherein one or more of the acoustic transducers are configured to perform at least one of:

generating, from a first position on the structure, bulk acoustic wave signals for propagation in the structure; and

detecting, at a second position on the structure, the bulk acoustic wave signals propagating in the structure; and

a processor configured to analyze the detected bulk acoustic wave signals to determine structural health of the structure,

wherein the plurality of acoustic transducers comprise a piezoelectric layer and electrode layers directly coated and patterned on the surface of the structure, and wherein the piezoelectric layer comprises a crystallized structure; and

wherein the piezoelectric layer is polarized in a polarization direction along the surface of the structure.

13. The system as claimed in claim 12, wherein the piezoelectric layer comprises a polymer.

14. The system as claimed in claim 12, wherein the piezoelectric layer comprises a ceramic, and wherein the ceramic is substantially lead-free.

15. The system as claimed in any one of claims 12 to 14, wherein the *in-situ* formed acoustic transducers comprise two groups of acoustic transducers disposed at the first and second positions respectively, and wherein one or more acoustic transducers of the first group are configured to generate the bulk acoustic wave signals and one or more acoustic transducers of the second group are configured to detect the bulk acoustic wave signals propagating in the structure.

16. The system as claimed in any one of claims 12 to 14, further comprising one or more discrete acoustic transducers disposed at the second position, wherein the *in-situ* formed acoustic transducers comprise one group of acoustic transducers disposed at the first position and configured to generate the bulk acoustic wave signals, and wherein the one or more discrete acoustic transducers are configured to detect the bulk acoustic wave signals.

17. The system as claimed in any one of claims 12 to 14, further comprising one or more discrete acoustic transducers disposed at the first position and configured to generate the bulk acoustic wave signals, wherein the *in-situ* formed acoustic transducers comprise one group of acoustic transducers disposed at the second position and configured to detect the bulk acoustic wave signals.