US Patent & Trademark Office
Patent Public Search | Text View

United States Patent	12386088
Kind Code	B2
Date of Patent	August 12, 2025
Inventor(s)	Van Os; Roel et al.

Acoustic transducer with trapezoidal, irregularly pitched, or widened transducer elements

Abstract

a Downhole Acoustic Measurement Tool that Includes a Transducer Operable for Emitting and/or Receiving Acoustic Signals to Perform Downhole Measurements. The Transducer Includes Multiple Piezoelectric Elements. Each Piezoelectric Element May have a First Axial End and a Second Axial End, and the Second Axial End May be Wider than the First Axial End in a Direction Along a Circumference of the Transducer. The Piezoelectric Elements May be Irregularly Pitched Azimuthally Around One or More Portions of a Circumference of the Transducer. The Piezoelectric Elements May be Spaced Apart by No More than the Distance Defined by W1*f1/F.sub.UL, where F.sub.UL is the Upper Limit of the Frequency Band of Interest, W1 is the Width of the Transducer Interelement Spacing that Produces Parasitic Mode at Frequency f1.

Inventors: **Van Os; Roel (Clamart, FR), Hori; Hiroshi (Clamart, FR), Guedes; Orland (Clamart, FR)**

Applicant: **Schlumberger Technology Corporation** (Sugar Land, TX)

Family ID: **1000008752314**

Assignee: **Schlumberger Technology Corporation (Sugar Land, TX)**

Appl. No.: **18/341824**

Filed: **June 27, 2023**

Prior Publication Data

Document Identifier	Publication Date
US 20250004152 A1	Jan. 02, 2025

Publication Classification

Int. Cl.: **G01V1/20** (20060101); **G01V1/02** (20060101); **H03H9/205** (20060101)

U.S. Cl.:

CPC **G01V1/20** (20130101); **G01V1/159** (20130101); **H03H9/205** (20130101);

Field of Classification Search

CPC: G01V (1/20); G01V (1/59); G01V (1/159); H03H (9/205); E21B (47/00); E21B (47/0025); B06B (1/00)

USPC: 367/86

References Cited

U.S. PATENT DOCUMENTS

Patent No.	Issued Date	Patentee Name	U.S. Cl.	CPC
4580252	12/1985	Mallett	181/104	B06B 1/0607
5164920	12/1991	Bast	600/459	B06B 1/0622
2007/0206440	12/2006	Fripp	367/157	E21B 47/16
2021/0247538	12/2020	Guedes	N/A	G01S 15/8945

FOREIGN PATENT DOCUMENTS

Patent No.	Application Date	Country	CPC
2287789	12/1994	GB	B06B 1/0633
WO-2017086933	12/2016	WO	E21B 47/00

Primary Examiner: Xiao; Yuqing

Assistant Examiner: Walker; Christopher Richard

Background/Summary

BACKGROUND OF THE DISCLOSURE

(1) Acoustic downhole imaging tools are used in oil and gas exploration and production (E&P) in both cased and uncased (“open”) boreholes. For example, when utilized in cased boreholes, such acoustic imaging is performed to inspect the casing and the cement securing the casing in the borehole. When utilized in open boreholes, acoustic imaging may be performed to obtain an image of the borehole surface, such as to identify vugs, fractures, texture, and acoustic properties of the subterranean formation penetrated by the borehole.

SUMMARY OF THE DISCLOSURE

(2) This summary is provided to introduce a selection of concepts that are further described below in the detailed description. This summary is not intended to identify indispensable features of the claimed subject matter, nor is it intended for use as an aid in limiting the scope of the claimed subject matter.

(3) The present disclosure introduces an apparatus including a downhole acoustic measurement tool that includes a transducer. The transducer is operable for emitting and/or receiving acoustic signals to perform downhole measurements. The transducer includes piezoelectric elements each having a first axial end and a second axial end. The second axial end is wider than the first axial end in a direction along a circumference of the transducer.

(4) The present disclosure also introduces an apparatus including a downhole acoustic measurement tool that includes a transducer operable for emitting and/or receiving acoustic signals to perform downhole measurements. The transducer includes piezoelectric elements that are irregularly pitched azimuthally around one or more portions of a circumference of the transducer.
(5) The present disclosure also introduces an apparatus including a downhole acoustic measurement tool that includes a transducer operable for emitting and/or receiving acoustic signals to perform downhole measurements. The transducer includes piezoelectric elements that are spaced at controlled distance by spacer made of electrically insulating and mechanically compliant material, for an example, resin or elastomer or their composite material.
(6) These and additional aspects of the present disclosure are set forth in the description that follows, and/or may be learned by a person having ordinary skill in the art by reading the material herein and/or practicing the principles described herein. At least some aspects of the present disclosure may be achieved via means recited in the attached claims.

Description

BRIEF DESCRIPTION OF THE DRAWINGS
(1) The present disclosure is understood from the following detailed description when read with the accompanying figures. It is emphasized that, in accordance with the standard practice in the industry, various features are not drawn to scale. In fact, the dimensions of the various features may be arbitrarily increased or reduced for clarity of discussion.
(2) FIG. **1** is a schematic view of at least a portion of an example implementation of apparatus according to one or more aspects of the present disclosure.
(3) FIG. **2** is a perspective view of an example implementation of a portion of the apparatus shown in FIG. **1**.
(4) FIG. **3** is a perspective view of another example implementation of the apparatus shown in FIG. **2**.
(5) FIGS. **4** and **5** are graphs depicting one or more aspects of the present disclosure.
(6) FIG. **6** is an unrolled view of an example implementation of a portion of the apparatus shown in FIG. **3**.
(7) FIG. **7** is an end view of the apparatus shown in FIG. **6**.
(8) FIG. **8**A is an unrolled view of another example implementation of the apparatus shown in FIG. **6**.
(9) FIG. **8**B is general matrix-array shape of an implementation of a transducer in **8**A.
(10) FIG. **9** is a graph depicting one or more aspects of the present disclosure.
(11) FIG. **10** is a perspective view of an example implementation of the apparatus shown in FIG. **6**.
(12) FIG. **11** is a perspective view of another example implementation of the apparatus shown in FIG. **10**.
(13) FIG. **12** is a perspective view of another example implementation of the apparatus shown in FIG. **10**.
DETAILED DESCRIPTION
(14) It is to be understood that the following disclosure provides many different embodiments, or examples, for implementing different features of various embodiments. Specific examples of components and arrangements are described below to simplify the present disclosure. These are, of course, merely examples and are not intended to be limiting. In addition, the present disclosure may repeat reference numbers and/or letters in the various examples. This repetition is for simplicity and clarity and does not in itself dictate a relationship between the various embodiments and/or configurations discussed. Moreover, the description of a first feature in contact with a second feature in the description that follows may include implementations in which the first and second

features are in direct contact, and may also include implementations in which additional features may interpose the first and second features, such that the first and second features may not be in direct contact.

(15) FIG. **1** is a schematic view of at least a portion of an example implementation of a wellsite system **100** to which one or more aspects of the present disclosure may be applicable. The wellsite system **100** may be onshore (as depicted) or offshore. In the example wellsite system **100** shown in FIG. **1**, a toolstring **104** is conveyed in a borehole **108** via a wireline, slickline, and/or other conveyance means **112**. The example wellsite system **100** may be utilized for evaluation of the borehole **108**, cement **116** securing casing **120** within the borehole **108**, a tubular (not shown) secured in the casing **120** (e.g., production services tubing), and/or a subterranean formation **124** penetrated by the borehole **108** in a cased section **150** and/or an open hole section **155**. Although the majority of the wellbore **108** is depicted in FIG. **1** as being cased, a majority of the wellbore may be uncased (“open,” without the casing **120** and cement **116**).

(16) The toolstring **104** is suspended in the borehole **108** from the lower end of the conveyance means **112**. The conveyance means **112** may be a single- or multi-conductor slickline or wireline logging cable spooled on a drum **113** of a winch **115** at the surface **128** of the wellsite from whence the borehole **108** extends. The wellsite surface **128** is the generally planar surface of the terrain (i.e., Earth's surface), a floor of a rig (not shown) at the wellsite, or other equipment at the wellsite, which is perpendicularly penetrated by the borehole **108**. Operation of the winch **115** rotates the drum **113** to reel in the conveyance means **112** and thereby pull the toolstring **104** in an uphole direction **101** in the borehole **108**, as well as to reel out the conveyance means **112** and thereby move the toolstring **104** in a downhole direction **102** in the borehole **108**. The conveyance means **112** may include at least one or more conductors (not shown) that facilitate data communication between the toolstring **104** and surface equipment **132** disposed at the wellsite surface **128**, including through one or more slip rings, cables, and/or other conductors (schematically depicted in FIG. **1** by reference number **133**) electrically connecting the one or more conductors of the conveyance means **112** with the surface equipment **132**. The conveyance means **112** may alternatively transport the tool string without a conductor inside the cable but with at least one module that can autonomously acquire and/or process and/or store downhole measurements in downhole memory without human intervention or communication with the surface equipment **132**.

(17) Although not illustrated as such in FIG. **1**, the winch **115** may be disposed on a service vehicle or a stationary skid/platform. The service vehicle or stationary skid/platform may also contain at least a portion of the surface equipment **132**.

(18) The toolstring **104** comprises a plurality of modules **136**, one or more of which may comprise an elongated housing, mandrel, chassis, and/or structure carrying various electronic and/or mechanical components. For example, at least one of the modules **136** may be or comprise at least a portion of a device for measuring a feature and/or characteristic of the borehole **108**, the casing **120**, a tubular installed in the casing **120** (not shown), the cement **116**, and/or the formation **124**, and/or a device for obtaining sidewall or inline core and/or fluid (liquid and/or gas) samples from the borehole **108** and/or formation **124**. Other implementations of the downhole toolstring **104** within the scope of the present disclosure may include additional or fewer components or modules **136** relative to the example implementation depicted in FIG. **1**.

(19) The wellsite system **100** also includes a data processing system that may include at least a portion of one or more of the surface equipment **132**, control devices and/or other electrical and/or mechanical devices in one or more of the modules **136** of the toolstring **104** (such as a downhole controller **140**), a remote computer system (not shown), communication equipment, and/or other equipment. The data processing system may include one or more computer systems or devices and/or may be a distributed computer system. For example, collected data or information may be stored, distributed, communicated to a human wellsite operator, and/or processed locally (downhole or at surface) and/or remotely.

(20) The data processing system may, whether individually or in combination with other system components, perform the methods and/or processes described below, or portions thereof. For example, the data processing system may include processor capability for collecting caliper, acoustic, ultrasonic, and/or other data related to the evaluation of the cement **116**, the casing **120**, a tubular installed in the casing **120** (not shown), and/or the formation **124**, according to one or more aspects of the present disclosure. Methods and/or processes within the scope of the present disclosure may be implemented by one or more computer programs that run in a processor located, for example, in one or more modules **136** of the toolstring **104** and/or the surface equipment **132**. Such programs may utilize data received from the downhole controller **140** and/or other modules **136** and may transmit control signals to operative elements of the toolstring **104**, where such communication may be via one or more electrical or optical conductors of the conveyance means **112**. The programs may be stored on a tangible, non-transitory, computer-usable storage medium associated with the one or more processors of the downhole controller **140**, other modules **136** of the toolstring **104**, and/or the surface equipment **132**, or may be stored on an external, tangible, non-transitory, computer-usable storage medium that is electronically coupled to such processor(s). The storage medium may be one or more known or future-developed storage media, such as a magnetic disk, an optically readable disk, flash memory, or a computer-readable device of another kind, including a remote storage device coupled over one or more wired and/or wireless communication links, among other examples.
(21) As designated in FIG. **1** by reference number **138**, at least one of the modules **136** may be or comprise a downhole acoustic measurement tool operable for acquiring acoustic measurements characterizing the borehole **108**, the casing **120**, a tubular installed in the casing **120** (not shown), the cement **116**, and/or the formation **124**. The downhole acoustic measurement tool **138** comprises a phased array module **139** of acoustic transducers (“active elements”) that may each be operated as an acoustic transmitter and/or receiver. Example implementations of the downhole acoustic measurement tool **138** within the scope of the present disclosure are described below.
(22) As designated in FIG. **1** by reference number **142**, another one (or more) of the modules **136** may be or comprise an orientation module permitting measurement of the azimuth of the downhole acoustic measurement tool **138**. Such module **142** may include, for example, one or more of a relative bearing (RB) sensor, a gravity/acceleration sensor, a magnetometer, and a gyroscopic sensor.
(23) As designated in FIG. **1** by reference number **146**, another one (or more) of the modules **136** may be or comprise a centralizer module. For example, the centralizer module **146** may comprise an electric motor driven by a controller (neither shown) and/or other means for actively extending (“opening”) and retracting (“closing”) a plurality of centralizing arms **147**. Although only two centralizing arms **147** are depicted in the example implementation shown in FIG. **1**, other implementations within the scope of the present disclosure may have more than two centralizing arms **147**. Extension of the centralizing arms **147** aids in urging the downhole acoustic measurement tool **138** to a central position within the casing **120**, another tubular, or the borehole **108** being investigated by the downhole acoustic measurement tool **138**. Implementations of toolstrings within the scope of the present disclosure may include more than one instance of the downhole acoustic measurement tool **138** and/or more than one instance of the centralizer module **146**. The modules **136** may be conveyed in either or both of open-hole sections **150** and cased-hole sections **155**, including implementations in which the centralizer module **146** and the phased array module **138** may be configured or configurable for use in either or both of the two sections. The toolstring **104** may also not comprise the centralizer module **146**, or may comprise another type of centralizer module, such as a passive centralizer module.
(24) FIG. **2** is a perspective view of at least a portion of an example implementation of active elements **202** of a phased array **200** that is a part of the acoustic measurement tool **138** according to one or more aspects of the present disclosure. The phased array **200** is an example implementation

of the phased array module **139** shown in FIG. **1**. The phased array **200** permits obtaining azimuthal measurements relative to the borehole, perhaps without mechanical rotation of the downhole acoustic measurement tool **138**.

(25) The example phased array **200** depicted in FIG. **2** comprises active elements **202** arranged in one or plural rows **204** and plural columns **206** extending around a central axis **208**. However, implementations of the phased array **200** and other phased arrays within the scope of the present disclosure may include different numbers (including one) of rows **204** and/or columns **206**. The phased array **200** may be configured such that the transducer elements **202** are collectively disposed azimuthally around a substantial portion (e.g., more than 50%) of the tool, perhaps the entire periphery of the tool, as depicted in FIG. **2**. However, the phased array **200** may include one or plural segments **210** that consists of plural elements **202**, as depicted by the phased array **201** shown in FIG. **3**. Azimuthal and axial elements **202** numbers depicted in one segment **210** are identical as an example. Other implementations of different numbers of elements **202** along azimuthal and axial direction are also within the scope of the present disclosure. The phased array **201** can be made of plural segments **210** that consists of different numbers of elements, are also within the scope of the present disclosure. The minimum number of elements **202** in the segment **210** along the orthogonal direction to azimuthal or axial phased array is 1. The segments **210** may also be immediately adjacent to one another, but they may also be spaced apart azimuthally and or axially with overlapping or non-overlapping elements in axial or azimuthal direction respectively. The shape of the segments **210** is not necessarily circumferentially rectangular as in FIG. **3**.

(26) The active part of acoustic transducers consists of a piezoelectric material. The shape of this piezoelectric element dictates the characteristics of the signals that the transducer emits and receives. However, in addition to the intended signal, the element can also generate parasitic signals that may be inherent to the shape of the element. These parasitic signals can hamper the application for which the transducer is built. Other potential parasitic signals can stem from the characteristics of the phased-array **200** or the segment **210** of which the piezoelectric element may be part, or of the general 3D structure of the phased-array or segment as shown later on in FIG. **10**.

(27) In the application of casing-thickness and annular impedance measurements for well-integrity evaluation, the frequency content of the signals from transducers is preferably wide-band and stable over a predefined range of frequencies. The piezoelectric elements are designed in a way that their emitted and received signal sensitivities are increased in the predefined range of frequencies thanks to their thickness-mode resonance. For such efficient emission and reception, the thickness of each element is preferably close to half the wavelength of the acoustic wave along thickness direction near the casing-thickness resonance frequency.

(28) The other dimensions of the element are dictated by the intended spatial resolution, signal strength, and/or available space for the transducer and/or numbers of driving circuit switches and connectors that are available in the acoustic measurement tool **139**. In multi-element phased array transducers, a certain number of elements are required, and their relative spacing (pitch) is determined by acoustics. These “secondary” elemental dimensions, in combination with the material properties of piezoelectric element, may excite unwanted signals at frequencies that are within the bandwidth of interest and that can be problematic for inverting signals from the casing **120** or another tubular **108** when their frequency bands are substantially close each other. The present disclosure introduces aspects that can be utilized to alleviate the parasitic modes.

(29) FIG. **4** is a graph depicting electrical impedance curves **300** resulting from numerical simulations of rectangular piezoelectric elements (or strips) in which just the thickness mode is permitted to exist. Each curve corresponds to the impedance curve of different width (ww) that is incremented by 11 percent of the minimum width **301**. The impedance curves **300** vary from the one from the minimum width **301** to the one from the maximum width **302**. The resulting impedance plot **300** confirms the idealized response, showing only resonant and anti-resonant peaks associated to the thickness resonance over the frequency band of interest for the

measurement, and the width of the element having no appreciable changes in impedance curve shapes except the vertical offsets resulting from electrical capacitance increase proportional to the width of the element.
(30) FIG. **5** is a graph depicting impedance curves **303** resulting from a similar numerical simulation allowing resonance modes also in the "secondary" elemental dimension, i.e. the width of the element. Parasitic modes **306**, **308** are present, notably in the sub-frequency ranges **307**, **309** of the frequency range of interest **310**. A wider element may decrease the amplitude of one parasitic contribution, for example, the parasitic resonance present in the sub-frequency range **307** can be reduced by decreasing the width element, however, the higher-order parasitic modes in another sub-frequency band **309** are still present and are shifted to frequencies closer to the center of the frequency range of interest **306** in these examples.
(31) FIG. **6** depicts an example implementation of a multi-elemental transducer **400** according to one or more aspects of the present disclosure. The transducer **400** is similar in form and function to one of the segments of transducer **210** shown in FIG. **3**. The transducer **400** can be a multi-element rectangular transducer. However, instead of rows **204** and columns **206** of active elements **202**, the transducer **210** is presented in multiple columns **406** and single row **404** which does not limit having multiple rows along the axial length **408**, as would be the case in a matrix-array. FIG. **6** depicts the transducer **400** as having been unrolled and lying flat on the surface of the page. FIG. **7** is an end view of the transducer **400**, depicting the elements **402** as being members extending from a backing **406**. Thickness **410** is set in such that the element excites its thickness mode resonance in the predetermined frequency range. Between the elements **402** and the backing **406**, an interface layer **415** that consists of one or more materials may be present. The materials of the interface layer are, for example, piezoelectric, electrical conductor or an acoustic impedance matching layer. Space **418** between piezoelectric elements **402** is an inter-element that is filled with filler material having more compliant mechanical properties than that of the piezoelectric elements **402**.
(32) Under the constraint of the total number of column elements **406** being fixed, parasitic modes can be reduced by slightly tapering the rectangular elements **402**, as depicted by the example transducer **420** in FIG. **8**A. The transducer **420** can be a multi-element rectangular transducer. Again, only a single row is depicted, which does not limit having multiple rows along the axial length **442** in the direction **440**, as would be the case in a matrix array. A general matrix-array shape is shown in FIG. **8**B. The parasitic mode can be smeared out and efficiently destructed, as depicted in the impedance curves **304** shown in FIG. **9**. In this particular example, the transducer **420** may have a rectangular outer-shape of the segment **210** depicted in FIG. **3** and of the total number of elements.
(33) In other words, each piezoelectric element **422** of the transducer **420** has a first axial end **424** and a second axial end **426**, wherein the second axial end **426** is wider than the first axial end **424** in a direction **421** along a circumference of the transducer **420** (e.g., across the page in FIG. **8**A). An outer-rectangular shape can be realized by taking a set of circumferential elements indicated in the horizontal range **421** as a representative of the transducer segment **210** depicted in FIG. **3**. Other elemental patterns are also within the scope of the present disclosure as are patterns that lead to non-rectangular outer shapes. The impedance curves depicted in FIG. **9** are numerical simulations for different values of a parameter "pp" that is the difference between the first **424** and second **426** axial ends varying from the minimum pp value of 0 to the maximum value of 66 percent by 22 percent increment, as examples. The corresponding four impedance curves **430**, **431**, **432**, **433** are presented in FIG. **9** in the order of the pp values. The impedance curves depicted in FIG. **9** indicate that the amplitude of the parasitic mode is greatly reduced by this reshaping of the elements **422**, comparing two curves (**432**, **433**) at the pp values respectively at 44 and 66 percent to the curve at pp value at 0 percent **430**.
(34) The piezoelectric elements **422** may be positioned azimuthally around one or more portions of a circumference of the transducer, similar to as shown in FIG. **3**. The piezoelectric elements **422**

may instead be azimuthally distributed around the full circumference of tool, similar to as shown in FIG. **2**.

(35) Each piezoelectric element **422** may be elongated in a direction **440** parallel to a longitudinal axis of the downhole acoustic measurement tool **138** and/or the central axis **208** of the transducer **420**. An axial length **442** of each piezoelectric element **422** is may be some factor larger than an average width of the first **424** and second **426** axial ends. For example, each first axial end **424** may have a width **444** of 50 percent and each second axial end **426** may have a width **446** of 150 percent, such that the average width of each element **422** is 100 percent. Aforementioned dimensions are merely examples and other dimensions are also within the scope of the present disclosure, as are paired elemental widths that do not average to 100 percent, for example when combining the trapezoidal shape with the below presented random elemental width.

(36) In this particular example, each neighboring pair of the piezoelectric elements **422** includes a first piezoelectric element **422***a* and a second piezoelectric element **422***b*, such that the first axial end **424** of each first piezoelectric element **422***a* is at an upper end **448** of the transducer **420** and the first axial end **424** of each second piezoelectric element **422***b* is at a lower end **450** of the transducer **420**. Also in this particular example, each piezoelectric element **422** includes a radially outer edge **452** extending parallel to the longitudinal axis **208** of the transducer **420**. Thus, a radially outward surface of each piezoelectric element **422** may form a right trapezoid. Other implementations with non-parallel edges or non-uniform upper and lower transducer endings are also within the scope of the present disclosure.

(37) When inspecting casing or production tubing with an acoustic (e.g., ultrasonic) phased array transducer disposed in the circumference of a cylindrical tool, it is possible to fire the phased array elements in different apertures and then combine several types of measurements. The piezoelectric elements are excited on their thickness to produce the intended signal. By cutting such active area in sub-elements or segment that consists of at least one element, parasitic modes are occurring in the other dimensions different from the thickness, e.g. the width, in other words, tool circumference or lateral direction. Typically, the modes induced by the width of the elements can be interfering with the modes related to their thickness. This can be addressed by one or more aspects described above.

(38) Other unintended modes are also related to the pattern of the array which is periodic and presents an interference other than the one attributed to the lateral mode of the single element. Such an unintended mode may be related to Lamb and leaky modes (or interface modes), propagating in a lateral direction of the periodic phased array and interfacing with well fluid. The characteristic propagation speeds and energies are modulated by the periodicity of the phased array. Such modes can be transmitted into the fluid as a result of mode conversions at the piezoelectric and inter-element boundaries due to acoustic impedance discontinuities, and may deteriorate phased array signals for resonant target characterizations, such as downhole cement evaluation applications using casing resonance analysis, as described in U.S. Pat. No. 5,216,638. The following description pertains to aspects directed to reducing the influence of such interference by adding an “alea”, which is defined as a “randomness” or “perturbation” to the pitch, and is intended to break the periodicity of the array.

(39) Lamb modes are well known to be present in parts presenting plate geometries, plane or cylindrical. These can be symmetric or antisymmetric.

(40) FIG. **10** is a perspective view of a portion of a transducer **500** that is similar to the transducer **400** shown in FIGS. **6** and **7**. The transducer **500** has a periodic structure with rectangular piezoelectric elements **502** each having a constant width **504** and a thickness **506**. The elements **502** are disposed with a constant pitch **508**. The elements **502** extend from a backing **512**. Between the elements **502** and the backing **512**, an interface layer **515** that consists of one or more materials may be present.

(41) A measurement of the radial displacement **516** at the front face **514** of the array of elements

502 shows the deformation of the array when an element is excited, and shows that this deformation is related to the pattern of the pitch **508**. As such pattern is perfectly periodic, a very sharp interference may appear in the frequency range **310**. This can be resolved by modifying the pitch **508** by introducing an "alea" (defined as a fraction of the pitch preferably in the order of several percent to several 10 percent) that is distributed randomly or deterministically between the elements **502** while maintaining the average pitch **508** across the array. The displacement **516** depicted is merely for an example, and may vary in the interested frequency range of interest **310**, defined by the lower and upper limits respectively F.sub.LL and F.sub.UL.
(42) FIG. **11** depicts an example implementation of such a transducer **520**, in which two of the elements **502** have the 100% of the original rectangular element width **504**, while two elements **522** have a width of about 78 percent of the original width **504**, two elements **524** have a width of about 122 percent of the original width **504**, one element **526** has a width of 61 percent of the original width **504**, and one element **528** has a width of 139 percent of the original width **504**. The spacing between each neighboring element remains the same as in FIG. **10**. Moreover, the average pitch **508** and width **504** of the elements of the array remains the same as for the transducer **500** shown in FIG. **10**.
(43) The objective is to randomize or distribute differently the structure to minimize the excitation mode related to the periodic array. Since the pitch is no longer aligned with the deformation profile of the Lamb mode, resulting sharp interference peaks (similar in appearance for example to the peaks **434**, **436** in the sub-frequency ranges **407**, **409**) will be spread over a wider band in the spectrum, and its impact will therefore be largely reduced, again similar to the impact on the impedance curves presented in FIG. **9**.
(44) The piezoelectric elements **502**, **522**, **524**, **526**, **528** may be irregularly pitched azimuthally around one or more portions of a circumference of the tool, similar to as shown in FIG. **3**, or irregularly pitched fully around the circumference of the tool, similar to as shown in FIG. **2**. The axial length of each piezoelectric element **502**, **522**, **524**, **526**, **528** may be some factor larger than an average width of the piezoelectric elements **502**, **522**, **524**, **526**, **528**. One or more of the piezoelectric elements **502**, **522**, **524**, **526**, **528** may be trapezoidal or otherwise non-rectangular as described above with respect to FIG. **8**A. As described below, the piezoelectric elements **502**, **522**, **524**, **526**, **528** may be spaced apart by a distance that is typically some factor smaller than the element width as detailed below.
(45) Parasitic modes visible on the response of a transducer as described herein can also be reduced by using an inter-element spacing that is thinner than the one used on a transducer that presents such parasitic modes. The presence of parasitic modes in the piezoelectric elements of the transducer disturbs the characterization of the resonance of the casing.
(46) The interelement spacing in the transducer **500** shown in FIG. **10** has the value of W1. FIG. **12** depicts an example implementation of a similar transducer **550** with a thinner interelement spacing **552** of W2 (W2<W1) which permits an increase of the width of the elements **554** by (W1−W2), while pitch and thickness remain the same.
(47) The thinner interelement spacing reduces the consequences of parasitic modes. For example, whereas the wider interelement spacing may provide a clear resonance in the frequency band of interest **310** used to process the pulse-echo signal, the thinner interelement may push the parasitic mode out of the frequency band of interest.
(48) If we consider N a frequency constant linked to this parasitic mode, it can be determined as: N=(d.sub.ie)(f.sub.ie). Considering the implementation depicted in FIG. **10**, if the interelement spacing (d.sub.ie=W1) is generating a perturbation at f.sub.ie=f1, then N=f1*W1. However, considering the implementation depicted in FIG. **12**, the thinner interelement spacing of d.sub.ie=W2 with same constant N raises the frequency of perturbation to f.sub.ie=f1*W1/W2. To push this parasitic mode frequency outside of the upper limit of the frequency band of interest F.sub.UL, W2 can be determined as W2<W1*f1/F.sub.UL. This thinner interelement spacing may

also be utilized with the non-rectangular and/or irregularly pitched implementations described above.

(49) The phased array can have several configurations. In one or more embodiments, the phased array can include a thin inter-element located between adjacent piezoelectric elements. The each piezoelectric elements can have a shape of a right trapezoid, a isosceles trapezoid, or rectangular. The pitch of the piezoelectric elements can be irregularly pitched azimuthally around one or more portions of a circumference of the transducer or can be pitched regularly around the circumference of the transducer at a predetermined pitch. In one or more embodiments, the piezoelectric elements can be aligned at their edge in an even fashion or in an uneven fashion. In one or more embodiments, piezoelectric elements can be in a 1 dimensional or 2 dimensional fashion.

(50) In one none limiting example, the phased array can include piezoelectric elements with a thin inter-element located therebetween, the piezoelectric elements can have a right trapezoid shape, the piezoelectric elements can be irregularly pitched azimuthally around one or more portions of a circumference of the transducer, the edges of the piezoelectric elements can be evenly aligned, and they can be arranged in a 1 D fashion. In another embodiment, the piezoelectric elements can be unevenly aligned at their edge

(51) In another none limiting example, the phased array can include rectangular shaped piezoelectric elements that are irregularly pitched azimuthally around one or more portions of a circumference of the transducer, and the edges of the piezoelectric elements can be evenly aligned at their edge. The piezoelectric elements can be arranged in a 1 dimensional fashion. In another embodiment, the piezoelectric elements can be unevenly aligned at their edge

(52) In another none limiting example, the phased array can include rectangular shaped piezoelectric elements that are regularly pitched azimuthally around one or more portions of a circumference of the transducer, and the edges of the piezoelectric elements can have an evenly alignment at their edge. The piezoelectric elements can be arranged in a 1 dimensional fashion. In another embodiment, the piezoelectric elements can be unevenly aligned at their edge

(53) In another none limiting example, the phased array can include rectangular shaped piezoelectric elements that are irregularly pitched azimuthally around one or more portions of a circumference of the transducer, and the edges of the piezoelectric elements can be unevenly aligned at their edge. The piezoelectric elements can be arranged in a 1 dimensional fashion. In one or more embodiments, the piezoelectric elements can have an evenly alignment at their edge. In one none limiting example, the phased array can include piezoelectric elements with a thin inter-element located therebetween, the piezoelectric elements can have a right trapezoid shape, the piezoelectric elements can be regularly pitched azimuthally around one or more portions of a circumference of the transducer, the edges of the piezoelectric elements can be unevenly aligned, and they can be arranged in a 1 D fashion. In another embodiment, the piezoelectric elements can be evenly aligned at their edge.

(54) In one or more embodiments, the piezoelectric elements can include an thin inter-element, have an isosceles trapezoid shape, one of a random pitch or an unique pitch, and one of and even or uneven edge alignment. In any of the foregoing examples, the piezoelectric elements can isosceles trapezoidal in shape, right trapezoidal in shape, or rectangular in shape. Furthermore, in any of the foregoing examples, the phased array can include piezoelectric elements arranged in a 2 dimensional fashion.

(55) In one or more embodiments an apparatus can include a downhole acoustic measurement tool that has a transducer. The transducer is operable for emitting and/or receiving acoustic signals to perform downhole measurements. The transducer has a plurality of piezoelectric elements. Each of the piezoelectric elements has a first axial end and a second axial end, and the second axial end is one of wider than the first axial end or equal to the first axial end in a direction along a circumference of the transducer.

(56) In one or more embodiments of the foregoing apparatus, the piezoelectric elements are

positioned azimuthally around one or more portions of a circumference of the transducer.
(57) In one or more embodiments of the foregoing apparatus, the piezoelectric elements are azimuthally distributed around a circumference of the transducer.
(58) In one or more embodiments of the foregoing apparatus, each piezoelectric element is elongated in a direction parallel to a longitudinal axis of the downhole acoustic measurement tool, wherein an axial length of each piezoelectric element is larger than an average width of first and second axial ends. In one or more embodiments of the foregoing apparatus, the piezoelectric elements are irregularly pitched azimuthally around one or more portions of a circumference of the transducer. In one or more embodiments of the foregoing apparatus, the piezoelectric element has a first width L0 at a first end and L1 at a second end, and wherein L0 is one of equal to L1, greater than L1, or less than L1.
(59) In one or more embodiments of the foregoing apparatus, each neighboring pair of the piezoelectric elements includes a first piezoelectric element and a second piezoelectric element. The first axial end of each first piezoelectric element is at an upper end of the transducer; and the first axial end of each second piezoelectric element is at a lower end of the transducer. In one or more embodiments of the foregoing apparatus, each piezoelectric element includes a radially outer edge extending parallel to a longitudinal axis of the transducer. In one or more embodiments of the foregoing apparatus, a radially outward surface of each piezoelectric element forms a right trapezoid. In one or more embodiments of the foregoing apparatus, the piezoelectric elements are spaced apart by no more than the distance defined by W1*f1/F.sub.UL, where F.sub.UL is the upper limit of the frequency band of interest, W1 is the width of the transducer interelement spacing that produces parasitic mode at frequency f1. In one or more embodiments of the foregoing apparatus, the piezoelectric elements are irregularly pitched azimuthally around one or more portions of a circumference of the transducer.
(60) In another embodiment, the apparatus is a downhole acoustic measurement tool that has a transducer. The transducer is operable for emitting and/or receiving acoustic signals to perform downhole measurements, and the transducer comprises a plurality of piezoelectric elements. The piezoelectric elements are irregularly pitched azimuthally around one or more portions of a circumference of the transducer. the piezoelectric elements are irregularly pitched fully around the circumference of the transducer.
(61) In one or more embodiments of the foregoing apparatus, each piezoelectric element is elongated in a direction parallel to a longitudinal axis of the downhole acoustic measurement tool, and wherein an axial length of each piezoelectric element is larger than an average width of the piezoelectric elements.
(62) In one or more embodiments of the foregoing apparatus, the piezoelectric elements are irregularly pitched azimuthally around one or more portions of a circumference of the transducer.
(63) In one or more embodiments of the foregoing apparatus, each neighboring pair of the piezoelectric elements includes a first piezoelectric element and a second piezoelectric element; and the first axial end of each first piezoelectric element is at an upper end of the transducer. The first axial end of each second piezoelectric element is at a lower end of the transducer.
(64) In one or more embodiments of the foregoing apparatus, the piezoelectric elements are spaced apart by no more than the distance defined by W1*f1/F.sub.UL, where F.sub.UL is the upper limit of the frequency band of interest, W1 is the width of the transducer interelement spacing that produces parasitic mode at frequency f1. In one or more embodiments of the foregoing apparatus, each piezoelectric element has a first axial end and a second axial end, and wherein the second axial end is wider than or equal to the first axial end in a direction along a circumference of the transducer, each piezoelectric element is elongated in a direction parallel to a longitudinal axis of the downhole acoustic measurement tool, and wherein an axial length of each piezoelectric element is larger than an average width of the piezoelectric elements, wherein the piezoelectric elements are spaced apart by no more than the distance defined by W1*f1/F.sub.UL, where F.sub.UL is the

upper limit of the frequency band of interest, W1 is the width of the transducer interelement spacing that produces parasitic mode at frequency f1, wherein the piezoelectric elements are irregularly pitched fully around the circumference of the transducer, or combinations thereof.
(65) In another embodiments of the apparatus, the apparatus is a downhole acoustic measurement tool comprising a transducer. The transducer is operable for emitting and/or receiving acoustic signals to perform downhole measurements. The transducer includes a plurality of piezoelectric elements spaced apart by no more than the distance defined by W1*f1/F.sub.UL, where F.sub.UL is the upper limit of the frequency band of interest, W1 is the width of the transducer interelement spacing that produces parasitic mode at frequency f1. In one or more embodiments of the foregoing apparatus, the piezoelectric elements are irregularly pitched azimuthally around one or more portions of a circumference of the transducer.
(66) The foregoing outlines features of several embodiments so that a person having ordinary skill in the art may better understand the aspects of the present disclosure. A person having ordinary skill in the art should appreciate that they may readily use the present disclosure as a basis for designing or modifying other processes and structures for carrying out the same functions and/or achieving the same benefits of the embodiments introduced herein. A person having ordinary skill in the art should also realize that such equivalent constructions do not depart from the spirit and scope of the present disclosure, and that they may make various changes, substitutions and alterations herein without departing from the spirit and scope of the present disclosure.
(67) The Abstract at the end of this disclosure is provided to comply with 37 C.F.R. § 1.72 (b) to permit the reader to quickly ascertain the nature of the technical disclosure. It is submitted with the understanding that it will not be used to interpret or limit the scope or meaning of the claims.

Claims

1. An apparatus comprising: a downhole acoustic measurement tool comprising a transducer, wherein: the transducer is operable for emitting and/or receiving acoustic signals to perform downhole measurements; the transducer comprises a plurality of piezoelectric elements; the piezoelectric elements are spaced apart by no more than the distance defined by W1*f1/F.sub.UL, where F.sub.UL is an upper limit of a frequency band of interest, and W1 is a width of the transducer interelement spacing that produces parasitic mode at frequency f1; and each piezoelectric element has a first axial end and a second axial end, wherein the second axial end is one of wider than the first axial end or equal to the first axial end in a direction along a circumference of the transducer.
2. The apparatus of claim 1 wherein the piezoelectric elements are positioned azimuthally around one or more portions of a circumference of the transducer.
3. The apparatus of claim 1 wherein the piezoelectric elements are azimuthally distributed around a circumference of the transducer.
4. The apparatus of claim 1 wherein each piezoelectric element is elongated in a direction parallel to a longitudinal axis of the downhole acoustic measurement tool, wherein an axial length of each piezoelectric element is larger than an average width of first and second axial ends.
5. The apparatus of claim 1 wherein the piezoelectric elements are irregularly pitched azimuthally around one or more portions of a circumference of the transducer.
6. The apparatus of claim 1, wherein each piezoelectric element has a first width LO at a first end and L1 at a second end, and wherein LO is one of equal to L1, greater than L1, or less than L1.
7. The apparatus of claim 1 wherein: each neighboring pair of the piezoelectric elements includes a first piezoelectric element and a second piezoelectric element; the first axial end of each first piezoelectric element is at an upper end of the transducer; and the first axial end of each second piezoelectric element is at a lower end of the transducer.
8. The apparatus of claim 6 wherein each piezoelectric element includes a radially outer edge

extending parallel to a longitudinal axis of the transducer.
9. The apparatus of claim 1 wherein a radially outward surface of each piezoelectric element forms a right trapezoid.
10. An apparatus comprising: a downhole acoustic measurement tool comprising a transducer, wherein: the transducer is operable for emitting and/or receiving acoustic signals to perform downhole measurements; the transducer comprises a plurality of piezoelectric elements; the piezoelectric elements are spaced apart by no more than the distance defined by W1*f1/F.sub.UL, where F.sub.UL is an upper limit of a frequency band of interest, and W1 is a width of the transducer interelement spacing that produces parasitic mode at frequency f1; and the piezoelectric elements are irregularly pitched azimuthally around one or more portions of a circumference of the transducer.
11. The apparatus of claim 10 wherein the piezoelectric elements are irregularly pitched fully around the circumference of the transducer.
12. The apparatus of claim 10 wherein each piezoelectric element is elongated in a direction parallel to a longitudinal axis of the downhole acoustic measurement tool, and wherein an axial length of each piezoelectric element is larger than an average width of the piezoelectric elements.
13. The apparatus of claim 10 wherein: each neighboring pair of the piezoelectric elements includes a first piezoelectric element and a second piezoelectric element; a first axial end of each first piezoelectric element is at an upper end of the transducer; and a first axial end of each second piezoelectric element is at a lower end of the transducer.
14. The apparatus of claim 10 wherein each piezoelectric element has a first axial end and a second axial end, and wherein the second axial end is wider than or equal to the first axial end in a direction along a circumference of the transducer, each piezoelectric element is elongated in a direction parallel to a longitudinal axis of the downhole acoustic measurement tool, wherein an axial length of each piezoelectric element is larger than an average width of the piezoelectric elements, and wherein the piezoelectric elements are irregularly pitched fully around the circumference of the transducer.
15. An apparatus comprising: a downhole acoustic measurement tool comprising a transducer, wherein: the transducer is operable for emitting and/or receiving acoustic signals to perform downhole measurements; and the transducer comprises a plurality of piezoelectric elements spaced apart by no more than the distance defined by W1*f1/F.sub.UL, where F.sub.UL is an upper limit of a frequency band of interest, and W1 is a width of the transducer interelement spacing that produces parasitic mode at frequency f1.
16. The apparatus of claim 15 wherein the piezoelectric elements are positioned azimuthally around one or more portions of a circumference of the transducer.
17. The apparatus of claim 15 wherein the piezoelectric elements are azimuthally distributed around a circumference of the transducer.