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(54) METHOD AND APPARATUS FOR PRE-LOADING A PIEZOELECTRIC TRANSDUCER FOR DOWNHOLE ACOUSTIC COMMUNICATION

VERFAHREN UND VORRICHTUNG ZUM VORSPANNEN EINES PIEZOELEKTRISCHEN WANDLERS FÜR AKUSTISCHE BOHRLOCHKOMMUNIKATION

PROCÉDÉ ET APPAREIL DE PRÉCHARGE D'UN TRANSDUCTEUR PIÉZOÉLECTRIQUE POUR COMMUNICATION ACOUSTIQUE EN FOND DE TROU

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(56) References cited:

WO-A1-2015/156768	**CN-A- 103 774 993**
US-A- 3 992 694	**US-A- 4 129 850**
US-A- 4 283 780	**US-A- 5 166 908**
US-A- 5 274 606	**US-A- 6 137 747**
US-A1- 2008 316 866	**US-A1- 2012 103 619**

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Description

Field

[0001] This disclosure relates generally to a downhole acoustic transmitter having a pre-loaded piezoelectric transducer and a method for pre-loading a piezoelectric transducer for use in downhole communication such as downhole acoustic telemetry.

Background

[0002] The evolution of modern oil and gas wells has led to increases in both the depth of the wells and the complexity of the procedures and equipment needed for drilling and completions operations. Additionally, there is an ongoing need for improved safety and efficiency in the drilling and completions process. The combination of these factors has created a need for improved visibility of the downhole conditions along the length of the drill string and at the bottom hole assembly (BHA) during drilling and completions operations. Downhole sensor measurements such as downhole bore and annular pressure, drill string torque and tension, and temperature can be transferred from a downhole location to the surface through one of several known telemetry methods.

[0003] One type of downhole communication method is wired drill pipe telemetry, which offers very high bandwidths, but tends to be expensive to deploy and prone to failure. Another known downhole communication method is mud pulse telemetry which encodes sensor data into pressure waves that are induced in the drilling fluid flowing in the drill string. Drawbacks to mud pulse telemetry include an inability to transmit when drilling fluid is not flowing, and relatively low data rate transmissions which decrease as the depth of the well increases. A third type of downhole communication is electromagnetic (EM) telemetry, which transmits digitally modulated electromagnetic waves through the formations surrounding the drill string to a surface receiver. EM telemetry does not require the flow drilling fluid and can provide a higher data transmission rate than mud pulse telemetry, but can be sensitive to the nature of the formations surrounding the well and may not be well suited for deeper wells.

[0004] A fourth type of downhole communication is acoustic telemetry, which has proven to be well suited for the modern drilling environment. Acoustic telemetry is capable of transmitting hundreds of bits per second, and since it uses the body of the drill pipe as its transmission medium it is insensitive to the surrounding formation or casing, and does not require any fluid flow to enable the transmission of data.

[0005] There are currently three different implementations of acoustic telemetry systems in downhole tools that use acoustic telemetry: probe-based, clamp-on, and collar-based. These systems typically comprise components including sensors, electronics, batteries and an acoustic transmitter. The probe-based implementation is mounted at least partially within the bore of the drill pipe. The clamp-on implementation is mounted on the external wall of the drill pipe. The collar-based implementation places the components within an annular space in the downhole tool.

[0006] In a typical drilling or completions environment, a number of acoustic transmitters can be spaced along the length of the drill string. The most common type of acoustic transducer used within downhole tools comprises a cylindrical piezoelectric stack mounted in a collar-based implementation. Such a stack comprises a number of thin piezoceramic discs layered with thin electrodes between each disc which are connected electrically in parallel. As is known in the art, such as disclosed in US 6,791,470, an advantage of the piezoelectric stack when compared to other acoustic transducer types is that the acoustic impedance of the stacked ring structure can be closely matched to the acoustic impedance of the tool's structure thereby optimizing the transfer of acoustic energy from the stack into the tool body, and subsequently into the drill string. Any acoustic impedance mismatch between the stack and the tool surrounding structure results in a reduction in the acoustic output power of the tool.

[0007] The piezoelectric stack structure offers a large displacement force combined with a high energy conversion efficiency and high compressive strength, but offers little resistance to tension, even that incurred when voltage is applied. Due to its low tensile strength, it is common practice to place a piezoelectric stack under a mechanical compressive preload along the stack's axis of operation in order to maintain stack integrity while being actuated. The magnitude of the preload can compensate for dynamic forces, but also affects the mechanical energy output from the stack. If there is no compressive preload or if the compressive preload exceeds the blocking force of the piezoelectric material, then there is no mechanical energy output from the stack. An optimum preload level that will maximize the output mechanical energy from the stack occurs when the stiffness of the preloaded stack is equal to the stiffness of the mechanical load.

[0008] Referring to Fig. 1 , a prior art collar-based piezoelectric stack-type acoustic transmitter 301 comprises first and second thermal expansion compensation rings 302a and 302b, a retaining ring 303, end coupling 304, a steel outer housing 305, a mandrel 306, a pin 307, and a piezoelectric stack 308. The first and second thermal expansion rings 302a and 302b are designed to compensate for the difference between the thermal expansion of the steel housing 305 and the piezoelectric stack 308. The mandrel 306 is threaded into the end coupling 304, and the first thermal expansion compensation ring 302a is slid down the mandrel 306 to an inner face 309 of the end coupling 304. The piezoelectric stack 308 is slid down the mandrel 306 to rest against the first thermal compensation ring 302a. The second thermal compensation ring 302b is slid down the mandrel 306 to rest against the end of the piezoelectric stack 308, and the retaining ring 303 is placed on the mandrel 306 against the second thermal compensation ring 302b. The outer housing 305 is placed over the mandrel 306, first and second thermal compensation rings 302a, 302b and the retaining ring 303 and threaded onto the end coupling 304. The pin 307 is threaded into the housing 305 until the thread is shouldered, and the inner face of the pin 310 is forced against the retaining ring 303 which in turn forces the thermal compensation rings 302a, 302b and the piezoelectric stack 308 against the immoveable inner face 309 of the end coupling 304, thereby creating a compressive preload force on the piezoelectric stack 308. The amount of compressive force on the piezoelectric stack can be controlled by varying the length of the retaining ring 303.

[0009] The prior art acoustic transmitter 301 will maintain a positive compressive preload on the piezoelectric stack 308 over a limited range of tension/compression on the downhole tool. However, in deeper wells such as those drilled offshore, the tension/compression applied to the downhole tool by external forces can result in the tool flexing enough to either reduce the preload to zero, or to compress the piezoelectric stack beyond its compressive limits. Thus there is a need for a method of applying a compressive preload to the piezoelectric stack in a downhole acoustic transmitter that will maintain an effective preload over the entire range of tension and compression applied to the downhole tool by the drill string while operating in a downhole environment.

[0010] US 6137747 discloses an acoustic transmitter that imparts vibratory stresses onto a signal propagation medium such as oil well tubing when actuated by an electric driver.

Summary

[0011] The present invention provides a downhole acoustic transmitter for use in downhole communication as claimed in claim 1.

[0012] The adjustable preload means can comprise one or more spacers contacting an inner face of the second end coupling, or be a retaining ring attached to an inner surface of the outer housing, or be a threaded nut attached to the mandrel. The piezoelectric transducer can comprise an annular stack of annular piezoceramic discs with annular electrodes between each disc, wherein the annular stack is slidable over the mandrel. The preload spring can be a metal tube slidable over the mandrel, or can be one or more metal rods or tubes each extending in the axial direction in the annular space.

[0013] The downhole acoustic transmitter further comprises an acoustic tuning element in the annular space and attached to the second end of the piezoelectric transducer. The acoustic tuning element has a selected acoustic impedance that when combined with the acoustic impedance of the preload spring, equals the acoustic impedance of the inner face of the first end coupling. The acoustic tuning element can comprise a metal cylinder having a first end attached to the second end of the piezoelectric transducer and a free second end. One or more of a mass density, mass distribution, length and cross sectional area of the acoustic tuning element can be selected to provide the selected acoustic impedance.

[0014] According to another aspect, there is provided a downhole acoustic telemetry node which comprises one or more sensors for measuring a local borehole environment and one or more mechanical conditions of a drill string (e.g. pressure, temperature, tension, compression and torque), a processor and memory communicative with the one or more sensors for storing measurements taken by the one or more sensors, and the downhole acoustic transmitter, which is communicative with the processor and memory and is operable to transmit the measurements.

[0015] The present invention also provides a method for acoustic transmission from a downhole location as claimed in claim 14.

Brief Description of Drawings

[0016]

Figure 1 is a schematic side sectioned view of a downhole acoustic transmitter used in a downhole acoustic communication system (PRIOR ART).

Figure 2 is a schematic representation of a drill string comprising a downhole acoustic communication system.

Figure 3 is a frequency response graph of a modulated acoustic signal transmitted by the downhole acoustic communication system of Figure 2.

Figure 4 is a schematic side sectioned view of a downhole acoustic transmitter comprising a preload spring compressed by adjustable spacers according to an arrangement.

Figure 5 is a schematic side sectioned view of a downhole acoustic transmitter comprising a preload spring compressed by an adjustable retaining ring according to an arrangement.

Figure 6(a) is a schematic side sectioned view of a downhole acoustic transmitter comprising a preload spring compressed by an adjustable retaining ring and an acoustic tuning element according to the invention, and Figure

6(b) is a detail view of an interface of the acoustic tuning element and a transducer stack of the downhole acoustic transmitter.

Figure 7 is a schematic side sectioned view of a downhole acoustic transmitter comprising a preload spring compressed by an adjustable threaded nut according to another arrangement.

Figure 8 is a schematic side sectioned view of a downhole acoustic transmitter comprising a preload spring compressed by an adjustable threaded nut and an acoustic tuning element according to the invention

Figure 9(a) is a graph showing a first resonance peak in an example steel cylinder having a first constrained end and a second free end, and Figure 9(b) is a graph showing the magnitude of the cylinder's acoustic impedance across a third acoustic passband of the drill string as shown in Figure 3.

Figure 10 is a graph of the acoustic impedance of a piezoelectric stack and the acoustic impedance of an acoustic tuning element of an example downhole acoustic transmitter.

Figure 11 is an acoustic amplitude vs. frequency graph illustrating the acoustic output of a prior art acoustic transmitter having a fixed preload, the acoustic transmitter with a preload spring and an adjustable preload means as shown in Figure 5, and the acoustic transmitter with a preload spring, adjustable preload means and an acoustic tuning element as shown in Figures 6(a) and (b).

Detailed Description

[0017] Directional terms such as "top", "bottom", "upwards", "downwards", "vertically", and "laterally" are used in the following description for the purpose of providing relative reference only, and are not intended to suggest any limitations on how any article is to be positioned during use, or to be mounted in an assembly or relative to an environment.

[0018] Additionally, the term "couple" and variants of it such as "coupled", "couples", and "coupling" as used in this description is intended to include indirect and direct connections unless otherwise indicated. For example, if a first device is coupled to a second device, that coupling may be through a direct connection or through an indirect connection via other devices and connections. Similarly, if the first device is communicatively coupled to the second device, communication may be through a direct connection or through an indirect connection via other devices and connections.

[0019] Furthermore, the singular forms "a", "an", and "the" as used in this description are intended to include the plural forms as well, unless the context clearly indicates otherwise.

[0020] The embodiments described herein relate generally to a downhole acoustic transmitter having a pre-loaded piezoelectric transducer and a method for pre-loading a piezoelectric transducer for use in downhole acoustic communication such as downhole telemetry. The transmitter comprises an enclosure in which the piezoelectric transducer is housed, a preload spring that biases the transducer against a first end coupling of the enclosure, and an adjustable preload means mounted to the enclosure such that a selected compressive force is applied to the preload spring, which in turn urges the transducer against a face of the first end coupling such that a mechanical preload is applied to the transducer. The position of the adjustable preload means and the spring compliance are selected so that the level of mechanical preload applied to the transducer compensates for an expected amount of flexing of the acoustic telemetry transmitter due to varying tension and compression applied to the transmitter, thereby maintaining an effective preload on the transducer.

[0021] In some embodiments, the downhole acoustic transmitter further comprises an acoustic tuning element positioned to contact the piezoelectric transducer at the same end as the preload spring. The acoustic tuning element is tuned such that the acoustic impedance seen by the piezoelectric transducer at that end, comprising the combination of the acoustic impedance of the tuning element and the acoustic impedance of the preload spring at that end, is equal to the acoustic impedance offered to the transducer at the other end by the face of the first end coupling, thereby maintaining the output power of the transducer while compensating for any variations in the mechanical preload applied by the preload spring.

[0022] Referring now to Figure 2, one or more of the acoustic telemetry transmitters can be installed in a drill string. Drill string tubing 103 is suspended in a borehole 108 from a drilling rig 102. The tubing 103 can extend for thousands of feet (1000 feet is 304.8m), and in a typical deployment an acoustic transmitter is part of a telemetry tool 105 in a bottom hole assembly (BHA) 104. Additional acoustic transmitters can be included in repeaters 106 along the length of the tubing 103, with the number of repeaters 106 and the spacing between them determined by the along-string measurements required, if any, at each of the additional locations, and the possible necessity to repeat the acoustic signal if the distance to the surface is too far to transmit successfully with a single acoustic transmitter. The acoustic signal is received at the surface by a receiver 107.

[0023] The acoustic transmitters in this embodiment have a collar-based configuration, with the components of the acoustic transmitter including the piezoelectric transducer, sensors, electronics and batteries being mounted in a wall of a tubular section of the repeater 106 or the telemetry tool 105. However, the acoustic transmitters can have a probe-based or clamp- on configuration according to other embodiments (not shown). As will be described in more detail below, each acoustic transmitter comprises a mandrel defining a through-bore which allows fluid to pass through repeater 106 or telemetry tool 105. Each acoustic transmitter is operable to transmit a modulated acoustic signal as an extensional wave through the drill string components. The connection of several lengths of tubing 103 of similar size and dimensions is well known to form an acoustic frequency response similar to a bandpass comb filter which comprises a number of passbands alternating with stopbands as shown in Figure 3. The bandwidth of the modulated acoustic signal is limited by the bandwidth of the acoustic passband used for the transmission, although more than one passband can be used to transmit simultaneously which increases the total bandwidth available for the signal and hence the data rate. The telemetry signal travels to the surface, either directly or through the repeaters 106, where it is received and decoded by the receiver 107.

[0024] According to a first arrangement and referring to Figure 4, the acoustic transmitter 401 used in the telemetry tool 105 and repeater 106 generally comprises an enclosure, a transducer 405 housed within the enclosure, a preload spring 407 contacting one end of the transducer 405, and one or more spacers 409 which provide an adjustable means for applying a selected compressive load (herein referred to as "preload") on the transducer 405 via the preload spring 407. The enclosure comprises a first end coupling 402, a tubular outer housing 403, a cylindrical inner mandrel 404 and a second end coupling 410 (also referred to as a "pin"). The first end coupling 402 has a body with threads on the outer surface of the body ("external threads"), and a central bore extending through the body. A first end of the inner mandrel 404 is externally threaded and engages internal threads in the central bore of the first end coupling 402 along a central axis. Both ends of the outer housing 403 are internally threaded, with an internally threaded first end engaging the external threads of the first end coupling 402 and an internally threaded second end engaging external threads of the second end coupling 410. The second end coupling 410 has a body with a bore extending through the body, and which engages a second end of the inner mandrel 404 by a threaded connection. When assembled, the enclosure defines a through bore that extends through the central bores of the end couplings 402, 410 and the bore of the mandrel 404, such that drilling fluid can flow through the acoustic transmitter 401. The assembled enclosure also defines a fluid-tight annular space 408 for housing the transducer 405, preload spring 407, and spacers 409.

[0025] The transducer 405 comprises a stack of thin annular piezoceramic discs layered with thin annular electrodes between each disc which are connected electrically in parallel (the transducer is herein alternatively referred to as a "piezoelectric stack" 405). As a result, the stack's electrical behavior is primarily capacitive. Applying a high voltage charges the piezoelectric stack 405 and causes it to increase and decrease in length. It is this deflection that launches extensional waves into the drill pipe (not shown). Data can be carried by the extensional waves by modulating the voltage applied to the piezoelectric stack 405.

[0026] The piezoelectric stack 405 slides over the mandrel 404 and has a first end that contacts an inner face of the first end coupling 402. The preload spring 407 is shown in Figure 4 as a coil spring that slides over the mandrel 404 with a first end that contacts a second end of the piezoelectric stack 405. However, the preload spring 407 can alternatively have different forms, including a metal cylinder (not shown) of selected length and spring constant that slides over the mandrel 404, or one or more metal rods or tubes (not shown) that extend axially in the annular space between the mandrel 404 and the outer housing 403.

[0027] One or more spacers 409 slide over the mandrel 404 to contact a second end of the preload spring 407. The pin 410 is threaded onto the internally threaded second end of the outer housing 403 such that an inner face of the pin 410 applies axial pressure against the spacer(s) 409, which in turn applies an axial compressive preload against the piezoelectric stack 405. Although only one spacer 409 is shown in Figure 4, additional spacers 409 can be inserted depending on the desired preload to be applied to the piezoelectric stack 405; that is, each spacer 409 has a certain thickness, and the more spacers 409 inserted between the pin end and the preload spring end, the higher the compressive preload will be applied to the transducer 405. The properties of the preload spring 407 are selected to provide a degree of compliance in the preload applied against the transducer 405, i.e. to mitigate against the varying external tensile and compressive forces imposed on the acoustic transmitter 401 during drill string operation.

[0028] That is, the physical environment imposed on the acoustic transmitter 401 can be particularly challenging, with the telemetry tool 106 in particular being subjected to extreme ranges of pressure, temperature, and tension/compression, all of which vary as a function of the tool's placement in the drill string, depth, and the rig's operational state. The orientation of the borehole 108 containing the tubing 103 can be vertical with an inclination of 0 degrees, or may have one or more deviations in orientation along its length resulting in changes of inclination as high as 90 degrees. Due to the length of the tubing 103 and the deviations in its orientation, the tensile and compressive forces that the telemetry tool 106 are subjected to during rig operations can be very high. For example, the telemetry tool 106 may be subject to pressures up to 206843 kPa (30 kpsi), tensions over 453592kg (1,000,000 pounds), and temperatures up to 175 °C. Of particular concern to the piezoelectric stack 405 is the flexing of the tool structure under various load conditions. These varying load conditions can affect the mechanical energy output by the piezoelectric stack 405 as the compressive load on the piezoelectric stack 405 varies. In the extreme, the piezoelectric stack 405 can be depolarized due to excessive compression caused by compression on the tool 106, or be damaged when the stack compression falls below safe operating levels during periods of high tension on the tool 106.

[0029] Because a selected compressive preload is applied to the piezoelectric stack 405 by the spacers 409 via the preload spring 407, the piezoelectric stack 405 can be subjected to relatively large variations in compressive load as the tool 106 is subjected to changes in the drill string tension and compression during the rig's operations. The amount of compressive preload applied to the piezoelectric stack 405 by the preload spring 407 and spacers 409 can be selected by selecting the spring constant of the preload spring 407 and selecting the number of spacers 409 between the preload spring 407 and the pin 410. An appropriate compressive preload maintains a positive compressive preload on the stack 405 over the entire range of tension and compression expected to be applied to the telemetry tool 105 by the drill string during a drilling operation. Determining the appropriate preload will be evident to one skilled in art based on certain properties of the drill string, borehole, reservoir, and drilling operation. Once the appropriate preload is determined, a spring 407 with a suitable spring constant and a suitable number of spacers 409 can be selected to provide the appropriate preload.

[0030] Referring to Figure 5 and according to another arrangement of the acoustic transmitter 501, a retaining ring 509 is used instead of spacers 409 to apply a compressive preload to a transducer 505 via a suitable preload spring 507. Like the first arrangement, this alternative arrangement also comprises an enclosure having first and second end couplings 502, 510, and an outer housing 503 and a mandrel 504 that connect to the end couplings 502, 510 to form a fluid-tight annular space 508 in which the transducer 505, preload spring 507 and retaining ring 509 are housed. The retaining ring 509 is fixedly mounted to the inner surface of the outer housing 503 in a location that provides the desired compressive preload to the transducer 505.

[0031] Referring to Figures 6(a) and (b) and according to the invention an acoustic transmitter 601 has the same elements as the acoustic transmitter 501 shown in Figure 5, and is further provided with an acoustic tuning element 606 that serves to match the acoustic impedance of the piezoelectric stack 605 with the first end coupling 602, thereby maintaining optimal power output by the acoustic transmitter 601. Like the arrangement shown in Figure 5, the acoustic transmitter 601 generally comprises an enclosure, a transducer 605 comprising the piezoelectric stack, a preload spring 607, and a retaining ring 609 for applying an axial compressive preload on the transducer 605 via the preload spring 607. The enclosure comprises a first end coupling 602 with an inner face 611, a tubular outer housing 603, a cylindrical inner mandrel 604 and a second end coupling 610 ("pin"). The acoustic tuning element 606 has a metal tubular body with a first end for contacting the piezoelectric stack 605 and an open second end 612.

[0032] The acoustic tuning element 606 is slid over the mandrel 604 such that the first end attaches to the piezoelectric stack 605 by a threaded connection, while leaving an annular space 608 between the outer surface of the mandrel 604 and the inner face of the acoustic tuning element 606. The preload spring 607 is slid over the mandrel 604 into the annular space 608 between the mandrel 604 and the acoustic tuning element 606 to contact the end of the piezoelectric stack 605. The outer housing 603 is slid over the assembly and threaded onto the external threads of the first end coupling 602, and the retaining ring 609 is slid over the mandrel 604 and comprises external threads which engage with internal threads of the outer housing 603 such that a compressive preload is applied to the piezoelectric stack 605 via the preload spring 607; consequently the piezoelectric stack 605 is compressed between the preload spring 607 and the inner face 611 of the first end coupling 602. The retaining ring 609 does not contact the second end 612 of the tuning element 606; therefore, the second end 612 of the tuning element remains "open". The pin 610 is threaded into the outer housing 603 and mandrel 604 to close and seal the annular space 608 but does not contribute to the preload on the piezoelectric stack 605.

[0033] The acoustic tuning element 606 comprises a resonant structure that is tuned such that when it is attached to the end of the piezoelectric stack 605 its acoustic impedance reduces the piezoelectric stack 605 compliance at the frequencies being transmitted, and restores the acoustic match between the piezoelectric stack 605 and the first end coupling 603 without affecting the preload applied to the piezoelectric stack 605 by the preload spring 607.

[0034] For optimal acoustic output power, the piezoelectric stack 605 should be matched at either end with acoustic impedances equal to that of the piezoelectric stack 605; however the additional compliance of the preload spring 607 reduces the acoustic impedance seen by the piezoelectric stack 605 at the end at which the preload force is applied. The acoustic impedance of a segment of a cylinder of length *l* can be determined using the four-pole matrix solution to the wave equation. The four-pole solution can be written as:

$$\begin{bmatrix} F(x+l) \\ V(x+l) \end{bmatrix} = \begin{bmatrix} cos(kl) & izsin(kl) \\ \frac{isin(kl)}{z} & cos(kl) \end{bmatrix} \begin{bmatrix} F(x) \\ V(x) \end{bmatrix}$$

in which $k = \left(\frac{2\pi f}{c}\right)$, where *c* is the wave speed which is defined as $c = \sqrt{\frac{E}{\rho}}$ where E is the Young's modulus of the cylinder material and ρ is the mass density of the material. The force at one end of the cylinder at *x* + *l* can be written as

$$F(x+l) = F(x)cos(kl) + izV(x)sin(kl) \qquad \text{Equation 1}$$

in which z is the wave impedance of the cylinder which is defined as $z = \rho ca$, and a is the cross sectional area of the cylinder. In the case of a cylinder with an open end $F(x + l) = 0$, resulting in an acoustic impedance at the opposing end of the cylinder of:

$$Z_a(x) = \frac{F(x)}{V(x)} = -\frac{izsin(kl)}{\cos(kl)} = -iztan(kl) \qquad \text{Equation 2}$$

wherein i indicates the imaginary part of a complex number and is defined as the sqrt(-1).

[0035] For example, a steel cylinder 3.2 m long and 0.1 m in diameter and a 3800 mm^2 cross sectional area can be used to represent the combined acoustic impedance of a preload spring and an acoustic tuning element; the acoustic impedance at a first end of the cylinder given a free end at the second end of the cylinder can be calculated using Equation 2. The resulting acoustic impedance contains resonant peaks and nulls which occur at frequencies corresponding to integer multiples of quarter wavelengths of the first resonant frequency. Figure 9(a) shows the first resonance occurring at a cylinder length of $l = \lambda/4$. The resonant impedance peak shown in Figure 9(a) is too high to be of any use, however the acoustic impedance level on the higher frequency side of the resonance peak is low enough to be useful. Figure 9(b) shows the magnitude of the cylinder's acoustic impedance across the third acoustic passband of the drill string as shown in Figure 3. The properties of the tuning element disclosed here is only one possible example; the impedance behavior of the tuning element can be controlled through choice of materials, the length of the tuning element, the mass of the tuning element and the distribution of the mass along the length of the tuning element.

[0036] Figure 6(b) shows a detailed view of the internal components of the acoustic transmitter 601. In particular, a first mechanical interface 613 is shown between the first end coupling 602 and the piezoelectric stack 605, and a second mechanical interface 615 is shown between the the piezoelectric stack 605 and both the cylindrical acoustic tuning element 606 and the preload spring 607. At the first mechanical interface 613, in an acoustically matched system the acoustic impedance Z_1 of the first end coupling 602 would be the same as the acoustic impedance of the piezoelectric stack 605. This condition is also true for the acoustic impedance Z_2 at the second mechanical interface 615. However if only the preload spring 607 is applied then the compliance of the preload spring 607 is too high to offer the required acoustic impedance and the output power of the piezoelectric stack 695 is reduced. The addition of the acoustic tuning element 606 reduces the compliance of the preload, restoring the acoustic impedance to the required value. Ideally, the acoustic tuning element 606 has a selected impedance that when combined with the acoustic impedance of the preload spring 607, equals the acoustic impedance at the first mechanical interface 613, i.e. the acoustic impedance of the first end coupling 602.

[0037] To demonstrate, given a common piezoelectric material with a density of 7.5 Mg/m^3, and a Young's modulus of $9.9 * 10^{10}$ N/m^2 , then a piezoelectric stack with a length of 0.142 m and a cross sectional area of 4200 mm^2 will have a wave impedance of 114Kg/s. Figure 10 shows that the combined acoustic impedance of the tuning element and the preload spring (labeled "cylinder" in Figure 10) is equal to that of the piezoelectric stack at 640 Hz ("center frequency"), with a useable operating frequency bandwidth across the 600 Hz to 700 Hz bandwidth of the third passband of the drill string. In other words, the usable range of acoustic impedance of the tuning element 606 in this example is between 70 kg/s and 160 kg/s for a selected operating frequency bandwidth of 600-700 Hz. While the usable operating frequency bandwidth of the tuning element in this case is about 15% of the center frequency, the usable operating frequency bandwidth and resulting usable acoustic impedance range of the tuning element can vary based on the physical properties of the piezoelectric stack and enclosure, as well as on the operating conditions. Generally speaking, the acoustic impedance of the tuning element is within a selected range that maximizes acoustic power transfer from the piezoelectric stack into the enclosure over a selected usable operating frequency bandwidth. Instead of spacers 409 or a retaining ring 509, other types of adjustable preload means can be used to provide a compressive preload to the transducer via the preload spring. For example, referring to Figure 7 and according to another arrangement, an acoustic transmitter 701 comprises a threaded nut 709 that is mounted to a mandrel 704 to apply a selected compressive preload to a transducer 705 via a preload spring 707. Like the previous arrangements and embodiments, an enclosure comprising first and second end couplings 702, 710, an outer housing 703 and the mandrel 704 provides a fluid tight space 708 to house the transducer 705, preload spring 707, and threaded nut 709. As shown in Figure 8, in accordance with the invention an acoustic tuning element 706 similar to the previous arrangements is installed to match the acoustic impedance of the transducer 705 with the first end coupling 702, thereby maintaining optimal power output by the acoustic transmitter 701.

Claims

1. A downhole acoustic transmitter (601, 701) for use in downhole communication, comprising:

   (a) an enclosure comprising a first end coupling (602, 702), a second end coupling (610, 710), a tubular outer housing (603, 703) having a first end coupled to the first end coupling (602, 702) and a second end coupled to the second end coupling (610, 710), and an inner mandrel (404, 504, 604, 704) inside the outer housing (603, 703) and extending between the first and second end couplings such that an annular space (608) is defined between the mandrel (404, 504, 604, 704) and the outer housing (603, 703);
   (b) a piezoelectric transducer (605, 705) in the annular space (608), and having a first end contacting an inner face of the first end coupling (602) in an axial direction;
   (c) a preload spring (607, 707) in the annular space (608) and having a first end contacting a second end of the piezoelectric transducer (605, 705) in the axial direction;
   (d) an adjustable preload means contacting the enclosure and a second end of the preload spring (607, 707) such that a compressive force in the axial direction is applied to the preload spring (607, 707), which in turn compresses the piezoelectric transducer (605, 705) against the inner face of the first coupling (602, 702);

   the downhole transmitter (601, 701) **characterized by**:
   (e) an acoustic tuning element (606) in the annular space (608) and attached to the second end of the piezoelectric transducer (605), wherein an acoustic impedance of the acoustic tuning element (606) combined with an acoustic impedance of the preload spring (607) is within a selected range of acoustic impedances that encompasses an acoustic impedance of the piezoelectric transducer (605) to maximize power transfer from the piezoelectric transducer (605) into the enclosure over a selected operating frequency bandwidth.

2. The downhole acoustic transmitter (601, 701) as claimed in claim 1 wherein the adjustable preload means comprises one or more spacers (409) contacting an inner face of the second end coupling (402).

3. The downhole acoustic transmitter (601, 701) as claimed in claim 1 wherein the adjustable preload means is a retaining ring (509) attached to an inner surface of the outer housing (503).

4. The downhole acoustic transmitter (601, 701) as claimed in claim 1 wherein the adjustable preload means is a threaded nut (709) attached to the mandrel (704).

5. The downhole acoustic transmitter (601, 701) as claimed in any of claims 1 to 4
   wherein the piezoelectric transducer (605, 705) comprises an annular stack of annular piezoceramic discs with electrodes between each disc, wherein the annular stack is slidable over the mandrel (404, 504, 604, 704).

6. The downhole acoustic transmitter (601, 701) as claimed in any of claims 1 to 4
   wherein the preload spring (607, 707) is a metal tube slidable over the mandrel (404, 504, 604, 704).

7. The downhole acoustic transmitter (601, 701) as claimed in any of claims 1 to 4
   wherein the preload spring (607, 707) comprises one or more metal rods or tubes each extending in the axial direction in the annular space (608, 708).

8. The downhole acoustic transmitter (601, 701) as claimed in any of claims 1 to 7
   wherein the acoustic tuning element (606) has a center frequency wherein the acoustic impedance of the acoustic tuning element (606) matches the acoustic impedance of the piezoelectric transducer (605, 705) and the selected operating frequency bandwidth is up to 15% of the center frequency.

9. The downhole acoustic transmitter (601, 701) as claimed in claim 8 wherein the acoustic tuning element (606) comprises a metal cylinder having a first end attached to the second end of the piezoelectric transducer (605) and a free second end (612).

10. The downhole acoustic transmitter (601, 701) as claimed in claim 8 wherein one or more of a mass density, mass distribution, length and cross sectional area of the acoustic tuning element (606) is selected to provide the acoustic impedance of the acoustic tuning element (606) so that the acoustic impedance of the acoustic tuning element, when combined with the acoustic impedance of the preload spring (607), is within the selected range of acoustic impedances.

11. The downhole acoustic transmitter (601, 701) as claimed in any one of claims 1 to 10, mounted in a telemetry tool (105) or a repeater (106) of a drill string (103), wherein the downhole acoustic transmitter (601, 701) has a configuration selected from a group consisting of: collar-based, clamp-on, and probe-based.

12. The downhole acoustic transmitter (601, 701) as claimed in any one of claims 1 to 11, wherein the acoustic impedance of the acoustic tuning element (606) combined with the acoustic impedance of the preload spring (607) equals the acoustic impedance of the inner face of the first end coupling (602, 702), wherein the end of the piezoelectric transducer (605, 705) contacting the acoustic tuning element (606) also contacts the preload spring (607, 707).

13. A downhole acoustic telemetry node comprising:

(a) one or more sensors for measuring a local borehole environment and one or more mechanical conditions of a drill string (103);
(b) a processor and memory communicative with the one or more sensors for storing measurements taken by the one or more sensors; and
(c) the downhole acoustic transmitter (601, 701) as claimed in any of claims 1 to 12 communicative with the processor and memory for transmitting the measurement.

14. A method for acoustic transmission from a downhole location, comprising:

(a) applying a compressive preload in an axial direction against a preload spring (607, 707), which in turn compresses a piezoelectric transducer (605, 705) against an inner face of a first end coupling (602, 702) of an enclosure of a downhole acoustic transmitter (601, 701), wherein the compressive preload is selected to place the piezoelectric transducer (605, 705) in compression over a range of expected operating conditions of the downhole acoustic transmitter (601, 701);
(b) applying a voltage to the piezoelectric transducer (605, 705) to generate an acoustic transmission;

the method **characterized by**:
(c) tuning an acoustic impedance of the piezoelectric transducer (605, 705) by contacting an end of the piezoelectric transducer (605, 705) with an acoustic tuning element (606) having a selected acoustic impedance such that when combined with an acoustic impedance of the preload spring (607, 707), equals the acoustic impedance of the inner face of the first end coupling (602, 702), wherein the end of the piezoelectric transducer (605, 705) contacting the acoustic tuning element (606) also contacts the preload spring (607, 707).

Patentansprüche

1. Akustischer Bohrlochsender (601, 701) zur Verwendung in der Bohrlochkommunikation, umfassend:

(a) eine Einfassung, umfassend eine erste Endkopplung (602, 702), eine zweite Endkopplung (610, 710), ein rohrförmiges Außengehäuse (603, 703), das ein erstes Ende, das mit der ersten Endkopplung (602, 702) gekoppelt ist, und ein zweites Ende aufweist, das mit der zweiten Endkopplung (610, 710) gekoppelt ist, und einem inneren Dorn (404, 504, 604, 704) innerhalb des Außengehäuses (603, 703), der sich zwischen der ersten und der zweiten Endkopplung erstreckt, sodass ein ringförmiger Raum (608) zwischen dem Dorn (404, 504, 604, 704) und dem Außengehäuse (603, 703) definiert ist;
(b) einen piezoelektrischen Wandler (605, 705) in dem ringförmigen Raum (608) und der ein erstes Ende aufweist, das eine Innenfläche der ersten Endkopplung (602) in einer axialen Richtung kontaktiert;
(c) eine Vorspannfeder (607, 707) in dem ringförmigen Raum (608) und der ein erstes Ende aufweist, das ein zweites Ende des piezoelektrischen Wandlers (605, 705) in der axialen Richtung kontaktiert;
(d) ein einstellbares Vorspannmittel, welches das Gehäuse und ein zweites Ende der Vorspannfeder (607, 707) kontaktiert, sodass eine Druckkraft in der axialen Richtung auf die Vorspannfeder (607, 707) ausgeübt wird, die wiederum den piezoelektrischen Wandler (605, 705) gegen die Innenfläche der ersten Kopplung (602, 702) drückt;

der Bohrlochsender (601, 701), **gekennzeichnet durch:**
(e) ein akustisches Abstimmelement (606) in dem ringförmigen Raum (608) und an dem zweiten Ende des piezoelektrischen Wandlers (605) befestigt, wobei eine akustische Impedanz des akustischen Abstimmelements (606) in Kombination mit einer akustischen Impedanz der Vorspannfeder (607) innerhalb eines ausgewählten Bereichs

von akustischen Impedanzen liegt, der eine akustische Impedanz des piezoelektrischen Wandlers (605) umfasst, um die Leistungssendung von dem piezoelektrischen Wandler (605) in das Gehäuse über eine ausgewählte Betriebsfrequenzbandbreite zu maximieren.

2. Akustischer Bohrlochsender (601, 701) nach Anspruch 1, wobei das einstellbare Vorspannmittel ein oder mehrere Abstandshalter (409) umfasst, die eine Innenfläche der zweiten Endkopplung (402) kontaktieren.

3. Akustischer Bohrlochsender (601, 701) nach Anspruch 1, wobei das einstellbare Vorspannmittel ein Haltering (509) ist, der an einer Innenoberfläche des Außengehäuses (503) befestigt ist.

4. Akustischer Bohrlochsender (601, 701) nach Anspruch 1, wobei das einstellbare Vorspannmittel eine Gewindemutter (709) ist, die an dem Dorn (704) befestigt ist.

5. Akustischer Bohrlochsender (601, 701) nach einem der Ansprüche 1 bis 4, wobei der piezoelektrische Wandler (605, 705) einen ringförmigen Stapel ringförmiger piezokeramischer Scheiben mit Elektroden zwischen jeder Scheibe umfasst, wobei der ringförmige Stapel über den Dorn (404, 504, 604, 704) geschoben werden kann.

6. Akustischer Bohrlochsender (601, 701) nach einem der Ansprüche 1 bis 4, wobei die Vorspannfeder (607, 707) ein Metallrohr ist, das über den Dorn (404, 504, 604, 704) geschoben werden kann.

7. Akustischer Bohrlochsender (601, 701) nach einem der Ansprüche 1 bis 4, wobei die Vorspannfeder (607, 707) einen oder mehrere Metallstäbe oder -rohre umfasst, die sich jeweils in axialer Richtung in den ringförmigen Raum (608, 708) erstrecken.

8. Akustischer Bohrlochsender (601, 701) nach einem der Ansprüche 1 bis 7, wobei das akustische Abstimmelement (606) eine Mittenfrequenz aufweist, wobei die akustische Impedanz des akustischen Abstimmelements (606) mit der akustischen Impedanz des piezoelektrischen Wandlers (605, 705) übereinstimmt und die ausgewählte Betriebsfrequenzbandbreite bis zu 15 % der Mittenfrequenz beträgt.

9. Akustischer Bohrlochsender (601, 701) nach Anspruch 8, wobei das akustische Abstimmelement (606) einen Metallzylinder umfasst, der ein erstes Ende, das an dem zweiten Ende des piezoelektrischen Wandlers (605) befestigt ist, und ein freies zweites Ende (612) aufweist.

10. Akustischer Bohrlochsender (601, 701) nach Anspruch 8, wobei eine oder mehrere von Massendichte, Massenverteilung, Länge und Querschnittsfläche des akustischen Abstimmelements (606) ausgewählt werden, um die akustische Impedanz des akustischen Abstimmelements (606) bereitzustellen, sodass die akustische Impedanz des akustischen Abstimmelements in Kombination mit der akustischen Impedanz der Vorspannfeder (607) innerhalb des ausgewählten Bereichs der akustischen Impedanzen liegt.

11. Akustischer Bohrlochsender (601, 701) nach einem der Ansprüche 1 bis 10, der in einem Telemetriewerkzeug (105) oder einem Repeater (106) eines Bohrstrangs (103) montiert ist, wobei der akustische Bohrlochsender (601, 701) eine Konfiguration aufweist, die aus einer Gruppe ausgewählt ist, die besteht aus: kragenbasiert, anklemmbar und sondenbasiert.

12. Akustischer Bohrlochsender (601, 701) nach einem der Ansprüche 1 bis 11, wobei die akustische Impedanz des akustischen Abstimmelements (606) in Kombination mit der akustischen Impedanz der Vorspannfeder (607) der akustischen Impedanz der Innenfläche der ersten Endkopplung (602, 702) entspricht, wobei das Ende des piezoelektrischen Wandlers (605, 705), welches das akustische Abstimmelement (606) kontaktiert, auch die Vorspannfeder (607, 707) kontaktiert.

13. Akustischer Bohrloch-Telemetrieknoten, umfassend:

(a) einen oder mehrere Sensoren zum Messen einer lokalen Bohrlochumgebung und eines oder mehrerer mechanischer Zustände eines Bohrstrangs (103);
(b) einen Prozessor und Speicher, die mit dem einen oder den mehreren Sensoren zum Speichern von Messungenkommunizieren, um Messungen zu speichern, die durch den einen oder die mehreren Sensoren vorgenommen wurden; und
(c) den akustischen Bohrlochsender (601, 701) nach einem der Ansprüche 1 bis 12, der mit dem Prozessor

und dem Speicher zum Senden der Messung kommuniziert.

14. Verfahren für eine akustische Sendung von einem Bohrlochstandort, umfassend:

    (a) Anlegen einer Druckvorspannung in einer axialen Richtung gegen eine Vorspannfeder (607, 707), die wiederum einen piezoelektrischen Wandler (605, 705) gegen eine Innenfläche einer ersten Endkopplung (602, 702) eines Gehäuses eines akustischen Bohrlochsenders (601, 701) drückt, wobei die Druckvorspannung ausgewählt ist, um den piezoelektrischen Wandler (605, 705) über einen Bereich von erwarteten Betriebsbedingungen des akustischen Bohrlochsenders (601, 701) in Druck zu versetzen;
    (b) Anlegen einer Spannung an den piezoelektrischen Wandler (605, 705), um eine akustische Sendung zu erzeugen;

    wobei das Verfahren **gekennzeichnet ist durch:**
    (c) Abstimmen einer akustischen Impedanz des piezoelektrischen Wandlers (605, 705) **durch** Kontaktieren eines Endes des piezoelektrischen Wandlers (605, 705) mit einem akustischen Abstimmelement (606), das eine ausgewählte akustische Impedanz aufweist, sodass in Kombination mit einer akustischen Impedanz der Vorspannfeder (607, 707) diese der akustischen Impedanz der Innenfläche der ersten Endkopplung (602, 702) entspricht, wobei das Ende des piezoelektrischen Wandlers (605, 705), welches das akustische Abstimmelement (606) kontaktiert, auch die Vorspannfeder (607, 707) kontaktiert.

Revendications

1. Émetteur acoustique de fond de trou (601, 701) pour une utilisation dans une communication de fond de trou, comprenant :

    (a) une enceinte comprenant un premier accouplement d'extrémité (602, 702), un second accouplement d'extrémité (610, 710), un boîtier externe tubulaire (603, 703) ayant une première extrémité accouplée au premier accouplement d'extrémité (602, 702) et une seconde extrémité accouplée au second accouplement d'extrémité (610, 710), et un mandrin interne (404, 504, 604, 704) à l'intérieur du boîtier externe (603, 703) et s'étendant entre les premier et second accouplements d'extrémité de sorte qu'un espace annulaire (608) est défini entre le mandrin (404, 504, 604, 704) et le boîtier externe (603, 703) ;
    (b) un transducteur piézoélectrique (605, 705) dans l'espace annulaire (608), et ayant une première extrémité en contact avec une face interne du premier accouplement d'extrémité (602) dans une direction axiale ;
    (c) un ressort de précharge (607, 707) dans l'espace annulaire (608) et ayant une première extrémité en contact avec une seconde extrémité du transducteur piézoélectrique (605, 705) dans la direction axiale ;
    (d) un moyen de précharge réglable en contact avec l'enceinte et une seconde extrémité du ressort de précharge (607, 707) de sorte qu'une force de compression dans la direction axiale est appliquée au ressort de précharge (607, 707), qui à son tour comprime le transducteur piézoélectrique (605, 705) contre la face interne du premier accouplement (602, 702) ;

    l'émetteur de fond de trou (601, 701) étant **caractérisé par** :
    (e) un élément d'accord acoustique (606) dans l'espace annulaire (608) et fixé à la seconde extrémité du transducteur piézoélectrique (605), dans lequel une impédance acoustique de l'élément d'accord acoustique (606) combinée avec une impédance acoustique du ressort de précharge (607) se trouve dans une plage sélectionnée d'impédances acoustiques qui englobe une impédance acoustique du transducteur piézoélectrique (605) pour maximiser le transfert de puissance du transducteur piézoélectrique (605) dans l'enceinte sur une largeur de bande de fréquence de fonctionnement sélectionnée.

2. Émetteur acoustique de fond de trou (601, 701) selon la revendication 1 dans lequel le moyen de précharge réglable comprend une ou des entretoises (409) en contact avec une face interne du second accouplement d'extrémité (402).

3. Émetteur acoustique de fond de trou (601, 701) selon la revendication 1 dans lequel le moyen de précharge réglable est une bague de retenue (509) fixée à une surface interne du boîtier externe (503).

4. Émetteur acoustique de fond de trou (601, 701) selon la revendication 1 dans lequel le moyen de précharge réglable est un écrou fileté (709) fixé au mandrin (704).

5. Émetteur acoustique de fond de trou (601, 701) selon l'une quelconque des revendications 1 à 4 dans lequel le transducteur piézoélectrique (605, 705) comprend un empilement annulaire de disques piézocéramiques annulaires avec des électrodes entre chaque disque, l'empilement annulaire pouvant coulisser sur le mandrin (404, 504, 604, 704).

6. Émetteur acoustique de fond de trou (601, 701) selon l'une quelconque des revendications 1 à 4 dans lequel le ressort de précharge (607, 707) est un tube métallique pouvant coulisser sur le mandrin (404, 504, 604, 704).

7. Émetteur acoustique de fond de trou (601, 701) selon l'une quelconque des revendications 1 à 4 dans lequel le ressort de précharge (607, 707) comprend un ou des tiges ou tubes métalliques s'étendant chacun dans la direction axiale dans l'espace annulaire (608, 708).

8. Émetteur acoustique de fond de trou (601, 701) selon l'une quelconque des revendications 1 à 7 dans lequel l'élément d'accord acoustique (606) a une fréquence centrale où l'impédance acoustique de l'élément d'accord acoustique (606) correspond à l'impédance acoustique du transducteur piézoélectrique (605, 705) et la largeur de bande de fréquence de fonctionnement sélectionnée va jusqu'à 15 % de la fréquence centrale.

9. Émetteur acoustique de fond de trou (601, 701) selon la revendication 8 dans lequel l'élément d'accord acoustique (606) comprend un cylindre métallique ayant une première extrémité fixée à la seconde extrémité du transducteur piézoélectrique (605) et une seconde extrémité libre (612).

10. Émetteur acoustique de fond de trou (601, 701) selon la revendication 8 dans lequel une ou plusieurs parmi une masse volumique, une répartition de masse, une longueur et une superficie en coupe transversale de l'élément d'accord acoustique (606) sont sélectionnées pour fournir l'impédance acoustique de l'élément d'accord acoustique (606) de sorte que l'impédance acoustique de l'élément d'accord acoustique, lorsqu'elle est combinée avec l'impédance acoustique du ressort de précharge (607), se trouve dans la plage sélectionnée d'impédances acoustiques.

11. Émetteur acoustique de fond de trou (601, 701) selon l'une quelconque des revendications 1 à 10, monté dans un outil de télémétrie (105) ou un répéteur (106) d'un train de tiges de forage (103), dans lequel l'émetteur acoustique de fond de trou (601, 701) a une configuration choisie dans un groupe constitué des configurations suivantes : en collier, à pince et en sonde.

12. Émetteur acoustique de fond de trou (601, 701) selon l'une quelconque des revendications 1 à 11, dans lequel l'impédance acoustique de l'élément d'accord acoustique (606) combinée avec l'impédance acoustique du ressort de précharge (607) est égale à l'impédance acoustique de la face interne du premier accouplement d'extrémité (602, 702), où l'extrémité du transducteur piézoélectrique (605, 705) en contact avec l'élément d'accord acoustique (606) entre également en contact avec le ressort de précharge (607, 707).

13. Noeud de télémétrie acoustique de fond de trou comprenant :

(a) un ou des capteurs pour mesurer un environnement de trou de forage local et une ou des conditions mécaniques d'un train de tiges de forage (103) ;
(b) un processeur et une mémoire communiquant avec le ou les capteurs pour stocker des mesures prises par le ou les capteurs ; et
(c) l'émetteur acoustique de fond de trou (601, 701) selon l'une quelconque des revendications 1 à 12 communiquant avec le processeur et la mémoire pour émettre la mesure.

14. Procédé d'émission acoustique depuis un emplacement de fond de trou, comprenant :

(a) l'application d'une précharge de compression dans une direction axiale contre un ressort de précharge (607, 707), qui à son tour comprime un transducteur piézoélectrique (605, 705) contre une face interne d'un premier accouplement d'extrémité (602, 702) d'une enceinte d'un émetteur acoustique de fond de trou (601, 701), la précharge de compression étant sélectionnée pour placer le transducteur piézoélectrique (605, 705) en compression sur une plage de conditions de fonctionnement prévues de l'émetteur acoustique de fond de trou (601, 701) ;
(b) l'application d'une tension au transducteur piézoélectrique (605, 705) pour générer une émission acoustique ;

le procédé étant **caractérisé par** :

(c) l’accord d’une impédance acoustique du transducteur piézoélectrique (605, 705) en mettant en contact une extrémité du transducteur piézoélectrique (605, 705) avec un élément d’accord acoustique (606) ayant une impédance acoustique sélectionnée de sorte que lorsqu’elle est combinée avec une impédance acoustique du ressort de précharge (607, 707), elle est égale à l’impédance acoustique de la face interne du premier accouplement d’extrémité (602, 702), l’extrémité du transducteur piézoélectrique (605, 705) en contact avec l’élément d’accord acoustique (606) entrant également en contact avec le ressort de précharge (607, 707).

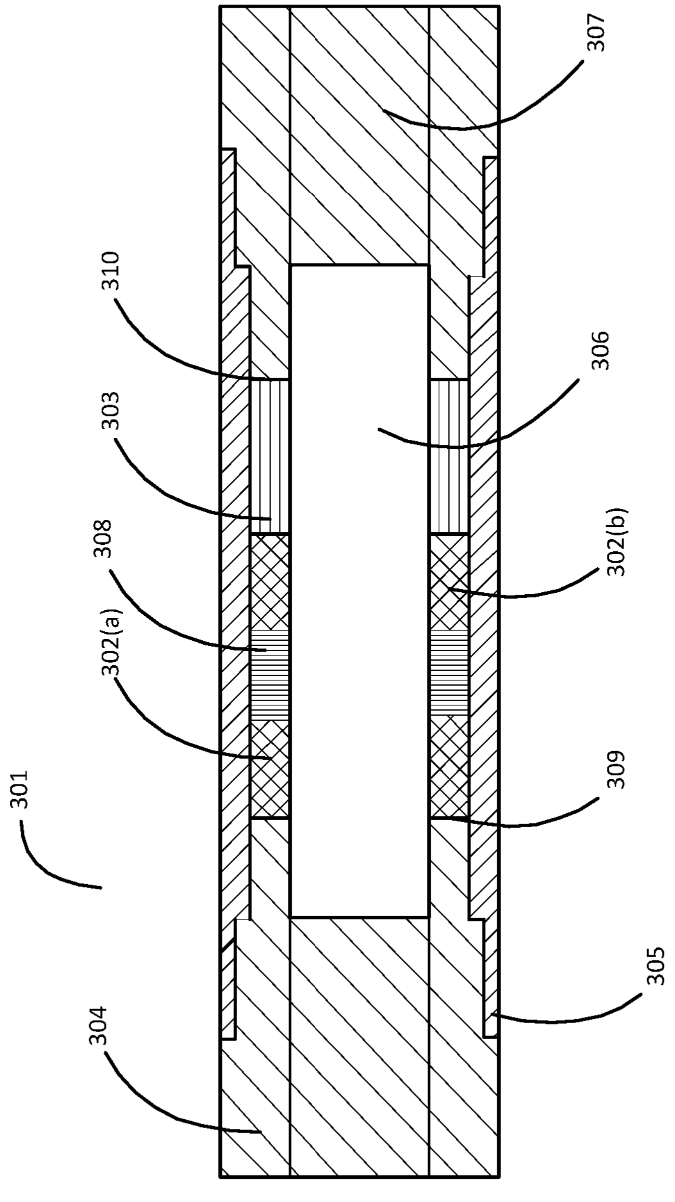

Figure 1 (PRIOR ART)

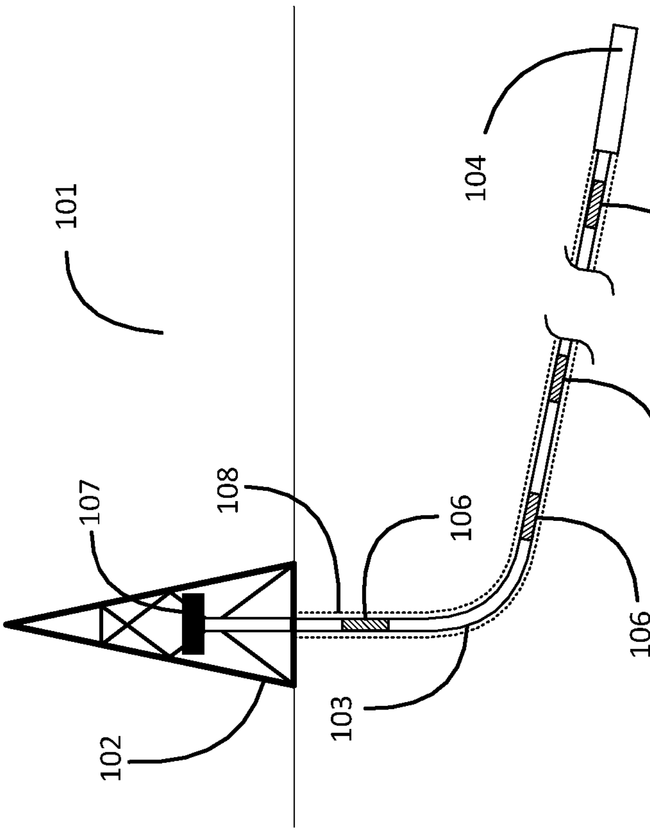

Figure 2

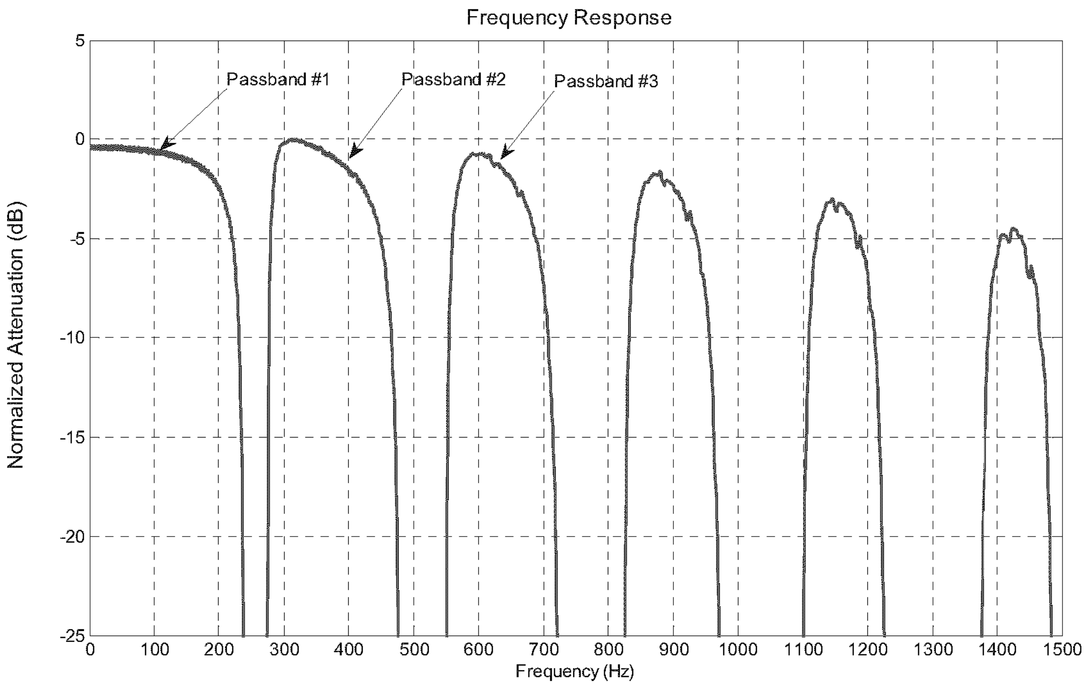
Frequency Response
Passband #1
Passband #2
Passband #3
Normalized Attenuation (dB)
5
0
-5
-10
-15
-20
-25
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
Frequency (Hz)

Figure 3

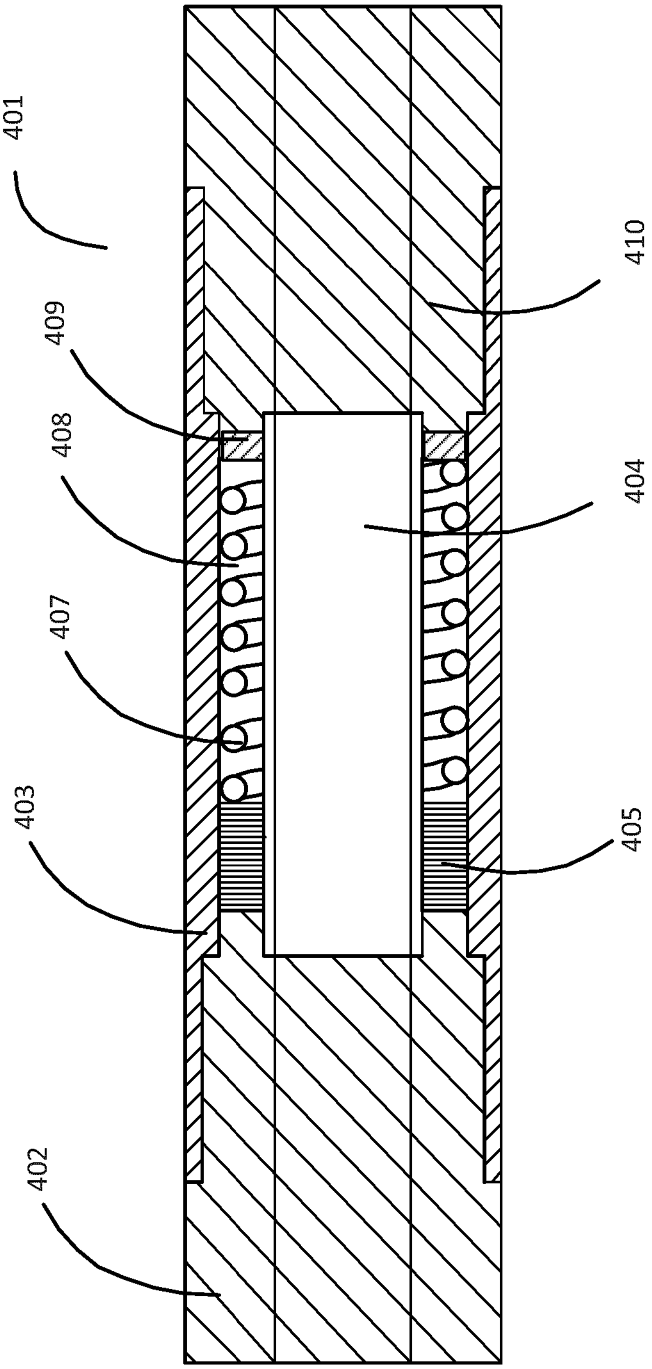

Figure 4

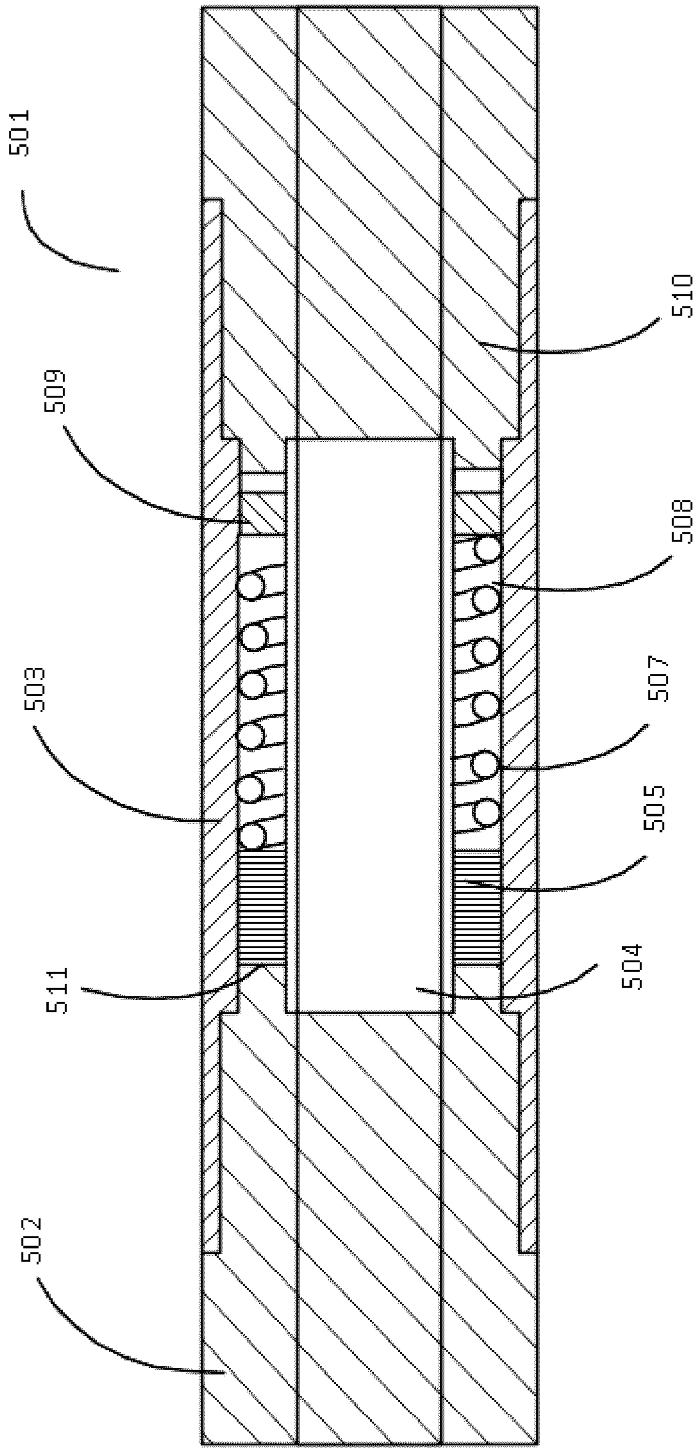

Figure 5

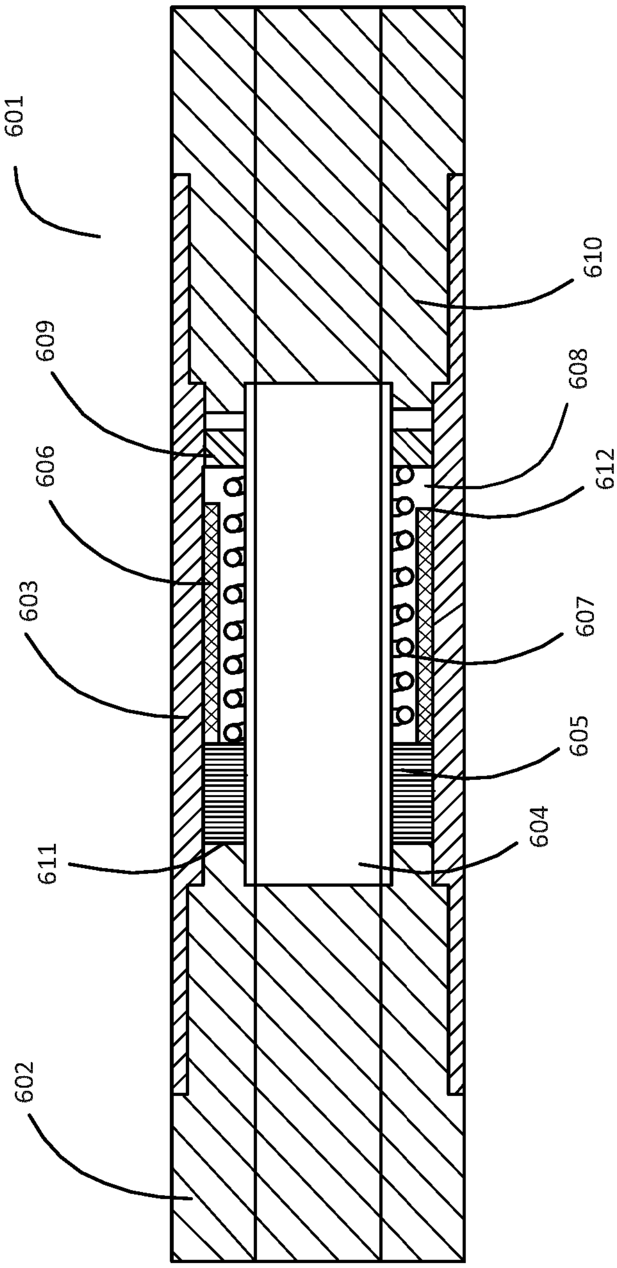

Figure 6(a)

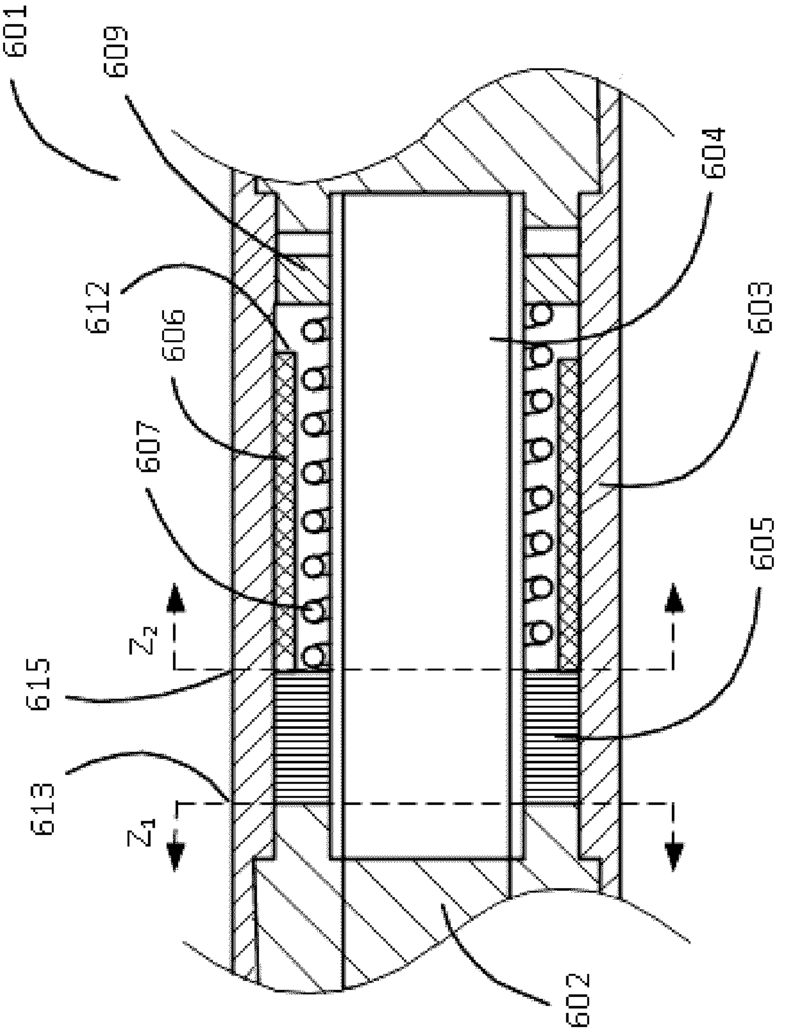

Figure 6(b)

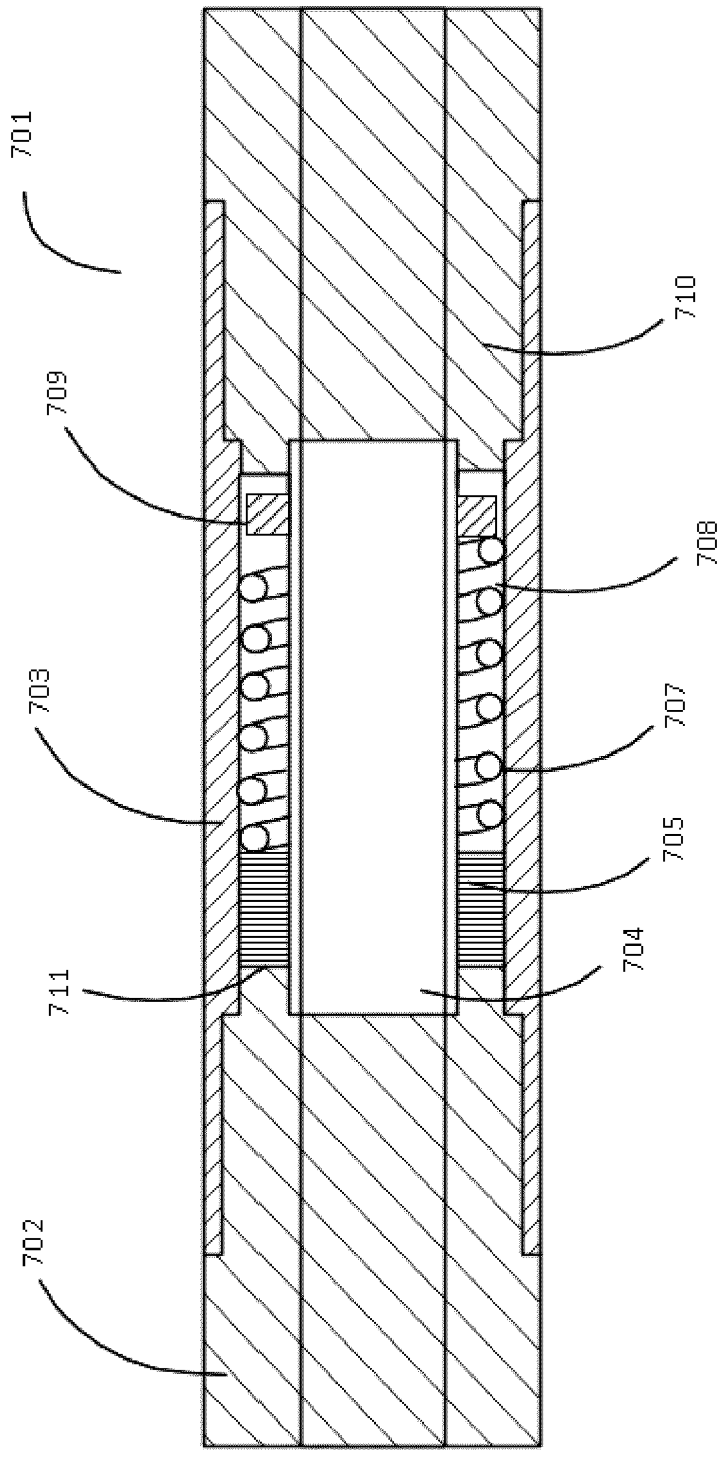

Figure 7

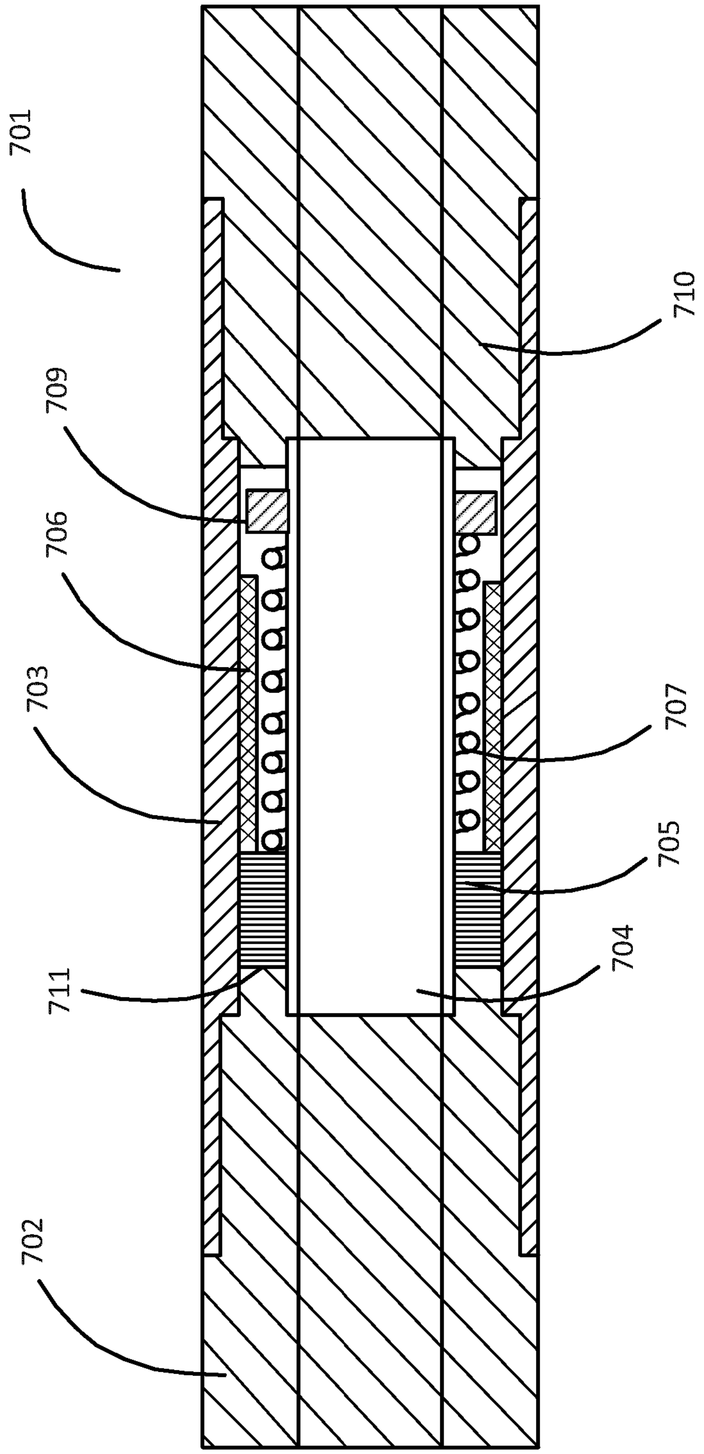

Figure 8

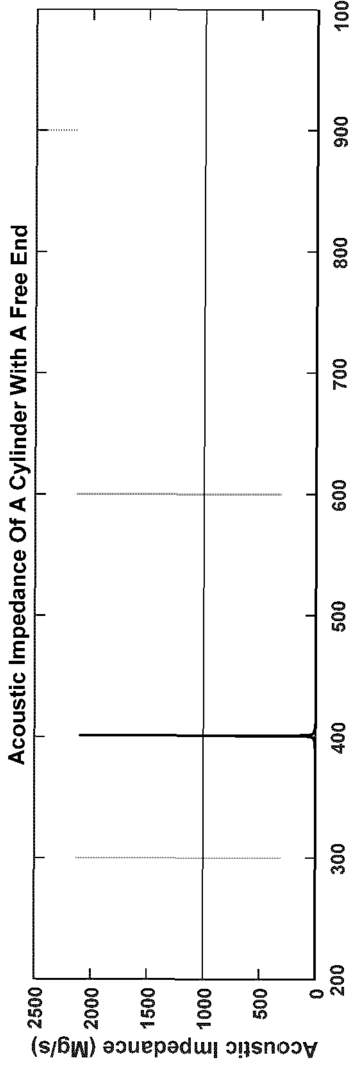

Figure 9(a)

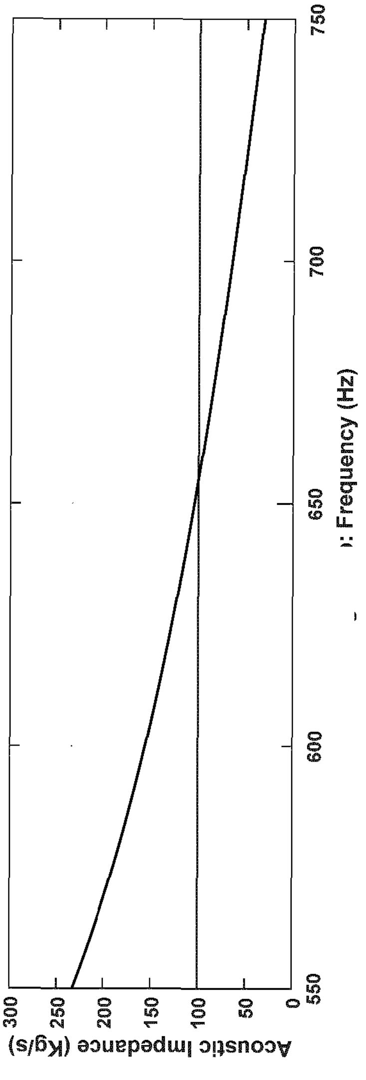

Figure 9(b)

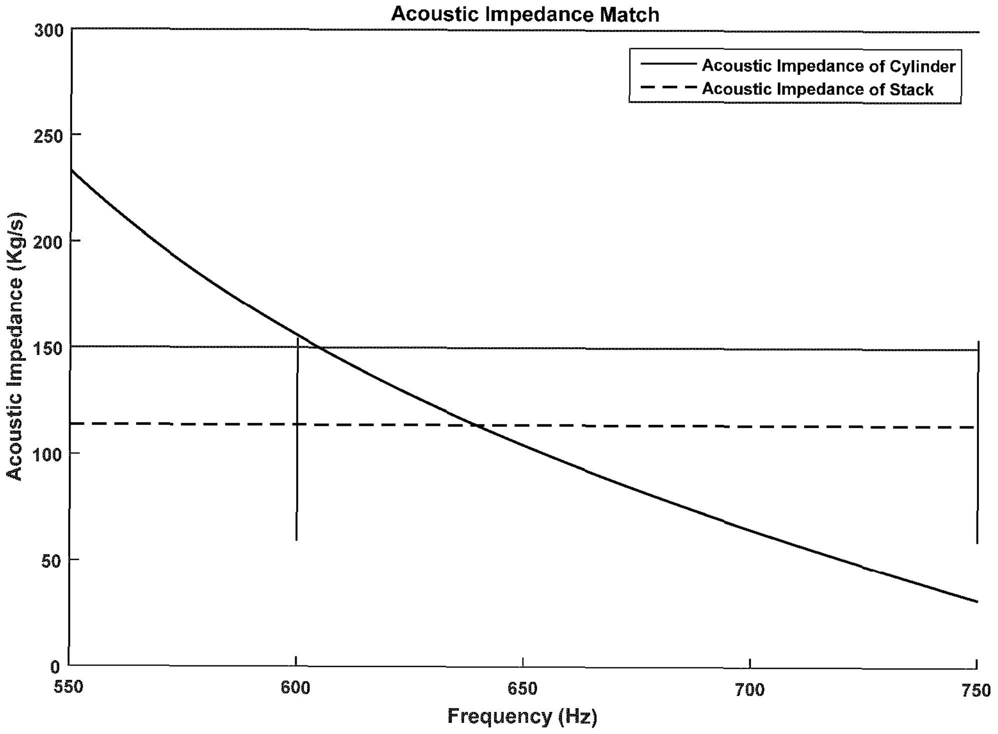
Acoustic Impedance Match
Acoustic Impedance of Cylinder
Acoustic Impedance of Stack
Acoustic Impedance (Kg/s)
300
250
200
150
100
50
0
550
600
650
700
750
Frequency (Hz)

Figure 10

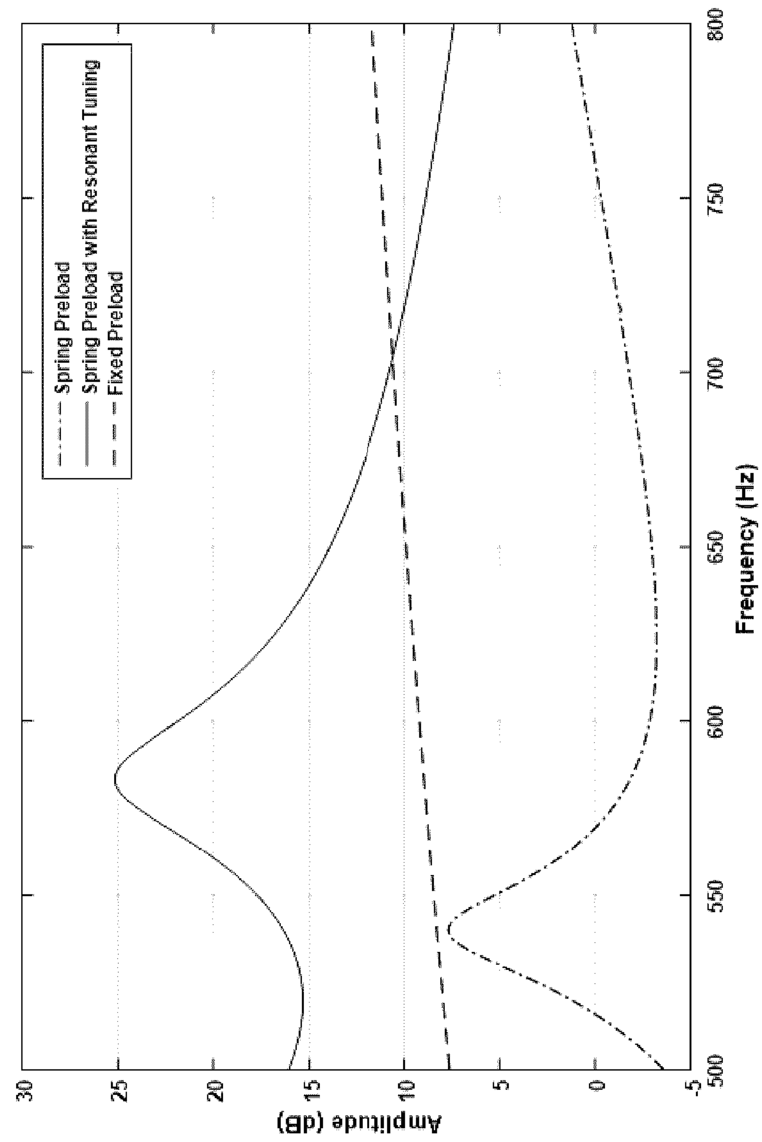
Spring Preload
Spring Preload with Resonant Tuning
Fixed Preload
Amplitude (dB)
30
25
20
15
10
5
0
-5
Frequency (Hz)
500
550
600
650
700
750
800

Figure 11

REFERENCES CITED IN THE DESCRIPTION

Patent documents cited in the description

- US 6791470 B **[0006]**
- US 6137747 A **[0010]**