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(54) Title: COMPRESSOR AND COMPRESSION USING MOTION AMPLIFICATION

(57) Abstract: A compressor system (20, 20', 20'') comprises a motion amplifier (22) which acts through a compressor head or piston (46) to compress fluid in a variable compression chamber (52). The motion amplifier (22) comprises a piezoelectric diaphragm (30) and drive electronics (26) for applying a drive signal to the piezoelectric diaphragm. The drive signal is generated to maintain the motion amplifier resonant at a predetermined frequency. The motion amplifier preferably comprises (in addition to the piezoelectric diaphragm) a reaction mass (34) connected to the piezoelectric diaphragm; a reacted mass (40) connected to the piezoelectric diaphragm; and, a reacted mass spring (50, 270) for resiliently carrying the reacted mass. The structure of the motion amplifier carried by the reacted mass spring (e.g., the piezoelectric diaphragm, the reaction mass, and the reacted mass) has a resonant frequency f_2 . The resonant frequency f_2 is related to a spring constant K_2 of the reacted mass spring and a sum of masses of the reaction mass and the reacted mass. Preferably the predetermined frequency is f_2 , which means that the drive signal is generated to maintain the motion amplifier resonant at a frequency f_2 , e.g., the drive signal is generated to urge the motion amplifier to the frequency f_2 as its operational frequency. Driving the motion amplifier (22) at the frequency f_2 achieves peak amplitude displacement of the motion amplifier, and thus peak displacement of the compressor head acting in the compression chamber.



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COMPRESSOR AND COMPRESSION USING MOTION AMPLIFICATION

BACKGROUND

[0001] This application claims the benefit and priority of the following United States
5 patent applications, all of which are incorporated herein by reference in their entirety:
US Provisional Patent application 60/747,286, entitled "COMPRESSOR AND
COMPRESSION USING MOTION AMPLIFICATION"; US Provisional Patent
application 60/747,287, entitled "MOTION AMPLIFICATION USING
10 PIEZOELECTRIC ELEMENT"; US Provisional Patent application 60/747,289,
entitled "VIBRATION AMPLIFICATION SYSTEM FOR PIEZOELECTRIC
ACTUATORS AND DEVICES USING THE SAME"; US Patent application
11/747,450, entitled "COMPRESSOR AND COMPRESSION USING MOTION
AMPLIFICATION"; US Patent application 11/747,469, entitled "MOTION
AMPLIFICATION USING PIEZOELECTRIC ELEMENT"; and US Patent application
15 11/747,516, entitled "VIBRATION AMPLIFICATION SYSTEM FOR
PIEZOELECTRIC ACTUATORS AND DEVICES USING THE SAME".

[0002] FIELD OF THE INVENTION

[0003] The present invention pertains to amplification of motion such as vibration
motion, and particularly to amplification of motion caused by a piezoelectric diaphragm
20 or the like.

[0004] RELATED ART AND OTHER CONSIDERATIONS

[0005] Piezoelectric diaphragms have been employed in various types of pumps and
actuators. As is well known, a piezoelectric material is polarized and will produce an
electric field when the material changes dimensions as a result of an imposed

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mechanical force. This phenomenon is known as the piezoelectric effect. Conversely, an applied electric field can cause a piezoelectric material to change dimensions.

[0006] One exemplary piezoelectric diaphragm, known as a ruggedized laminated piezoelectric or RLPTM, has a central piezoelectric wafer which is laminated to a stainless steel substrate and preferably also has an aluminum cover laminated thereover. Examples of such RLPTM elements, and in some instances pumps employing the same, are illustrated and described in one or more of the following: PCT Patent Application PCT/US01/28947, filed 14 September 2001; United States Patent Application Serial Number 10/380,547, filed March 17, 2003, entitled "Piezoelectric Actuator and Pump Using Same"; United States Patent Application Serial Number 10/380,589, filed March 17, 2003, entitled "Piezoelectric Actuator and Pump Using Same", and United States Patent Application 11/279,647 filed April 13, 2006, entitled "PIEZOELECTRIC DIAPHRAGM ASSEMBLY WITH CONDUCTORS ON FLEXIBLE FILM", all of which are incorporated herein by reference.

[0007] The displacement of a ruggedized laminated piezoelectric, while large compared to other piezoelectric devices, is still small in relation to the diameter of a pumping chamber in which it can be employed. Hence, compression ratios are still small, e.g., in a range on the order of 1.1 to 1.0, for example. An increased stroke for the piezoelectric diaphragm would facilitate an increased compression ratio.

[0008] What is needed, therefore, and an object of the present invention, are apparatus, method, and technique for achieving motion amplification of a piezoelectric element.

BRIEF SUMMARY

[0009] A compressor system comprises a motion amplifier which acts through a compressor head or piston to compress fluid in a variable compression chamber. The motion amplifier comprises a piezoelectric diaphragm and drive electronics for applying a drive signal to the piezoelectric diaphragm. The drive signal is generated to maintain the motion amplifier resonant at a predetermined frequency.

[00010] The motion amplifier preferably comprises a piezoelectric diaphragm and drive electronics for applying a drive signal to the piezoelectric diaphragm; a reaction mass

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connected to the piezoelectric diaphragm; a reacted mass connected to the piezoelectric diaphragm; and, a reacted mass spring for resiliently carrying the reacted mass. The reacted mass either forms or is connected to an actuator portion or actuator surface which, in turn, either forms or is connected to an actuator element. For example, the actuator portion or surface can serve as a piston head or a cylinder head, or as a surface or portion to which a further element such as an actuator shaft of the like can be connected.

[00011] The structure of the motion amplifier carried by the reacted mass spring (e.g., the piezoelectric diaphragm, the reaction mass, and the reacted mass) has a resonant frequency f_2 . The resonant frequency f_2 is related to a spring constant K_2 of the reacted mass spring and a spring constant of any load upon which the reacted mass acts, as well as a sum of masses of the reaction mass and the reacted mass. Preferably the predetermined frequency is f_2 , which means that the drive signal is generated to maintain the motion amplifier resonant at a frequency f_2 , e.g., the drive signal is generated to urge the motion amplifier to the frequency f_2 as its operational frequency. Driving the motion amplifier 22 at the frequency f_2 achieves peak amplitude displacement of the motion amplifier, and thus peak displacement of the compressor head acting in the compression chamber.

[00012] The drive electronics generates a drive signal to maintain the motion amplifier resonant at a predetermined frequency. In particular, in an example illustrated embodiment the drive electronics generates the drive signal to maintain a predetermined phase angle between the drive signal and a signal indicative of displacement of the motion amplifier system. To this end, the drive electronics comprises a sensor for sensing displacement of the motion amplifier and for generating the signal indicative of displacement of the motion amplifier.

[00013] In one example embodiment, the piezoelectric diaphragm is mounted to and carried by the reacted mass. The reacted mass comprises a reacted mass cup which defines a reacted mass cavity. In one example implementation of this embodiment, a periphery of the piezoelectric element is held by the reacted mass cup while the center of the piezoelectric diaphragm is free to vibrate. The reaction mass is preferably centrally suspended from the piezoelectric diaphragm in the reacted mass cavity.

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[00014] Compressor assemblies of differing embodiments can incorporate the embodiments of motion amplifiers. The compressor assembly can include an amplifier base which carries the piezoelectric diaphragm, the reaction mass, the reacted mass, and the reacted mass spring. The amplifier base at least partially defines the compression chamber. The reacted mass spring can also at least partially defines the compression chamber. As one aspect of the technology, means are provided for resiliently mounting the amplifier base relative to the outside world, and thereby mitigating any damping caused by the outside world.

[00015] In one example embodiment of a motion amplifier, the reacted mass spring comprises a diaphragm which also at least partially defines and covers the compression chamber. The diaphragm comprising the reacted mass spring is a preferably a corrugated diaphragm. Corrugation of the diaphragm provides increased motion for the motion amplifier. In an embodiment of a compressor assembly incorporating a diaphragm-type reacted mass spring, the amplifier base can have an inlet and an outlet for respectively intaking and exhausting fluid in accordance with displacement of the reacted mass (the reacted mass serving as the compression or piston head in the compression chamber).

[00016] Another example embodiment of a motion amplifier comprises a bellows assembly. The bellows assembly has a sidewall for at least partially defining the compression chamber. The sidewall comprises and serves as the reacted mass spring. The bellows assembly further comprises an amplifier base for defining a valve assembly cavity. The valve assembly cavity and the compression chamber are sized to accommodate a valve assembly through which fluid is introduced into the compression chamber and compressed in the compression chamber by displacement of the motion amplifier.

[00017] The technology also includes a method of operating a compressor assembly for compressing a fluid. The method includes displacing a motion amplifier having a compressor head in a compressor chamber, the motion amplifier comprising a piezoelectric diaphragm, a reaction mass connected to the piezoelectric diaphragm, a reacted mass connected to the piezoelectric diaphragm, and a reacted mass spring for resiliently carrying the reacted mass. The method further includes selectively admitting and exhausting fluid from the compressor chamber in accordance with displacement of

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the motion amplifier. The step of displacing the motion amplifier comprises generating and applying a drive signal to the piezoelectric diaphragm, the drive signal being generated to maintain the motion amplifier resonant at a predetermined frequency. Preferably, the method includes generating the drive signal to urge the motion amplifier to the frequency f_2 as its operational frequency.

[00018] A further aspect of the method includes resiliently mounting the compressor assembly (e.g., an amplifier base) relative to the outside world.

[00019] The compressor assembly includes an inlet valve and an outlet valve for respectively admitting and exhausting fluid relative to the compression chamber. As another aspect of the technology, the natural frequency of the inlet valve and the natural frequency of the outlet valve are each greater than an operating frequency of the motion amplifier. For example, in an example embodiment, the natural frequency of each of the inlet valve and the outlet valve is at least twice the operating frequency of the motion amplifier.

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BRIEF DESCRIPTION OF THE DRAWINGS

[00020] The foregoing and other objects, features, and advantages of the invention will be apparent from the following more particular description of preferred embodiments as illustrated in the accompanying drawings in which reference characters refer to the same parts throughout the various views. The drawings are not necessarily to scale, emphasis instead being placed upon illustrating the principles of the invention.

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[00021] Fig. 1 is a front perspective view of an example embodiment of a compressor assembly which includes an example embodiment of a motion amplifier.

[00022] Fig. 2 is an exploded view of the compressor assembly of Fig. 1.

[00023] Fig. 3 is top view of the compressor assembly of Fig. 1.

[00024] Fig. 4 is a front view of the compressor assembly of Fig. 1.

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[00025] Fig. 5 is a bottom view of the compressor assembly of Fig. 1.

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[00026] Fig. 6 is a right side view of the compressor assembly of Fig. 1.

[00027] Fig. 7 is a sectioned view of portions of the compressor assembly of Fig. 1, showing the compressor assembly without a valve assembly.

5 [00028] Fig. 8A is a sectioned view showing portions of a motion amplifier and an alternate way of retaining the motion amplifier in place.

[00029] Fig. 8B is a sectioned view showing portions of a motion amplifier and another alternate way of retaining the motion amplifier in place.

[00030] Fig. 9 is schematic view of a drive model for the compressor assembly of Fig. 1 combined with a sectioned view of the compressor assembly of Fig. 1.

10 [00031] Fig. 10 is a front perspective view of an example embodiment of a valve assembly for the compressor assembly of Fig. 1.

[00032] Fig. 11 is an exploded view of the valve assembly of Fig. 10.

[00033] Fig. 12 is a top view of the valve assembly of Fig. 10.

[00034] Fig. 13 is a front view of the valve assembly of Fig. 10.

15 [00035] Fig. 14 is a bottom view of the valve assembly of Fig. 10.

[00036] Fig. 15 is a right side view of the valve assembly of Fig. 10.

[00037] Fig. 16 is a front perspective of a exhaust valve housing of the valve assembly of Fig. 10.

20 [00038] Fig. 17 is a front perspective of an intake valve housing of the valve assembly of Fig. 10.

[00039] Fig. 18A is a cross sectional view showing an example embodiment of a compressor housing and a first mode of resiliently mounting a compressor assembly in the compressor housing.

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[00040] Fig. 18B is a cross sectional view showing another example embodiment of a compressor housing and a second mode of resiliently mounting a compressor assembly in the compressor housing.

5 [00041] Fig. 19A is a partial cross sectional view showing an example technique for mounting a sensor system for a motion amplifier.

[00042] Fig. 19B is a partial cross sectional view showing another example technique for mounting a sensor system for a motion amplifier.

[00043] Fig. 20 is a schematic view of a generic, example sensing system for a motion amplifier.

10 [00044] Fig. 21 is a schematic view of control circuit for the compressor assembly of Fig. 1.

[00045] Fig. 22 is a graph showing frequencies of a system which includes a motion amplifier

[00046] Fig. 23 is a graph showing a plot of amplitude verses phase angle.

15 [00047] Fig. 24 is a graph showing a plot of a sense position signal (in voltage) as a function of position.

[00048] Fig. 25 is a schematic sectioned view of portions of a compressor assembly according to another example embodiment.

20 [00049] Fig. 26 is a schematic sectioned view of portions of a compressor assembly according to yet another example embodiment, and particularly comprising plural motion initiator elements.

DETAILED DESCRIPTION OF THE DRAWINGS

[00050] In the following description, for purposes of explanation and not limitation, specific details are set forth such as particular architectures, interfaces, techniques, etc.

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in order to provide a thorough understanding of the present invention. However, it will be apparent to those skilled in the art that the present invention may be practiced in other embodiments that depart from these specific details. That is, those skilled in the art will be able to devise various arrangements which, although not explicitly described or shown herein, embody the principles of the invention and are included within its spirit and scope. In some instances, detailed descriptions of well-known devices, circuits, and methods are omitted so as not to obscure the description of the present invention with unnecessary detail. All statements herein reciting principles, aspects, and embodiments of the invention, as well as specific examples thereof, are intended to encompass both structural and functional equivalents thereof. Additionally, it is intended that such equivalents include both currently known equivalents as well as equivalents developed in the future, i.e., any elements developed that perform the same function, regardless of structure.

[00051] Thus, for example, it will be appreciated by those skilled in the art that block diagrams herein can represent conceptual views of illustrative circuitry embodying the principles of the technology. The functions of the various elements including functional blocks labeled as “processors” or “controllers” may be provided through the use of dedicated hardware as well as hardware capable of executing software in association with appropriate software. When provided by a processor, the functions may be provided by a single dedicated processor, by a single shared processor, or by a plurality of individual processors, some of which may be shared or distributed. Moreover, explicit use of the term “processor” or “controller” should not be construed to refer exclusively to hardware capable of executing software, and may include, without limitation, digital signal processor (DSP) hardware, read only memory (ROM) for storing software, random access memory (RAM), and non-volatile storage.

[00052] Fig. 1 – Fig. 7 illustrate an example, non-limiting embodiment of a compressor assembly 20. As seen in Fig. 2, compressor assembly 20 comprises a motion amplifier 22 and valve assembly 24. The motion amplifier 22 can serve as a driver for compressor assembly 20. The valve assembly 24 is further illustrated by Fig. 10 – Fig. 17. Also included in compressor assembly 20 is a sensor and control system, an example embodiment of which is illustrated as sensor and control system 26 illustrated in Fig. 20. As used herein, “drive electronics” encompasses one or more elements of sensor and control system 26.

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[00053] The motion amplifier 22 comprises an actuator or motion initiator element which, in the illustrated example embodiment, takes the form of a piezoelectric diaphragm 30. The piezoelectric diaphragm 30 is mounted (such as by example ways described hereinafter) preferably with its peripheral edge constrained and in a manner to permit its central portion to move, displace, or deflect through a range of positions in accordance with a drive signal applied to piezoelectric diaphragm 30 by sensor and control system 26. For example, when a zero volt signal is applied to piezoelectric diaphragm 30, the piezoelectric diaphragm 30 has a slightly domed configuration with respect to an axial direction 31. On the other hand, upon application of a non-zero voltage piezoelectric the central region of diaphragm 30 may displace or dome more significantly. In the illustrated embodiment, the drive signal is applied to motion initiator element 30 by radially extending electrodes 32.

[00054] The piezoelectric diaphragm 30, serving as the motion initiator element, has a reaction mass 34 mounted or adhered to an underside of its central region. Although shown in the illustrated embodiment as being a disc, reaction mass 34 can take a variety of other shapes.

[00055] The piezoelectric diaphragm 30 is mounted to and carried by a reacted mass which includes a reacted mass cup 40. The reacted mass cup 40 is preferably cylindrical in shape, having a cylindrical sidewall 42 which is surmounted by a relatively thinner or sharp crown or "knife edge" 44 (see Fig. 2 and Fig. 7). The reacted mass cup 40 has an essentially flat bottom wall 46 (see Fig. 7) which also serves essentially as a piston head or cylinder head or compressor head. A reacted mass cup cavity 48 is formed interior to the cylindrical side wall 42. The reacted mass cup cavity 48 is sized so that reaction mass 34, suspended on the underside of piezoelectric diaphragm 30, is accommodated in reacted mass cup cavity 48. The perimeter of piezoelectric diaphragm 30 sits on reacted mass cup crown edge 44. Thus, in the example implementation shown in Fig. 2, a periphery of the piezoelectric element 30 is held by the reacted mass cup 48 while the center of the piezoelectric diaphragm 30 is free to vibrate. The reacted mass need not take the form of a cup, but can have other configurations. The reaction mass 34 is preferably centrally suspended from the piezoelectric diaphragm 30 in the reacted mass cup cavity 48.

[00056] The reacted mass 40 either forms or is connected to an actuator portion or

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actuator surface, such as the essentially flat bottom wall 46 described above. The actuator portion or actuator surface can, in turn, either form or be connected to an actuator element. For example, the actuator portion or surface can serve as a piston head or a cylinder head, or as a surface or portion to which a further element such as an actuator shaft of the like can be connected.

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[00057] Suspended in axial direction 31 from reacted mass cup 40 is a bellows assembly 50. As shown in Fig. 7, bellows assembly 50 has an essentially inverted-cup shape for defining a compression chamber 52. The compression chamber 52 is partially bounded by flexible interior cylindrical wall 54 and interior upper wall 56 of bellows assembly 50. The interior cylindrical wall 54 is sealed to an interior of rigid amplifier base 58 by bellows seal 59. The amplifier base 58 also has a shape of an inverted cup to define valve assembly cavity 60, and has a cylindrical sidewall having a slightly larger diameter than elements carried or mounted thereover. The amplifier base 58 also has a radial channel, port, or slot 61 formed in its cylindrical sidewall thereof to accommodate portions of valve assembly 24 as herein after described.

[00058] The bellows assembly 50 further comprises a resilient and flexible exterior cylindrical sidewall 62. The bellows exterior sidewall 62 can be pleated in resilient fashion or, more preferably, has a coiled spring 64 or other elastic member embedded therein or carried thereon. A bottom of bellows exterior sidewall 62 is mounted to a top of amplifier base 58; a top of bellows exterior sidewall 62 is sealingly connected to an underside of reacted mass cup bottom wall 46. As shown in Fig. 7, a compression space 66 is defined between bellows interior cylindrical wall 54 and bellows exterior sidewall 62.

[00059] In the example embodiment illustrated in Fig. 1 and Fig. 2, motion amplifier 22 has one or more amplifier sleeve sections 70 which at least partially surround piezoelectric diaphragm 30, reacted mass cup 40, and the flexible portion of bellows assembly 50. The amplifier sleeve 70 can be a single hollow cylindrical member which essentially completely encloses these interior elements, or two or sections (which, when positioned, define a cylindrical cavity) as shown in Fig. 2. In the illustrated embodiment, the amplifier sleeve section(s) 70 can be affixed or fastened to a top surface of amplifier base 58, as evidenced by aligned fastener holes 72 and 74 formed in amplifier sleeve sections 70 and amplifier base 58, respectively. In addition, the motion amplifier 22 is covered by a ceiling board 76 which is mounted, affixed, or fastened to amplifier sleeve section(s) 70. For example, ceiling board 76 can be fastened to amplifier sleeve section(s) 70 as evidenced by aligned fastener holes 77 and 78 formed in ceiling board 76 and amplifier sleeve section(s) 70, respectively. As explained subsequently, ceiling board 76 can carry some or all portions of sensor and control system 26.

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[00060] As mentioned above, and as shown in Fig. 7, piezoelectric diaphragm 30 is carried on reacted mass cup crown edge 44. The peripheral edge of piezoelectric diaphragm 30 can be constrained by any of several mounting methods. For example, a bead of an adhesive or the like can be applied circumferentially underneath
5 piezoelectric diaphragm 30 and around reacted mass cup crown edge 44 in the region 80 illustrated in Fig. 7. Such adhesive should preferably be sufficiently sticky but also allow shear movement between layers of the piezoelectric diaphragm 30. One example of such adhesive is a 467MP adhesive supplied by Minnesota Mining & Manufacturing.

[00061] As another example, illustrated in Fig. 8A, an intermediate clamping sleeve 82
10 can be arranged circumferentially around piezoelectric diaphragm 30 and reacted mass cup 40. The intermediate clamping sleeve 82 has an overhanging rim section 84 which has a distal depending contact foot 86. A (rubber) gasket 88 or the like is interposed between contact foot 86 and an upper circumferential edge of piezoelectric diaphragm 30, to apply a retaining force on the top periphery of piezoelectric diaphragm 30. The
15 intermediate clamping sleeve 82 is retained in position by affixation to the exterior sidewall of reacted mass cup 40 by, e.g., fasteners or the like such as fastener 90 illustrated in Fig. 8A.

[00062] In a yet further alternate implementation, rather than or in addition to having fastener 90, intermediate clamping sleeve 82 has a bottom rim 92. In the Fig. 8B
20 embodiment, piezoelectric diaphragm 30 and reacted mass cup 40 are securely clamped between overhanging rim section 84 and bottom rim 92 of intermediate clamping sleeve 82.

[00063] As shown in Fig. 1 – 6, valve assembly 24 fits internally into bellows assembly 50, occupying at least a portion of compression chamber 52 and valve assembly cavity
25 60. Fig. 10 – Fig. 17 illustrate valve assembly 24 or portions thereof in more detail. For example, Fig. 11 shows (in exploded fashion) valve assembly 24 as comprising exhaust valve housing 102 and intake valve housing 104. Both exhaust valve housing 102 and intake valve housing 104 comprise two essentially half-cylindrical sections, with a lower of the two cylindrical sections having a larger diameter than an upper
30 section. The exhaust valve housing 102 has an intake port 106 and an exhaust port 108, which communicate with an intake chamber 110 and an exhaust chamber 112, respectively, of exhaust valve housing 102 as shown in Fig. 16. The intake valve

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housing 104 has a ramped intake chamber 116 and a smaller ramped exhaust chamber 118. The ramped intake chamber 116 of intake valve housing 104 communicates through a compression chamber intake port 120 formed on a top surface of intake valve housing 104 for admitting fluid into compression chamber 52 (see Fig. 7). Similarly, exhaust chamber 118 communicates through a compression chamber exhaust port 122 formed on the top surface of intake valve housing 104 for exhausting fluid from compression chamber 52.

[00064] A valve seat 130 is interposed between exhaust valve housing 102 and intake valve housing 104. The valve seat 130 has valve seat intake port 132 and valve seat exhaust port 134. An exhaust tape seal 136 is interposed between exhaust valve housing 102 and valve seat 130; an intake tape seal 138 is interposed between intake valve housing 104 and valve seat 130. The exhaust tape seal 138 is profiled for insertion between exhaust valve housing 102 and valve seat 130, and has apertures or cutouts corresponding in position and size to intake chamber 110 and exhaust chamber 112 of exhaust valve housing 102. Similarly, intake tape seal 136 is profiled for insertion between intake valve housing 104 and valve seat 130, and has apertures or cutouts corresponding in position and size to ramped intake chamber 116 and exhaust chamber 118 of intake valve housing 104. An exhaust reed valve 140 is retained in cantilever fashion between intake tape seal 138 and valve seat 130, a base or proximal end of exhaust reed valve 140 being held in position between intake tape seal 138 and valve seat 130 by laser weld retainer 142 while a distal or upper end of exhaust reed valve 140 selectively covers valve seat exhaust port 134 of valve seat 130. In similar fashion, intake reed valve 144 is retained in cantilever fashion between exhaust tape seal 136 and valve seat 130, a base or proximal end of intake reed valve 144 being held in position between exhaust tape seal 136 and valve seat 130 by laser weld retainer 146 while a distal or upper end of intake reed valve 144 selectively covers valve seat intake port 132. The exhaust valve housing 102, intake tape seal 138, valve seat 130, exhaust tape seal 136, and intake valve housing 104 are held in alignment by a pair of alignment pins 147 which extend through corresponding apertures in each of the elements aligned thereby. When exhaust valve housing 102 and intake valve housing 104 are joined together with each of intake tape seal 138, valve seat 130, and exhaust tape seal 136 aligned therebetween by the alignment pins 147, and with the exhaust reed valve 140 and intake reed valve 144 properly positioned, a valve assembly gasket 148 is fit over the top sections of both exhaust valve housing 102 and intake valve housing 104.

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Interface tubes 149 are then inserted into intake port 106 and exhaust port 108 for providing a conduit for fluid to enter and exit from valve assembly 24.

[00065] The compressor assembly 20 is resiliently mounted with respect to the outside world. Resilient mounting of compressor assembly 20 can be accomplished in several ways. As a first example, Fig. 18A shows compressor assembly 20 as being located at least partially within a compressor housing 150. The compressor housing 150 comprises a housing base 152; one or more housing sidewall(s) 154; and housing cover 156. The housing base 152 can have a plurality of short mounting pedestals 158 extending upwardly therefrom, with the mounting pedestals 158 being positioned in a pattern or arrangement adapted for support of compressor assembly 20. However, compressor assembly 20 does not rest on mounting pedestals 158 directly. Rather, the mounting pedestals 158 have proximal ends of resilient beams 160 mounted thereto in cantilever fashion. The compressor assembly 20 is situated on distal or second ends of the resilient beams 160. For example, an underside of amplifier base 58 can be fixedly mounted to upper surfaces of resilient beams 160. The resilient beams 160 can be, for example, a springy or resilient metallic material. Thus, in the implementation of Fig. 18A, the compressor assembly 20 is mounted on a series of radially extending (with respect to axial direction 31) resilient cantilever beams 160 which resemble diving boards.

[00066] Alternatively, as shown in Fig. 18B, compressor assembly 20 can be resiliently mounted on coiled springs 162. The coiled springs 162 can be circularly mounted, for example, on housing base 152, and have one end connected to a top surface of housing base 152 and another end connected to an underside of amplifier base 58.

[00067] The compressor assembly 20 thus comprises both motion amplifier 22 and valve assembly 24. In an illustrated embodiment of Fig. 1, motion amplifier 22 has a peripheral edge of its piezoelectric diaphragm 30 attached or secured (e.g., with a flexible epoxy) to reacted mass cup crown edge 44 so that the periphery of piezoelectric diaphragm 30 is constrained while the piezoelectric diaphragm 30 is otherwise free to flex. The piezoelectric diaphragm 30 flexes as a voltage is applied from sensor and control system 26 via electrodes 32. The reaction mass 34 is carried by piezoelectric diaphragm 30 to increase its inertia. The flexing of piezoelectric diaphragm 30 reciprocates reaction mass 34. By Newton's Third Law, the moving mass produces a

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force on reacted mass cup 40. Thus, the energy input is transformed first to a force and ultimately to motion of reacted mass cup 40 and of reacted mass cup bottom wall 46, which serves as a compression head or piston head. The reacted mass cup 40 vibrates and deflects into the compression chamber 52 defined partially by the bellows assembly 50 that carries reacted mass cup 40. As explained subsequently, large deflections are produced when the piezoelectric diaphragm 30 is driven/operated at the resonant frequency of the piston head assembly, e.g., the assembly carried by bellows assembly 50. The maximum stroke of the piston head is limited only by structural damping. In an example implementation, such damping is on the order of 3%-6% of critical damping, so the maximum stroke can be ten to thirty times the stroke or displacement of the piezoelectric diaphragm 30 itself.

[00068] There is an energy cost to operating at resonance. The work done against the internal losses is not useful work and it increases with stroke. Fortunately, this component of the total work is manageable. In fact, this work term is masked by the capacitor-like nature of the piezoelectric diaphragm 30 with a conventional drive circuit. The pumping work is equivalent to a damping term. For incompressible flow and as an approximation to compressors at low pressure ratio, pumping work is simply the product of pressure rise and flow rate. This work must be supplied each cycle. The work provides useful compression of the fluid.

[00069] The motion amplifier 22 thus can be used, when employed within a compressor context, to create a variable volume in compression chamber 52. Fluid is admitted into and exhausted from compression chamber 52 by valve assembly 24. As the volume in compression chamber 52 increases, fluid is drawn in through the intake valve of valve assembly 24. As the volume decreases, fluid is expelled or exhausted through the exhaust valve of valve assembly 24.

[00070] The motion amplification created by motion amplifier 22 is particularly useful when working with gases because the large motion makes it easy to achieve a large ratio of maximum to minimum volume (e.g., the so-called compression ratio), which is necessary for achieving a large output pressure. The large motion may also facilitate producing a large swept volume and hence flow rate. Producing both a high pressure and a large flow rate simultaneously depends on having adequate input power.

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[00071] Preferably motion amplifier 22 works in conjunction with a motion sensing system. In one non-limiting example embodiment, such a motion sensing system can include an optical emitter 170 and an optical sensor 172 (e.g., phototransistor). The optical emitter 170 is positioned to direct an electromagnetic (e.g., optical) beam onto a top surface of piezoelectric diaphragm 30. The optical sensor 172 is situated and positioned to detect reflection of the beam from piezoelectric diaphragm 30.

[00072] Fig. 19A shows a first example technique for mounting optical emitter 170 and optical sensor 172. In the technique of Fig. 19A, optical emitter 170 and optical sensor 172 are both mounted on an underside of a sensor system cantilever support member 174. The sensor system cantilever support member 174 is held aloft above compressor housing 150. The housing cover 156 of compressor housing 150 has a cover aperture 176 which is preferably centrally located above a center portion of piezoelectric diaphragm 30. The optical emitter 170 and optical sensor 172 are held by sensor system cantilever support member 174 so that optical emitter 170 directs a beam 178 toward the (preferably shiny) top surface of piezoelectric diaphragm 30, and so that optical sensor 172 receives the beam as reflected by piezoelectric diaphragm 30. If desired, the aforementioned sensor and control system 26 can also be mounted on sensor system cantilever support member 174, e.g., on an underside of sensor system cantilever support member 174.

[00073] Fig. 19B shows another example technique for mounting optical emitter 170 and optical sensor 172. The Fig. 19B technique is useful for an embodiment of a compressor assembly which has one or more amplifier sleeve sections 70 such as illustrated in Fig. 1 and Fig. 8A and Fig. 8B, with a ceiling board 76 which fits over amplifier sleeve sections 70. In the Fig. 19B technique; the optical emitter 170 and sensor system cantilever support member 174 are mounted on the underside of ceiling board 76. Again, if desired, the sensor and control system 26 can also be mounted as a circuit board on the underside of ceiling board 76.

[00074] Fig. 20 illustrates that sensor and control system 26 includes the optical emitter 170 and optical sensor 172 described above. In accordance with the amplitude of the beam reflected from the piezoelectric diaphragm 30, optical sensor 172 generates a sense position signal which is applied to control circuit 200. The value of the sense position signal indicates the degree of motion (displacement, deflection) of the entire

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motion amplifier. The control circuit 200, described in more detail along with other elements with reference to Fig. 21, resembles a phase locked loop voltage control output circuit. An output signal of control circuit 200 is applied to power amplifier 202, which generates the drive signal which is applied by electrodes 32 to piezoelectric diaphragm 30.

[00075] An example embodiment of control circuit 200 is illustrated in Fig. 21. In one sense, the control circuit 200 resembles a phase lock loop. However, control circuit 200 differs from a conventional phase locked loop in that the drive signal applied by control circuit 200 to piezoelectric diaphragm 30 is a sine wave (rather than a square wave) and the output of sensor and control system 26 depends on the amplitude of motion, which decreases greatly for off resonant conditions.

[00076] The control circuit 200 of Fig. 21 includes an optical sensor 206 which includes both the optical emitter 170 and optical sensor 172. A buffer 208 buffers the signal generated by optical sensor 206. The signal is amplified (two stages of amplification) by amplifier 210 and amplifier 220. The amplified signal OPT is applied to phase detector 222. The phase detector 222 detects the phase output from optical sensor 206 relative to phase output from variable frequency oscillator 223. The output from phase detector 222 is applied to low pass filter 224 to produce a phase angle signal PHAZ. The phase angle of phase angle signal PHAZ is compared to a reference by phase error amplifier 226. The compared signal is inverted by inverter 228. A frequency range selector 230 selects a frequency range, which goes to the control line for controlling the frequency. The sine wave output SINE is applied to power amplifier 202, as well as to a squaring circuit 234 which squares it and feeds it back phase detector 222.

[00077] As understood from the foregoing, a motion amplifier comprises a piezoelectric diaphragm, a reaction mass carried or attached to the piezoelectric diaphragm; drive electronics for driving the piezoelectric diaphragm; a reacted mass; and, a reacted mass spring. Preferably the motion amplifier, and any compressor assembly comprised by the same, is resiliently mounted on yet another spring. These aspects of a motion amplifier can be implemented in many ways, including but not limited to the embodiments already described with reference to previously described figures. Fig. 9 shows that a generic system encompassed hereby includes a first mass

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M1 corresponding to the reaction mass; a first spring constant K1 corresponding to the spring constant or resilience of the piezoelectric diaphragm; a second mass M2 corresponding to a reacted mass of the system; a second spring constant K2 corresponding to the reacted mass spring any load acted upon by the reacted mass; a third mass M3 corresponding to a base of the system; and, a third spring constant K3 corresponding to the system resilient mounting spring.

[00078] More particularly, Fig. 9 further illustrates mapping of the model of the general system to structure of the example embodiments already described. In accordance with such mapping, the first mass M1 corresponding to the reaction mass is the mass of reaction mass 34 carried by piezoelectric diaphragm 30. The first spring constant K1 is the spring constant or resilience of piezoelectric diaphragm 30, and affords a first degree of freedom. The second mass M2 corresponds to a reacted mass is the mass of reacted mass cup 40. The second spring constant K2 corresponds to the reacted mass spring and any load upon which the reacted mass acts, and affords a second degree of freedom. Thus, the second spring constant K2 is the spring constant of bellows assembly 50 and any load acted upon by bellows assembly 50, e.g., any load acted upon by piston head 46. The load acted upon by the reacted mass may be, for example, fluid (gas or liquid) being compressed or acted upon by piston head 46. The third mass M3 corresponding to a base of the system is the mass of bellows assembly 58; and, the third spring constant K3 corresponding to the system resilient mounting spring is the spring constant of the resilient means which resiliently mounts the entire foregoing structure relative to the outside world, e.g., either resilient beams 160 (in Fig. 18A) or coiled springs 162 (in Fig. 18B). The third spring constant K3 affords a third degree of freedom. C1, C2, and C3 are damping coefficients, and as shown in Fig. 9 correspond to intrinsic damping (and, the case of C3, work done on the fluid).

[00079] The use of the third spring, as represented by third spring constant K3 and implemented, for example, by resilient beams 160 (in Fig. 18A) or coiled springs 162 (in Fig. 18B), thus affords or invokes a third degree of freedom. Unless the compressor assembly 20 is firmly clamped to a rigid base (in which case it transmits vibration force, but no energy) or is free (in which case it transmits vibration displacement but also no energy), the vibration will be damped. Therefore, the third spring constant provides a resilient mounting of the compressor assembly 20 within compressor housing 150. An alternative configuration would be to place two well matched units

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back to back to cancel vibration.

[00080] While specific embodiments have been described, the scope hereof is not so limited. For example, the reaction mass can be added or carried elsewhere than on a central underside of the piezoelectric diaphragm. What is preferred is that one of the reaction mass and the reacted mass be at the center of the piezoelectric diaphragm, and the other carried or attached at the periphery of the piezoelectric diaphragm. The reacted mass spring contributes to the spring constant K_2 preferably has a first end attached to the reacted mass and a second end attached to a base or housing which serves as the third mass M_3 . In the particular embodiment that has a third spring, such third spring serves for resiliently mounting the entire system (relative to the rest of the world) and preferably has a first end connected to the amplifier base and a second end connected to a system housing. Alternatively, if there is no such third spring (e.g., no resilient mounting), the amplifier base is rigidly fixed (e.g., to earth) or allowed to float freely.

[00081] The springs (having spring constants K_1 , K_2 , and K_3) and masses M_1 , M_2 , and M_3 of the system are selected such that the desired operating frequency is at a strategic natural frequency of the system. The reaction mass, the working stroke, and the frequency combine to define the load on the piezoelectric diaphragm. In order to maximize the power transfer from the piezoelectric diaphragm, the load on the piezoelectric diaphragm should lie at half of the blocked force. The blocked force is the force produced by a piezoelectric actuator when "blocked" from moving. In other words, the static force that it can impart on an immovable object. The power transferred is then twenty five percent of the product of blocked force, free displacement, and frequency.

[00082] In the Fig. 9 depiction, since there are three masses (M_1 , M_2 , and M_3) and three degrees of freedom, there are also three natural or resonant frequencies f_1 , f_2 , and f_3 . These three resonant frequencies correspond to the three peaks labeled as f_1 , f_2 , and f_3 in Fig. 22. In Fig. 22, the first peak is frequency f_1 which is the resonant frequency of the entire mounting (the natural frequency of everything that is bouncing on K_3 , e.g., all the structure carried by the resilient beams 160, for example). This first resonant frequency f_1 is low and serves to isolate the vibrations of the system from its housing. The third frequency is essentially mass M_1 (e.g., reaction mass 34) bouncing on spring

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K1 (e.g., piezoelectric diaphragm 30). The second resonant frequency is the resonant frequency of the structure carried by spring K2 (e.g., the resonant frequency of the structure carried by the reacted spring mass (the reacted spring mass being reacted mass cup 40 in the illustrated embodiments)). It is this second resonant frequency, f2, which is chosen as the desired operational frequency of the motion amplifier 22. Both first resonant frequency f1 and third resonant frequency f3 are kept reasonably far from the operating frequency f2.

[00083] As an aside, in addition to the three resonant frequencies of the system, there are also three partial frequencies Ω_1 , Ω_2 , and Ω_3 , thus making a total of six frequencies. The three partial frequencies are $\Omega_1 = K1/M1$, $\Omega_2 = K2/M2$, and $\Omega_3 = K3/M3$, respectively. Preferably the first partial frequency $\Omega_1 = K1/M1$ is made to be a high frequency; the second partial frequency $\Omega_2 = K2/M2$ is made equal to about the operating frequency (an intermediate frequency), and the third partial frequency $\Omega_3 = K3/M3$ is made to be a fairly low frequency (if operating frequency is about 250 Hz, $K3/M3$ is made about 40 Hz).

[00084] As mentioned above, the motion amplifier 22 is preferably operated at the second resonance frequency (f2). This second resonance frequency is essentially the square root of the quantity K2 divided by the sum of the masses M1 and M2. Because the first spring constant K1 is stiff, mass M1 does essentially the same thing as mass M2 does. So these two masses M1 and M2 bounce on the spring having spring constant K2, and this bouncing is what determines the peak at frequency f2. Advantageously, the displacement amplitude of the motion amplifier increases considerably at the frequency f2, as shown in Fig. 22. For example, operating at the resonant frequency f2 may provide as much as a twenty five fold in displacement amplitude. That is, the amplitude of the displacement of the motion amplifier is twenty five times the amplitude of the displacement of the piezoelectric diaphragm by itself.

[00085] Thus, frequency f2 is the operating frequency which produces a greatly amplified motion of the cylinder head (e.g., of flat bottom wall 46 of reacted mass cup 40). Energy is required to drive this large amplitude displacement. There is also a differential motion between mass M1 and mass M2, but such differential motion is not a concern because stresses of the piezoelectric diaphragm are set by the total motion of mass M1 rather than the differential motion.

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[00086] Of interest also is the phase angle between the motion of the piezoelectric diaphragm and the voltage driving the piezoelectric diaphragm. Line 250 of Fig. 22 shows phase angle as a function of frequency. For a sharply resonant peak like the amplitude peak that occurs for resonant frequency f_2 , the phase angle goes through a ninety degree phase shift at the resonant frequency and is fairly steep. As Fig. 22 shows, there is almost no phase shift until approaching the resonant frequency f_2 , and then right after the resonant frequency the phase shift is one hundred eighty degrees. Fig. 23 shows a graph of amplitude versus phase angle, which results in a fairly broad curve. The particular curve shown in Fig. 23 is for a particular damping ratio. The lower the damping ratio, the higher the relative response. So operating on the curve of Fig. 23 provides a fairly broad phase angle change for a fairly small change in amplitude. Accordingly, if the phase angle between the displacement of the system and the drive voltage applied to the piezoelectric diaphragm is maintained to, e.g., 10 degrees of the 90 degree resonant frequency f_2 , the displacement amplitude will be at its peak amplitude almost exactly.

[00087] The displacement of the system here is superposition of the displacements X_1 , X_2 , and X_3 in Fig. 9. Thus, the displacement of the system includes the motion of the piezoelectric diaphragm 30. But since the piezoelectric diaphragm 30 is attached to other masses (actually two masses M_1 [reaction mass 34] and M_2 [reacted mass 40]) that is moving with the bellows, the displacement of the system is a superposition of the motion of the piezoelectric diaphragm 30 and the other structure attached thereto. Of course, peak amplitude is desired in order to obtain maximum motion amplification, and thus the greatest possible compression ratio when the motion amplifier is used in a compressor assembly.

[00088] The sensor and control system 26 thus controls the phase angle between the displacement of the system and the drive voltage applied to the piezoelectric diaphragm 30 to be within a predetermined neighborhood of the second resonant frequency (e.g., within ten degrees of ninety degrees), in order to achieve peak amplitude of displacement of motion amplifier 22. In this regard, sensor and control system 26 employs optical emitter 170 and optical sensor 172 to measure the displacement of the top surface of piezoelectric diaphragm 30. The optical sensor senses displacement of the motion amplifier 22 relative to bellows base 58.

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[00089] Thus, the sensor and control system 26 measures displacement of piezoelectric diaphragm as well, and thus in actuality measures both displacement of the entire motion amplifier 22 (displacement X1) and the displacement of piezoelectric diaphragm 30 (displacement X2), relative to a fixed position (X3), e.g., on bellows base 58. But as a practical matter, displacement X1 of the piezoelectric diaphragm 30 is fairly small, and displacement X2 is much larger.

[00090] The optical sensor comprising optical emitter 170 and optical sensor 172 measures the displacement by reflection (using a simple type of sensor similar that detects whether door is open or closed). The optical sensor is biased into the linear region. As the distance separating the optical sensor 172 and the piezoelectric diaphragm 30 changes, so does the response as indicated by the sense position signal (see Fig. 20). Fig. 24 is a voltage verses distance graph showing an example response signal (e.g., sense position signal). Operating close to the second resonant frequency, e.g., at point x_0 , give a high voltage for the sense position signal, but moving away from the second resonant frequency causes the sense position signal voltage to decrease.

[00091] The motion amplifier is operated by phase control feedback, as implemented by sensor and control system 26, to lock the system to the second resonant frequency f_2 in spite of variations in the load, system non-linearity, and the like. The sensor and control system 26 thus includes a feedback loop to lock the frequency of the drive signal to the piezoelectric diaphragm 30 to produce a fixed value of the phase. The operation of the feedback loop to lock the frequency of the drive signal is understood with reference to control circuit 200 of Fig. 21.

[00092] Other aspects of the example control circuit 200 of Fig. 21 will now be described. It should be understood again that the structure and operation of example control circuit 200 of Fig. 21 are merely illustrative, and that other forms of control circuitry (e.g., primarily digital circuitry) may instead be implemented.

[00093] The motion of the motion amplifier is sensed by a miniature reflective photointerrupter (e.g., optical sensor 172) of example control circuit 200 of Fig. 21. The photointerrupter is electrically biased to provide a monotonic response with position. The signal from the position detector is buffered by U1B of buffer 208. The series resistance to the optical sensor 172 is set by potentiometer P6 so that, at the

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nominal position of the piezoelectric diaphragm 30 (about 0.070 inch to the front of the sensor 172), the signal at testpoint 2 is four volts. During operation, the signal is sinusoidal with an amplitude of about two volts peak to peak about the nominal reset point of four volts. The buffered signal is ground referenced by C3. The ground
5 referenced peak to peak signal is available at test point 3 as an output. The ground referenced signal is then amplified by the two stage squaring amplifier 210 and 220 comprising U2B and U2A, respectively, until it becomes a square wave.

[00094] The optical sensor is phase detected relative to the drive signal. The drive signal is converted to a square wave by amplifying the sine wave used to drive the
10 piezoelectric diaphragm 30 until it saturates the amplifier. The phase angle is detected by the flip flop circuit U4 of phase detector 222. The two square waves are first differentiated by capacitors C5 and C6 to produce spikes which turn the flip flop U4 on and then off with each cycle of the square waves. While the flip flop U4 is on, a voltage is produced at the output Q. The DC level of this voltage is detected by the low
15 pass filter 224 (in U1A). This voltage is proportional to the phase difference between the optical response and the drive voltage.

[00095] The phase angle is used to control frequency as follows. The difference between the measured phase angle and a fixed "set point" voltage set by potentiometer P2 is integrated by capacitor C28. The integrator output is inverted by U3A and
20 amplified relative to a frequency set point in U3B. In principle, both inverter 228 and the center frequency setpoint amplifier, U3B and U3A, could be omitted. However, they may be useful because, by shorting capacitor C28, the frequency can be adjusted by potentiometer P8 to sweep over a wide range. The output of U3B drives a voltage variable frequency. This sine wave is offset, buffered, and amplified by U6A, U6B,
25 and U7B. The conditioned sine wave is fed to the high voltage amplifier which drives piezoelectric diaphragm 30. The U8A amplifies the sine wave to produce the square wave needed for the phase detector.

[00096] Thus, feedback control is based on the phase angle between the motion of the piezoelectric diaphragm and the drive voltage applied to piezoelectric diaphragm. As
30 explained above, if the phase angle is kept between sixty and one hundred twenty degrees, the motion amplitude will be within 5% of the second resonant frequency peak. Such a relatively broad range in phase space is due to the sharpness of the

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resonance.

[00097] As in the preceding example, the motion sensor may typically detect position. Other types of detection are also possible, such as velocity or acceleration, for example. The currently preferred embodiment is to use an optical sensor comprised of an LED
5 (as optical emitter 170) and phototransistor (as optical sensor 172) where the transconductance depends on position in a relatively linear fashion. Such a sensor provides the additional function of limiting the stroke of the compressor in order to prevent the drive from impacting the cylinder head.

[00098] The example compressor assembly embodiment 20 of Fig. 1 includes bellows
10 assembly 50, which can be desirable because the compression chamber at least partially defined thereby can be smaller (e.g., in diameter) than the piezoelectric diaphragm 30 and because stock bellows are available for reasonable cost. In the bellows embodiment, the second spring constant K2 corresponds in part to the reacted mass spring and thus includes the spring constant of bellows assembly 50 (as well as the
15 spring constant of any load acted upon by the reacted mass, e.g., the actuator portion of surface).

[00099] Fig. 25 illustrates another example embodiment of a compressor assembly, particularly compressor assembly 20'. The compressor assembly 20' includes many of the like-referenced elements of the first embodiment compressor assembly 20 of Fig. 7,
20 including piezoelectric diaphragm 30 which carries reaction mass 34, the piezoelectric diaphragm 30 and reaction mass 34 in turn being carried within reacted mass cup cavity 48 by reacted mass cup 40. The bottom of reacted mass cup 40 (e.g., reacted mass cup bottom wall 46) provides or serves as a compression head or piston, e.g., as the actuator portion or surface of the motion amplifier.

[000100] The compressor assembly 20' of Fig. 25 differs in the form of the second
25 spring K2 which carries the reacted mass cup 40. In particular, the second spring having spring constant K2 of the Fig. 25 embodiment comprises corrugated diaphragm 270. A rim or periphery of corrugated diaphragm 270 is attached to an amplifier base 58'. Corrugations in the diaphragm 270 enhance motion of the entire motion amplifier
30 structure. Amplifier base 58' at least partially defines a crater-type cavity which serves as compression chamber 52'. The crater-type cavity formed by amplifier base 58' may

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itself have an undulating surface to accommodate corrugations in the diaphragm 270. The corrugated diaphragm 270 also at least partially defines the compression chamber 52' by serving as a cover therefore (in addition to serving to support the reacted mass cup 40). An intake or inlet valve 272 is provided in amplifier base 58', as is an outlet or exhaust valve 274.

[000101] The corrugated diaphragm 270 can be provided in the form of an essentially solid member upon which the reacted mass cup 40 is situated. In this implementation, the corrugated diaphragm 270 can have reacted mass cup 40 adhered or otherwise secured thereover.

10 [000102] Alternatively, the corrugated diaphragm 270 can have a central aperture or the like through which the bottom (e.g., the compression head) of reacted mass cup 40 protrudes. The reacted mass cup 40 is, in this implementation, securely engaged by corrugated diaphragm 270 in its central aperture.

15 [000103] The corrugated diaphragm 270 may be fabricated from a flexible material such as elastomer, or of a rigid material such as nickel, silver, or steel. In the size ranges of commercial interest, a flat rigid diaphragm would have a very non-linear deflection curve which might create a challenge for maintaining resonant operation. Therefore, a corrugated diaphragm is recommended. The end wall of the amplifier base 58' may be contoured to provide minimum dead volume.

20 [000104] Other embodiments and ways of employing a motion amplifier in a compressor assembly are also possible. For example, a motion amplifier reciprocate in a base defining a compression chamber, with sliding seals provided between the motion amplifier and the base. Alternatively, a rubber-edged disk or bellofram may be utilized. As another alternative, a Peek diaphragm or electroformed bellows may be employed.

25 [000105] Whatever embodiment the motion amplifier 22 takes, including the embodiment of Fig. 25 described above and the embodiment of Fig. 26 described hereinafter, providing a third degree of freedom eliminates or mitigates any dampening imposed or caused by the outside world. To this end, coiled springs 162 are shown in Fig. 25 as providing the spring constant K3 and thus the third degree of freedom. Other
30 resilient mounting structure or techniques can be employed, such as (by way of non-

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limiting example) the resilient beams hereinbefore described.

[000106] As mentioned above, the drive signal can be applied to motion initiator element 30 by radially extending electrodes or leads 32. Flexures can be arranged in these leads or electrodes to pass electricity to the motion initiator element 30 since the motion initiator element 30 moves with respect to the housing in which the power supply may be fixed. Moreover attachment points of the flexing leads, one being on the motion initiator element 30 and the other being fixed in space, may lie directly over each other as to form a hairpin shape, which is efficient with respect to bending stresses on the attachment points.

[000107] Fig. 26 illustrates another embodiment of a compressor assembly 20 wherein the motion amplifier comprises plural motion initiator elements, e.g., plural piezoelectric diaphragms 30. In the illustrated example of Fig. 26, a second piezoelectric diaphragm 30-2 is positioned by mounting member 180 above the first piezoelectric diaphragm 30. The mounting member 180 can take the form of pedestals or a ring. More than one auxiliary piezoelectric diaphragm 30 can be provided, e.g., in stacking arrangement, in similar manner, not only for the illustrated embodiment having a corrugated diaphragm, but for the bellows embodiment and other embodiments as well.

[000108] In whatever embodiment of compressor assembly is utilized, the valves employed in the compressor assembly should open and close efficiently at the operating frequency, and will in fact do so if the valves have a sufficiently high natural frequency. Since valve pressure drop and bending stress increase with the valve natural frequency, the valves will ultimately set an upper operating limit on the compressor. To help limit the stress and improve the time response of the valves, as one example technique stops can be utilized to limit the travel of the valves. Fig. 25 illustrates stop 276 for inlet valve 272 and stop 278 for exhaust valve 274. These stops should reasonably conform to the shape of the deflected element (e.g., to the reed for a reed valve), and also allow some clearance. Without a technique such as stops, the blast of fluid forces the valves open too far (dynamically), and the valves then shut and reopen several times during the cycle, which does not improve the fluid flow.

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[000109] In an example embodiment, valve natural frequency is selected and set at 650 Hz and the operating frequency at 250 Hz. The equivalent mass is about 20% of the mass of the reed (rather than about 33% as expected for a regular spring). If the natural frequency of the valves (e.g., the reeds of the valves) is at least twice the operating frequency, the valves do not have timing issues at some of the larger backpressure levels.

[000110] In a preferred embodiment and mode of operation, piezoelectric diaphragm 30 more particularly takes the form of a ruggedized laminated piezoelectric member. Examples of such ruggedized laminated piezoelectric members are provided in PCT Patent Application PCT/US01/28947, filed 14 September 2001; United States Patent Application Serial Number 10/380,547, filed March 17, 2003, entitled "Piezoelectric Actuator and Pump Using Same"; United States Patent Application Serial Number 10/380,589, filed March 17, 2003, entitled "Piezoelectric Actuator and Pump Using Same", and United States Patent Application 11/279,647 filed April 13, 2006, , entitled "PIEZOELECTRIC DIAPHRAGM ASSEMBLY WITH CONDUCTORS ON FLEXIBLE FILM", all of which are incorporated herein by reference.

[000111] The motion amplifier 22 uses the displacement/motion of piezoelectric diaphragm 30 (such displacement being on the order of 0.1 mm for an example embodiment) to drive an actuator region or surface (e.g., compressor head) to large displacements. In illustrated embodiment, the actuator surface (also known as a cylinder head or piston head) may take the form of flat bottom wall 46 of reacted mass cup 40.

[000112] For example, a displacement of 2 mm (e.g., strokes of 2 mm) is possible in motion amplifier 22 having a 25 mm piezoelectric diaphragm 30 operating at 400 volts peak to peak. Such a drive voltage would only produce a 0.16 mm stroke if applied directly to the piezoelectric diaphragm 30 alone. Since the motion of the piezoelectric diaphragm 30 in the motion amplifier 22 is at most half of this 0.16, or only 0.08 mm, a "gain" of 25 is achieved. This gain occurs at the operating frequency which is a resonant condition. This resonant condition (frequency and gain) change with load and system nonlinearities, such as a hardening spring (typical of diaphragms and gas springs).

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[000113] In addition to large amplitude, an advantage of the motion amplifiers described herein are their ability to impedance match to a variable load. When the motion amplifier is used in compressor assembly 20 or 20', for example, the load impedance changes as the flow rate and pressure rise of the compressor change. Over
5 wide ranges the piezoelectric diaphragm can still drive the load efficiently because of the flexibility afforded by the resonant drive of the sensor and control system. Thus, at low flow rates, pressures up to the limit imposed by the maximum achievable compression can be reached. Work is not expended until the valves open to allow fluid
10 to escape the compression chamber. With no flow (and also with no pressure rise), no energy is lost from the system. At low pressures, the flow is only limited by the maximum possible displacement. Intermediate operating points tend to fall on a hyperbolic operating curve representing constant input power. By way of contrast, centrifugal and axial compressors have very little tolerance to changes in load.

[000114] The described embodiments are particularly suitable, but not limited to,
15 compressors for air or other fluid which are generally in a flow range of from 0.01 to 10 liters per minute, and pressure ratios up to 2:1 with weights in the 50 gram range and power efficiencies up to about 30%.

[000115] Although various embodiments have been shown and described in detail,
20 the claims are not limited to any particular embodiment or example. None of the above description should be read as implying that any particular element, step, range, or function is essential such that it must be included in the claims scope. The scope of patented subject matter is defined only by the claims. The extent of legal protection is defined by the words recited in the allowed claims and their equivalents. It is to be
25 understood that the invention is not to be limited to the disclosed embodiment, but on the contrary, is intended to cover various modifications and equivalent arrangements.

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WHAT IS CLAIMED IS:

- 1 1. A fluid compressor assembly comprising:
2 a motion amplifier (22) comprising:
3 a piezoelectric diaphragm (30);
4 a reaction mass (34) connected to the piezoelectric diaphragm (30);
5 a reacted mass (40) connected to the piezoelectric diaphragm (30), the
6 reacted mass (40) forming a compression head;
7 a reacted mass spring for resiliently carrying the reacted mass (40);
8 an amplifier base (58) for at least partially defining a compression
9 chamber (52) into which fluid is selectively admitted and exhausted;
10 drive electronics for driving the piezoelectric diaphragm (30) and thereby
11 displacing the compression head for compressing fluid in the compression chamber
12 (52);
13 an inlet valve and an outlet valve for respectively admitting and exhausting fluid
14 relative to the compression chamber (52).

- 1 2. The apparatus of claim 1, wherein the drive electronics generates and applies
2 the drive signal to the piezoelectric diaphragm (30) so as to maintain the motion
3 amplifier (22) resonant at a predetermined frequency.

- 1 3. The apparatus of claim 2, wherein structure of the motion amplifier (22)
2 carried by the reacted mass spring has a resonant frequency f_2 , wherein the
3 predetermined frequency is f_2 , and wherein the drive signal is generated to urge the
4 motion amplifier (22) to the frequency f_2 as its operational frequency.

- 1 4. The apparatus of 3, wherein the resonant frequency f_2 is related to a spring
2 constant K_2 of the reacted mass spring and a sum of masses of the reaction mass (34)
3 and the reacted mass (40).

- 1 5. The apparatus of 1, wherein the drive electronics generates the drive signal
2 to maintain a predetermined phase angle between the drive signal and a signal
3 indicative of displacement of the motion amplifier (22).

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1 6. The apparatus of claim 5, wherein the drive electronics comprises a sensor for
2 sensing displacement of the motion amplifier (22) and for generating the signal
3 indicative of displacement of the motion amplifier (22).

1 7. The apparatus of 1, wherein a periphery of the piezoelectric diaphragm (30) is
2 held and carried by the reacted mass (40).

1 8. The apparatus of 1, wherein the piezoelectric diaphragm (30) is mounted to
2 and carried by the reacted mass (40); wherein the reacted mass (40) comprises a reacted
3 mass (40) cup which defines a reacted mass (40) cavity, and wherein the reaction mass
4 (34) is suspended from the piezoelectric diaphragm (30) in the reacted mass (40) cavity.

1 9. The apparatus of claim 1, further comprising an amplifier base (58) for at
2 least partially defining a compression chamber (52), wherein the reacted mass spring
3 also at least partially defines the compression chamber (52), and further comprising
4 means for resiliently mounting the amplifier base (58) relative to the outside world.

1 10. The apparatus of claim 9, wherein the amplifier base (58) carries the
2 piezoelectric diaphragm (30), the reaction mass (34), the reacted mass (40), and the
3 reacted mass (40) spring.

1 11. The apparatus of 1, further comprising an amplifier base (58) for at least
2 partially defining a compression chamber (52), wherein the reacted mass spring
3 comprises a diaphragm which also at least partially defines and covers the compression
4 chamber (52), the amplifier base (58) having an inlet and an outlet for respectively
5 intaking and exhausting fluid in accordance with displacement of the reacted mass (40).

1 12. The apparatus of claim 11, wherein the diaphragm comprising the reacted
2 mass spring is a corrugated diaphragm.

1 13. The apparatus of claim 11, further comprising means for resiliently
2 mounting the amplifier base (58) relative to the outside world.

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1 14. The apparatus of 1, further comprising a bellows assembly, and wherein the
2 bellows assembly comprises a sidewall for defining a compression chamber (52), the
3 sidewall comprising the reacted mass (40) spring.

1 15. The apparatus of claim 14, wherein the bellows assembly further comprises
2 an amplifier base (58) for defining a valve assembly cavity, the valve assembly cavity
3 and the compression chamber (52) being sized to accommodate a valve assembly
4 through which fluid is introduced into the compression chamber (52) and compressed in
5 the compression chamber (52) by displacement of the motion amplifier (22).

1 16. The apparatus of claim 14, wherein the bellows assembly further comprises
2 an amplifier base (58), and further comprising means for resiliently mounting the
3 amplifier base (58) relative to the outside world.

1 17. The apparatus of claim 1, wherein the natural frequency of the inlet valve
2 and the natural frequency of the outlet valve are greater than an operating frequency of
3 the motion amplifier (22).

1 18. The apparatus of claim 17, wherein the natural frequency of each of the
2 inlet valve and the outlet valve is at least twice the operating frequency of the motion
3 amplifier (22).

1 19. A method of operating a compressor assembly for compressing a fluid
2 comprising:

3 displacing a motion amplifier (22) having a compressor head in a compressor
4 chamber, the motion amplifier (22) comprising a piezoelectric diaphragm (30), a
5 reaction mass (34) connected to the piezoelectric diaphragm (30), a reacted mass (40)
6 connected to the piezoelectric diaphragm (30), and a reacted mass spring for resiliently
7 carrying the reacted mass (40);

8 selectively admitting and exhausting fluid from the compressor chamber in
9 accordance with displacement of the motion amplifier (22);

10 wherein the displacing the motion amplifier (22) comprises generating and
11 applying a drive signal to the piezoelectric diaphragm (30), the drive signal being
12 generated to maintain the motion amplifier (22) resonant at a predetermined frequency.

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1 20. The method of claim 19, wherein structure of the motion amplifier (22)
2 carried by the reacted mass spring has a resonant frequency f_2 , wherein the
3 predetermined frequency is f_2 , and further comprising generating the drive signal to
4 urge the motion amplifier (22) to the frequency f_2 as its operational frequency.

1 21. The method of claim 20, wherein the resonant frequency f_2 is related to a
2 spring constant K_2 of the reacted mass spring and a sum of masses of the reaction mass
3 (34) and the reacted mass (40).

1 22. The method of claim 19, further comprising generating the drive signal to
2 maintain a predetermined phase angle between the drive signal and a signal indicative
3 of displacement of the motion amplifier (22).

1 23. The method of claim 22, further comprising sensing displacement of the
2 motion amplifier (22) and generating the signal indicative of displacement of the
3 motion amplifier (22).

1 24. The method of claim 19, wherein the compressor assembly further
2 comprises an amplifier base (58) for at least partially defining the compression chamber
3 (52), and further comprising resiliently mounting the amplifier base (58) relative to the
4 outside world.

1 25. The method of claim 24, mounting the piezoelectric diaphragm (30), the
2 reaction mass (34), the reacted mass (40), and the reacted mass spring on the amplifier
3 base (58).

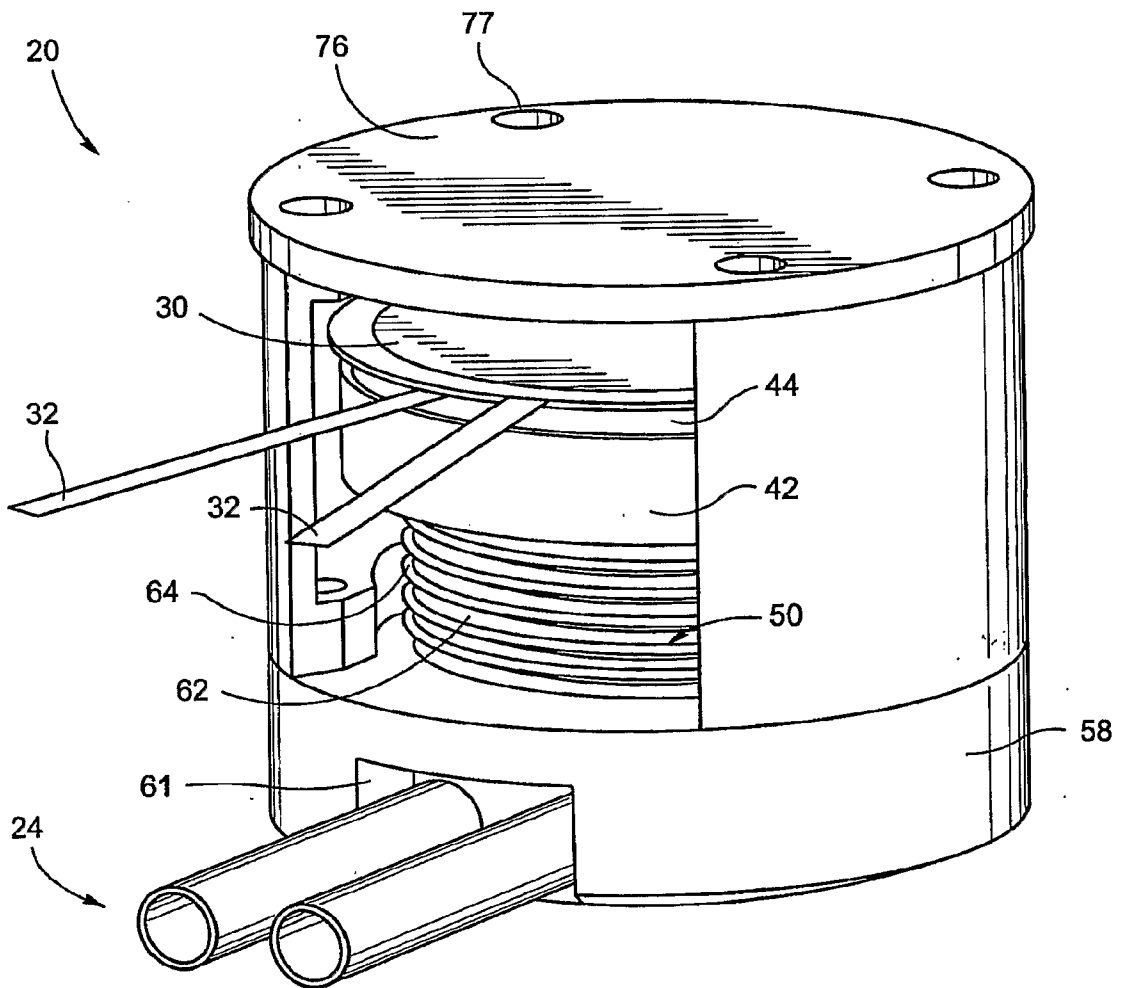


Fig. 1

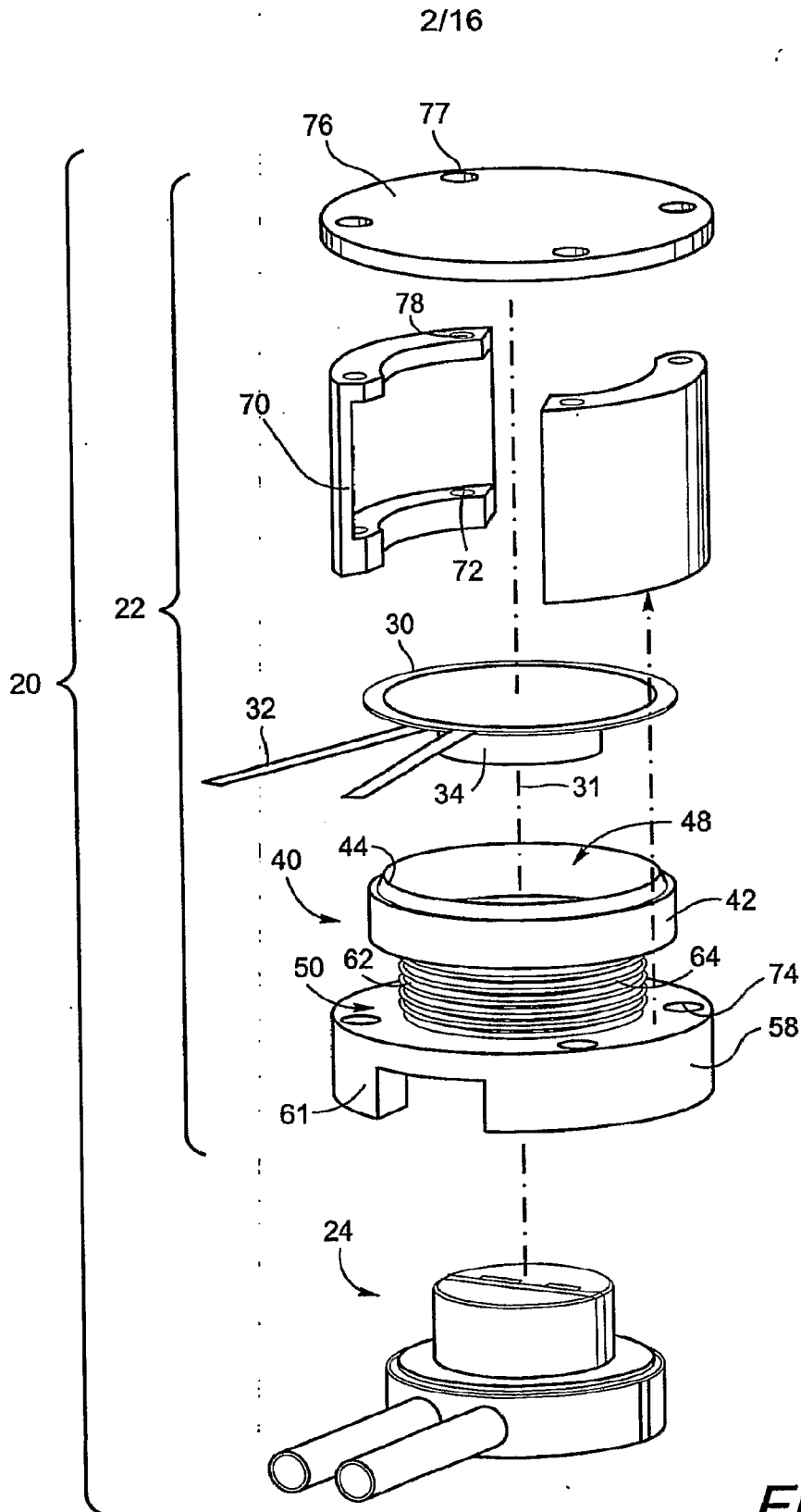


Fig. 2

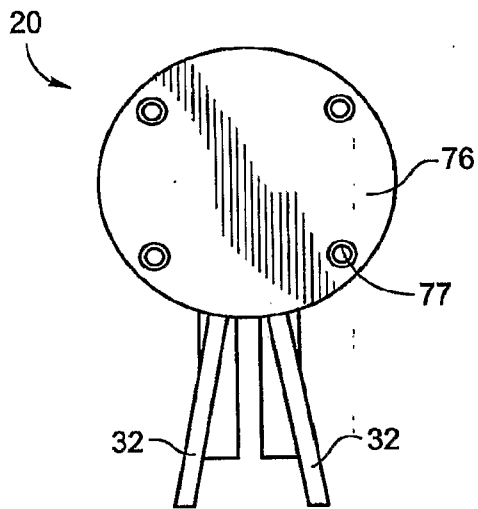


Fig. 3

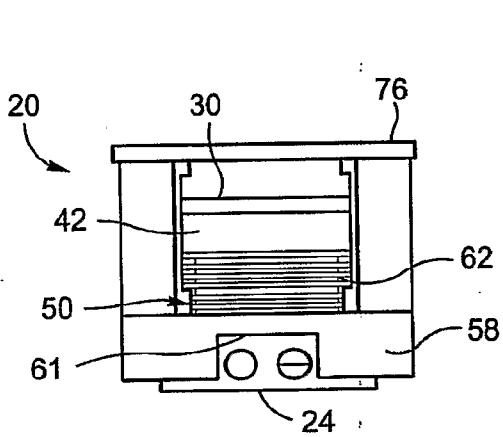


Fig. 4

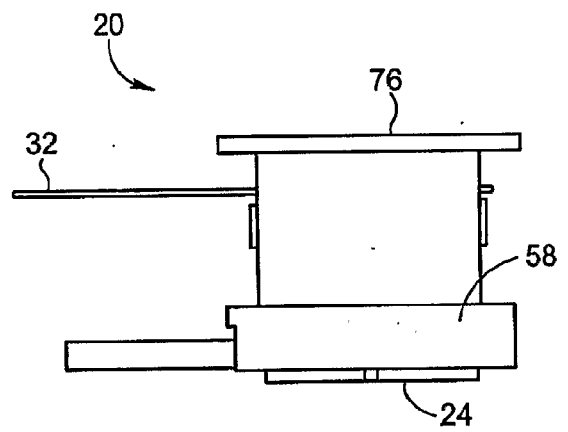


Fig. 6

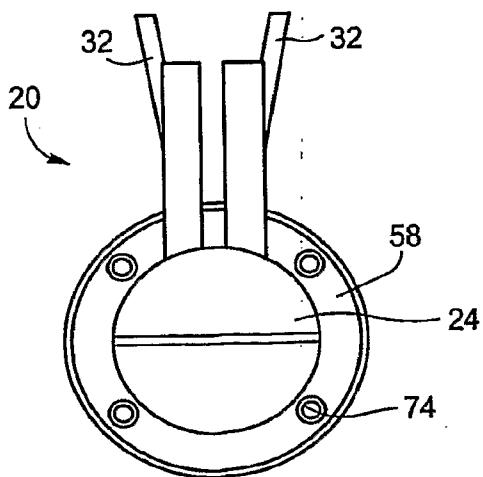


Fig. 5

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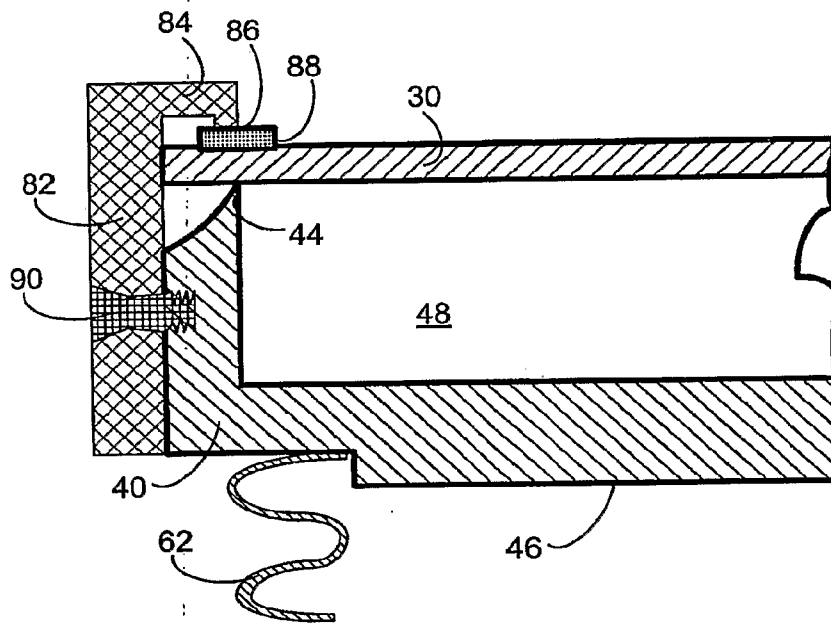


Fig. 8A

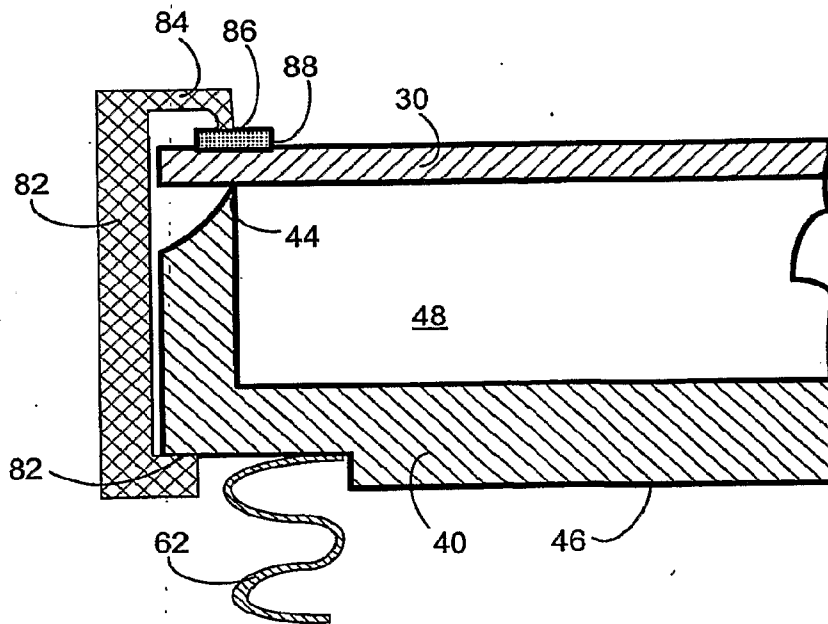


Fig. 8B

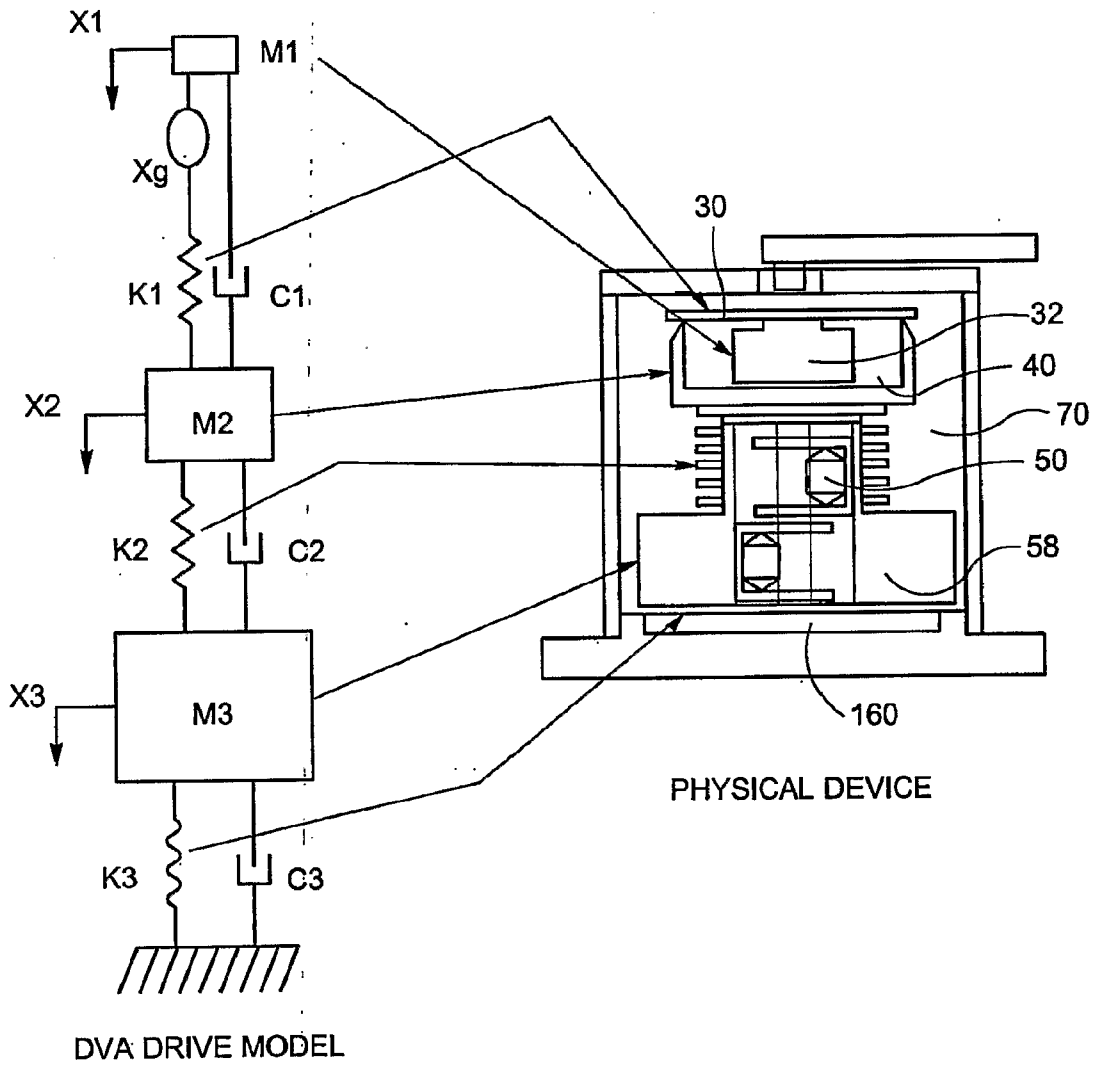


Fig. 9

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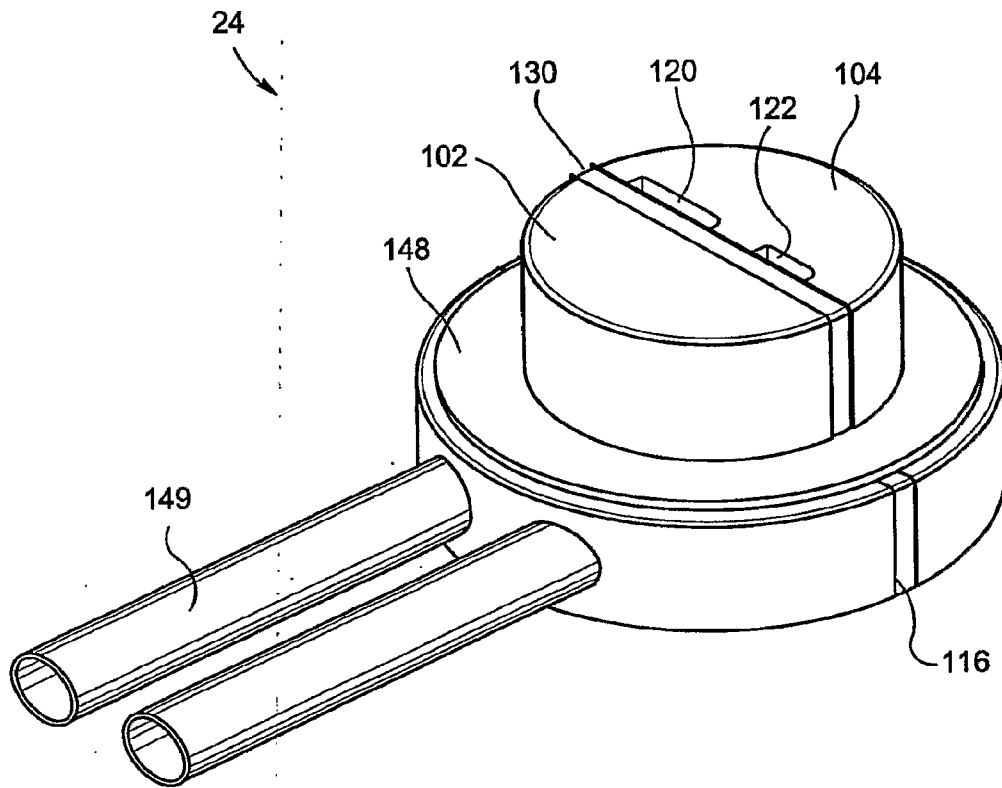


Fig. 10

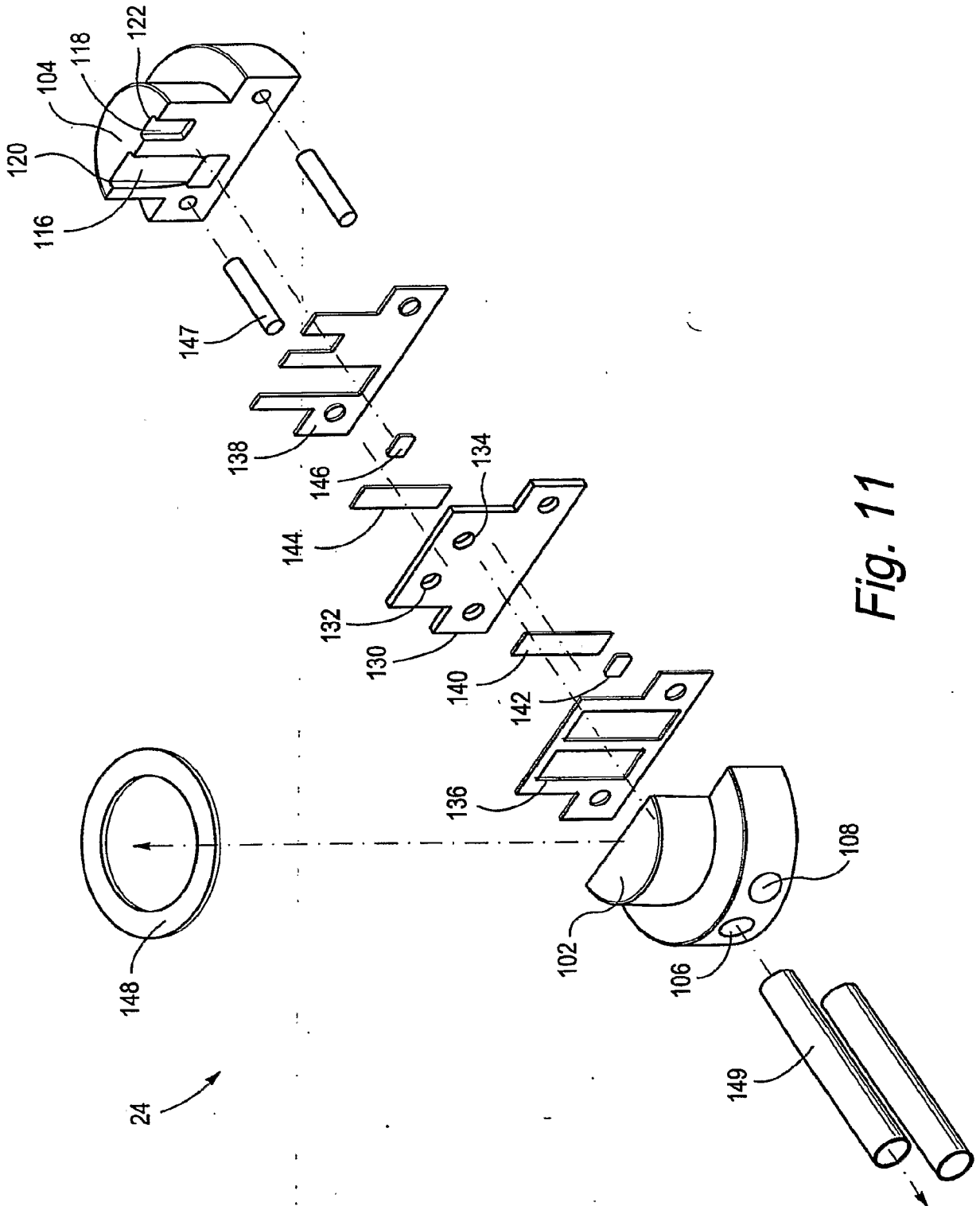


Fig. 11

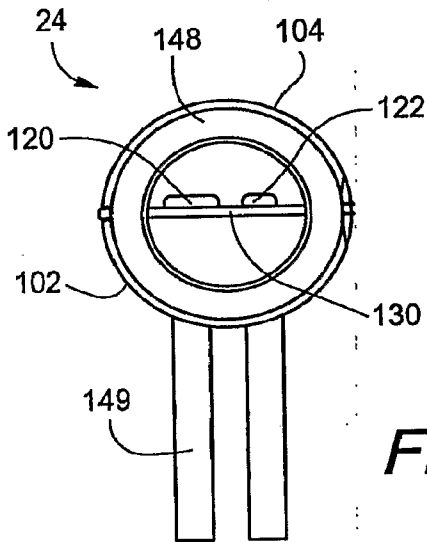


Fig. 12

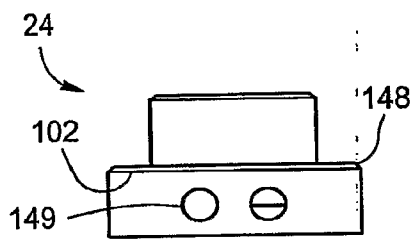


Fig. 13

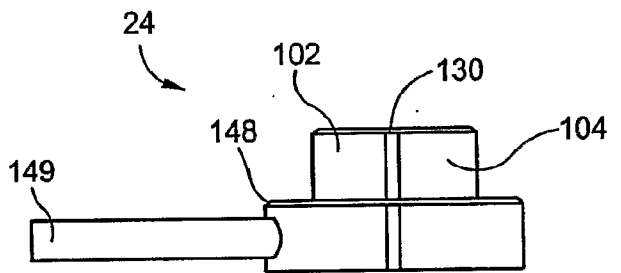


Fig. 15

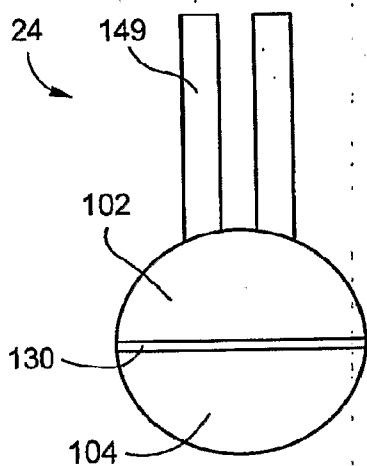


Fig. 14

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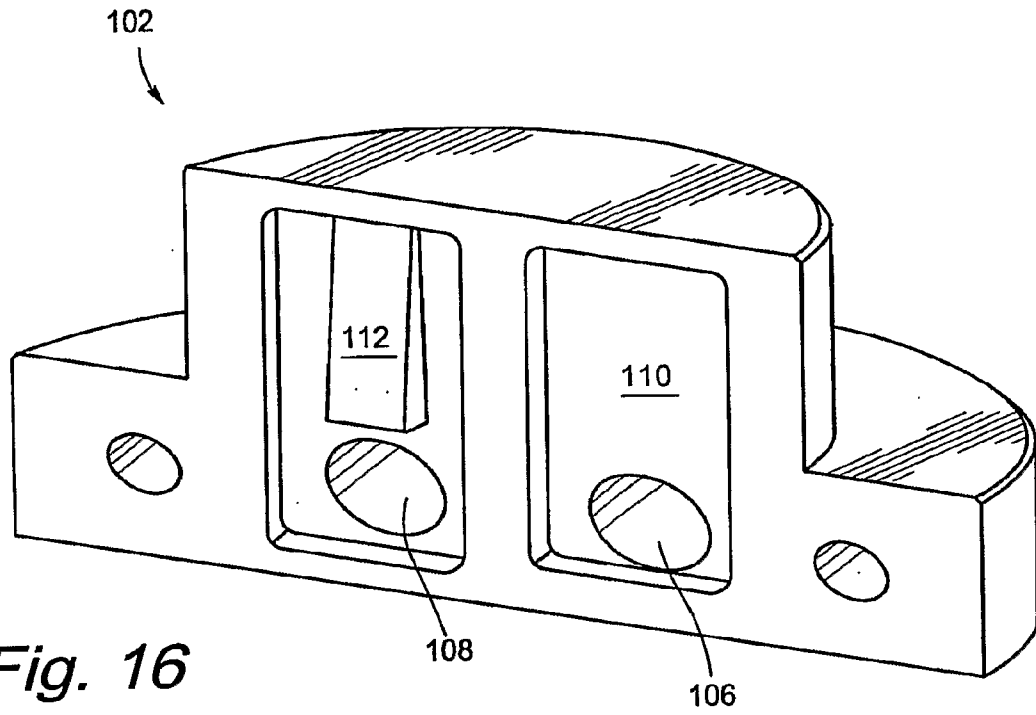


Fig. 16

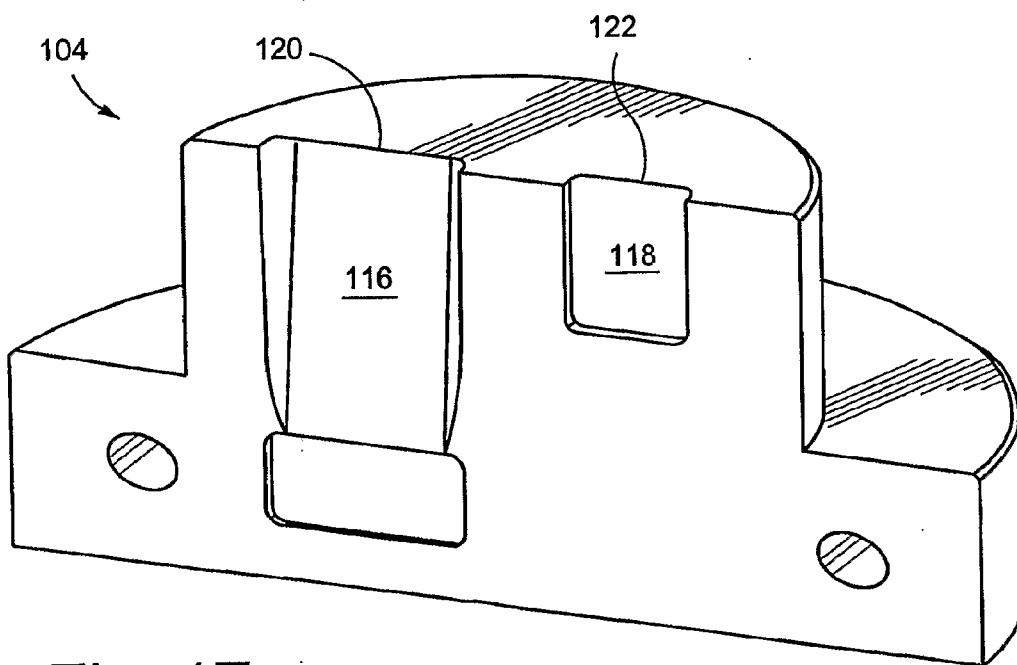


Fig. 17

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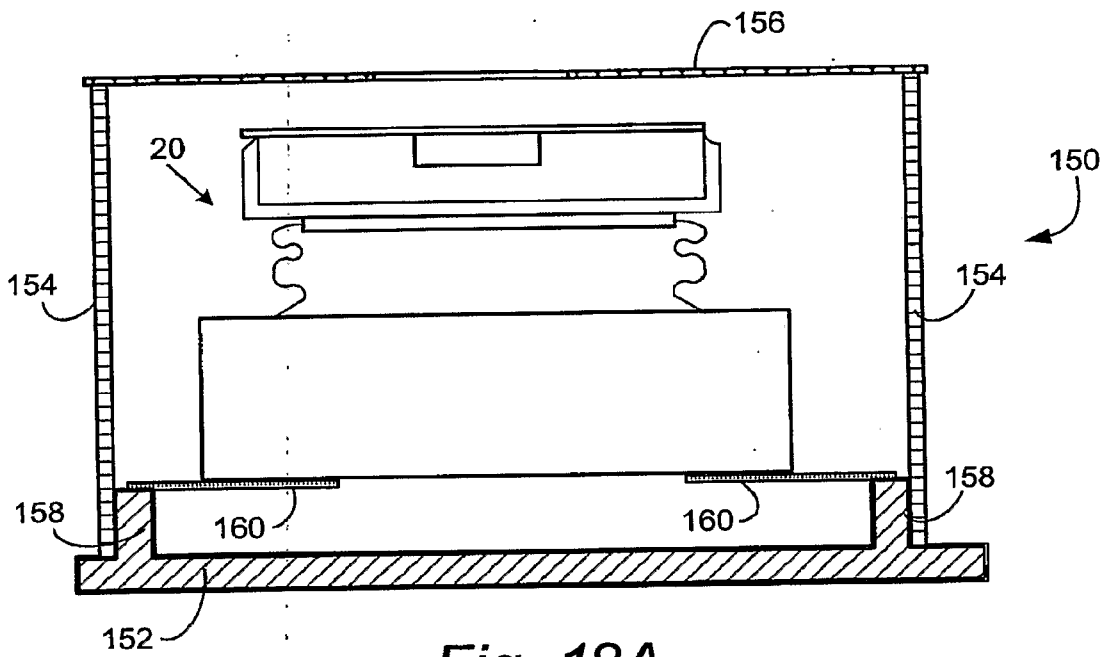


Fig. 18A

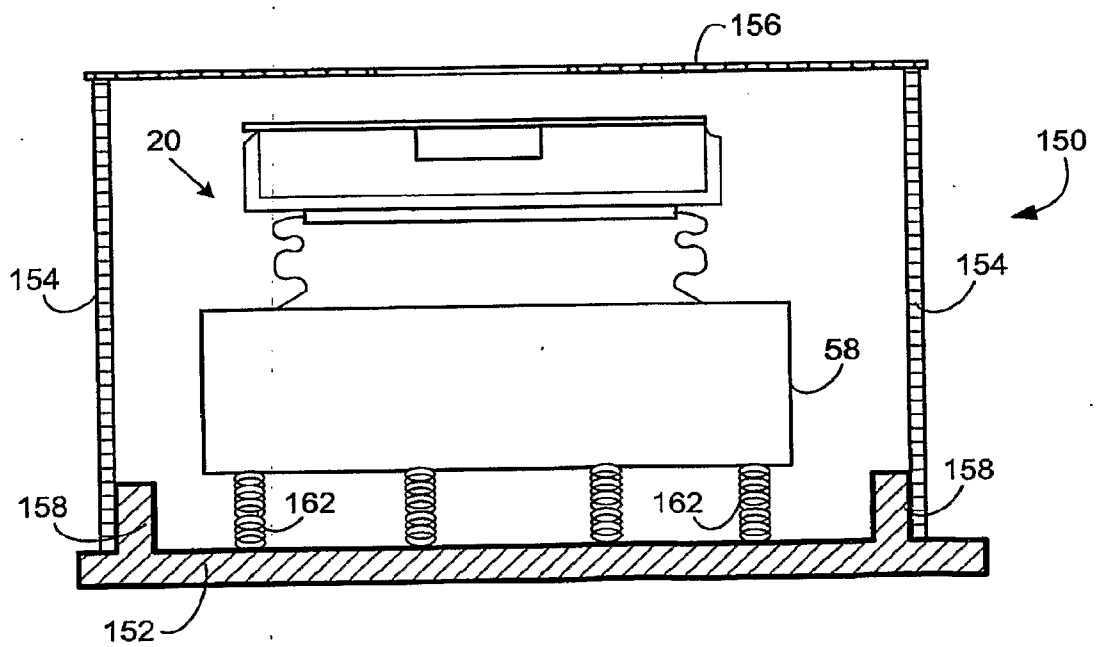


Fig. 18B

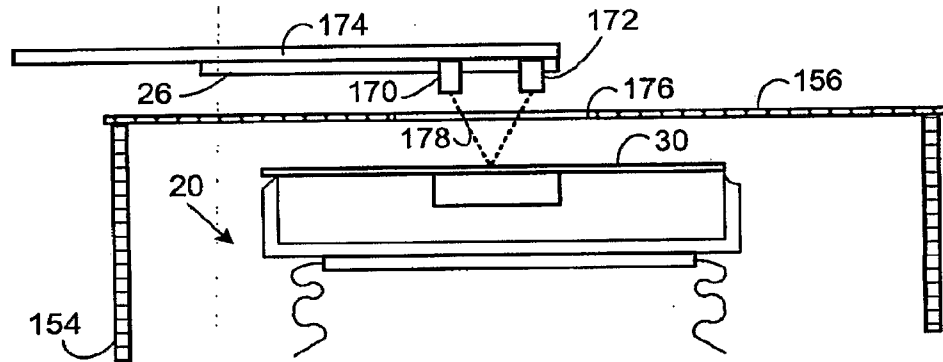


Fig. 19A

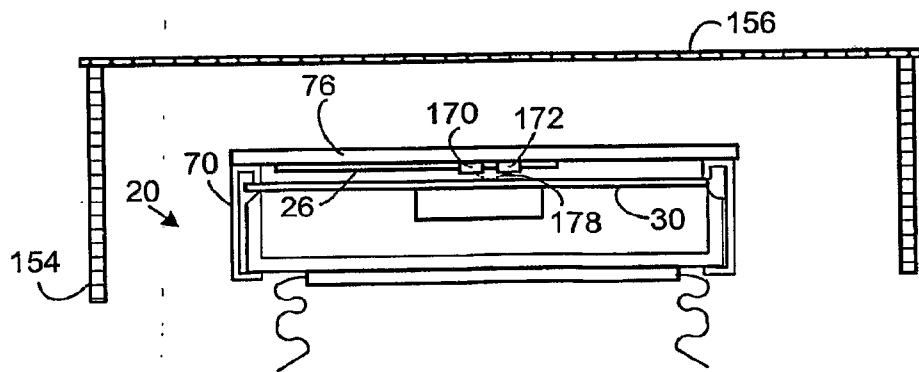


Fig. 19B

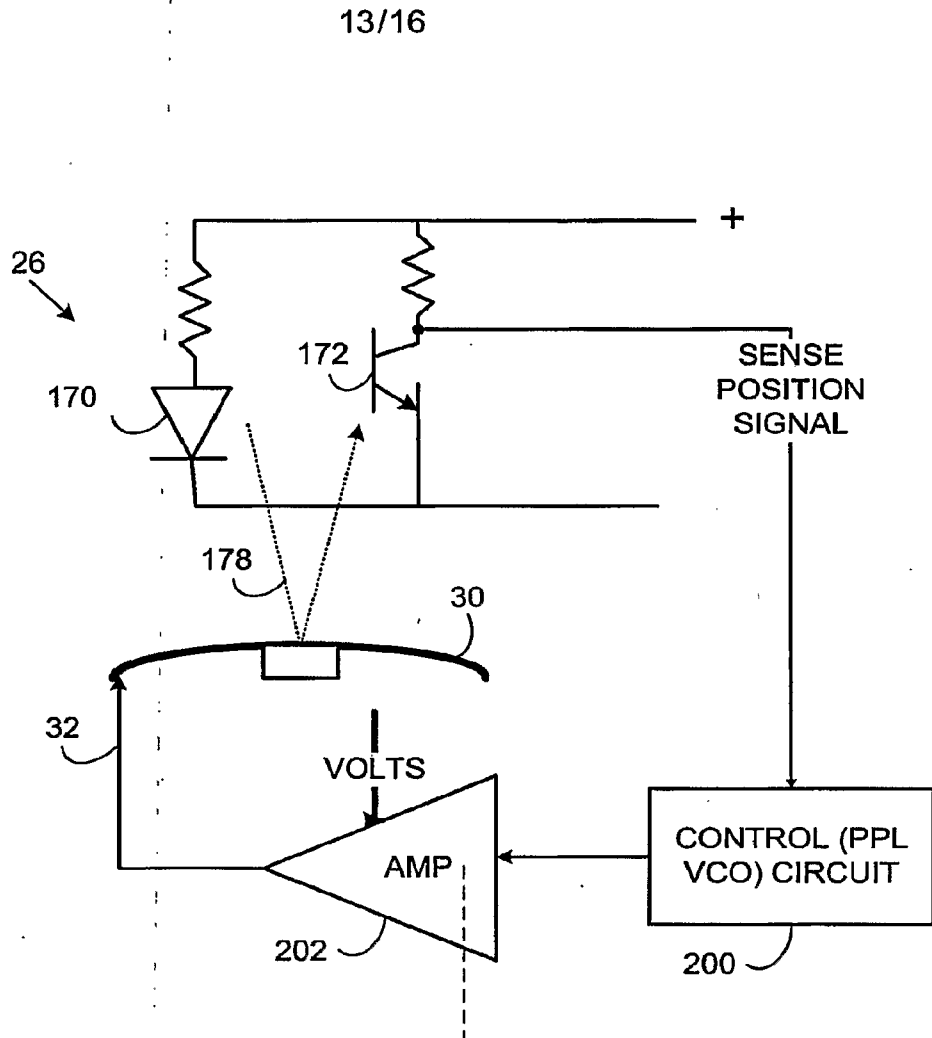


Fig. 20

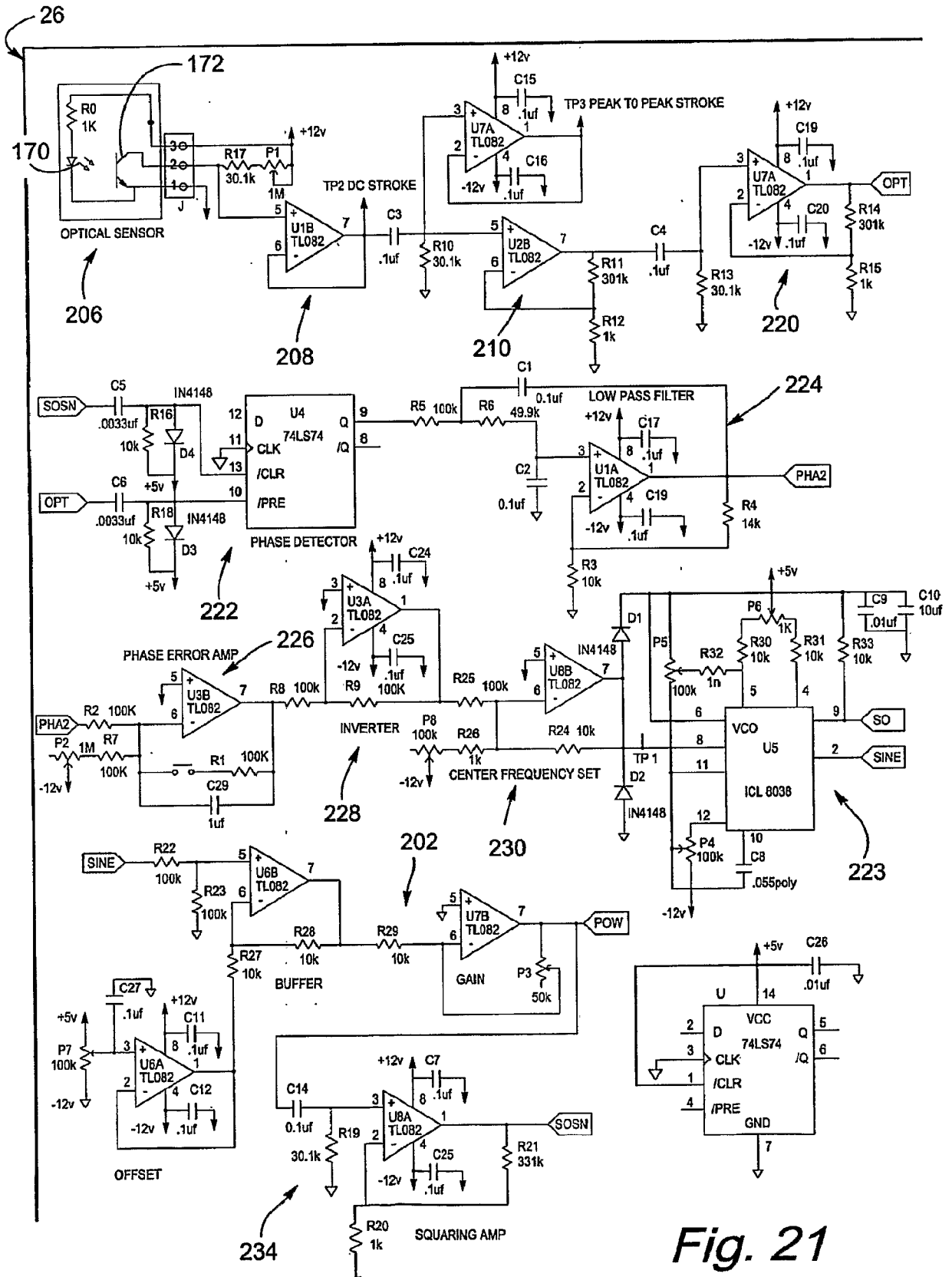


Fig. 21

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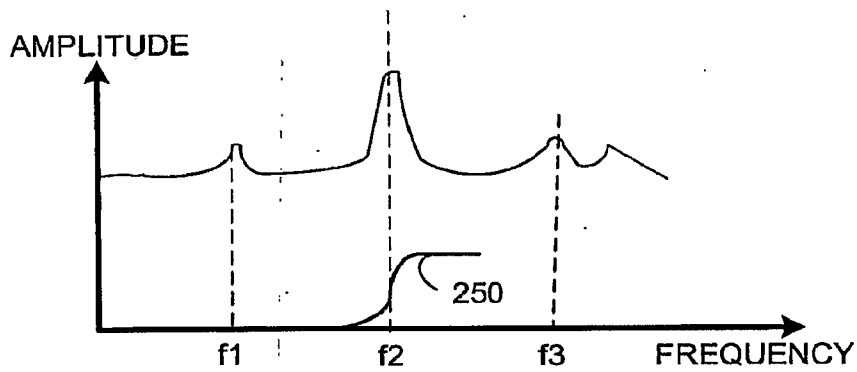


Fig. 22

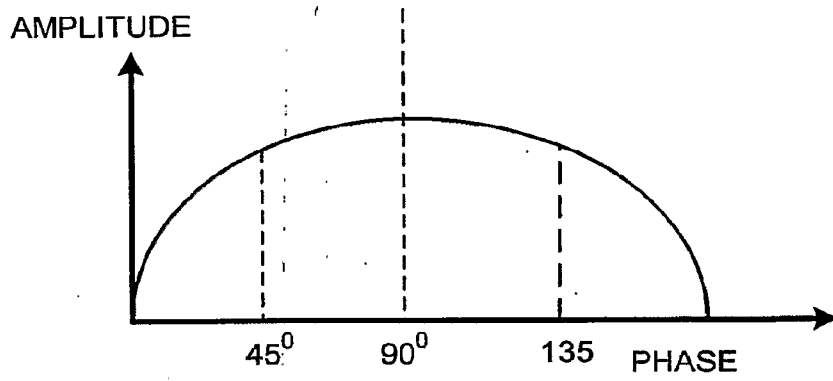


Fig. 23

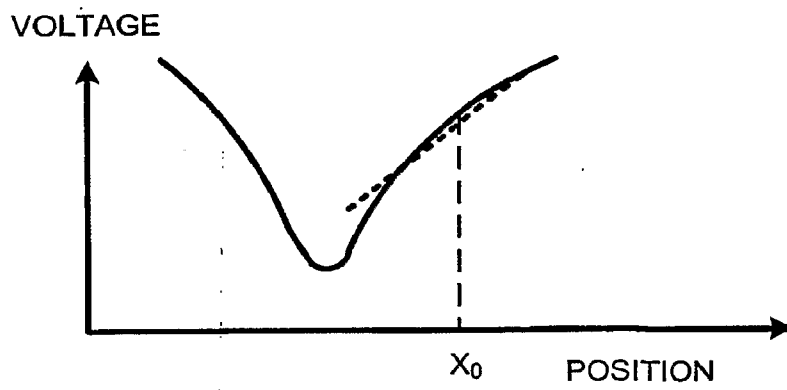


Fig. 24

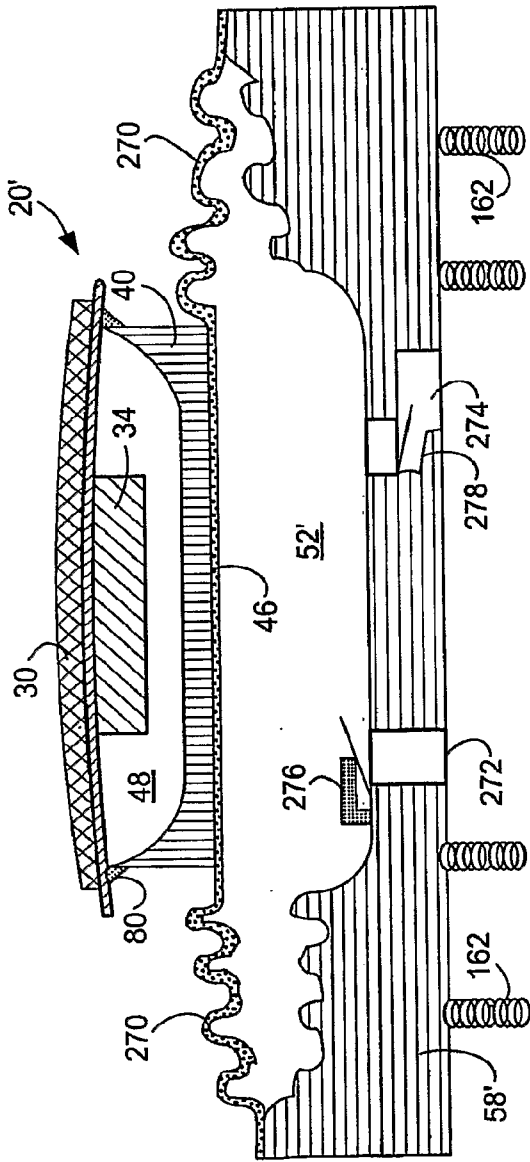


Fig. 25

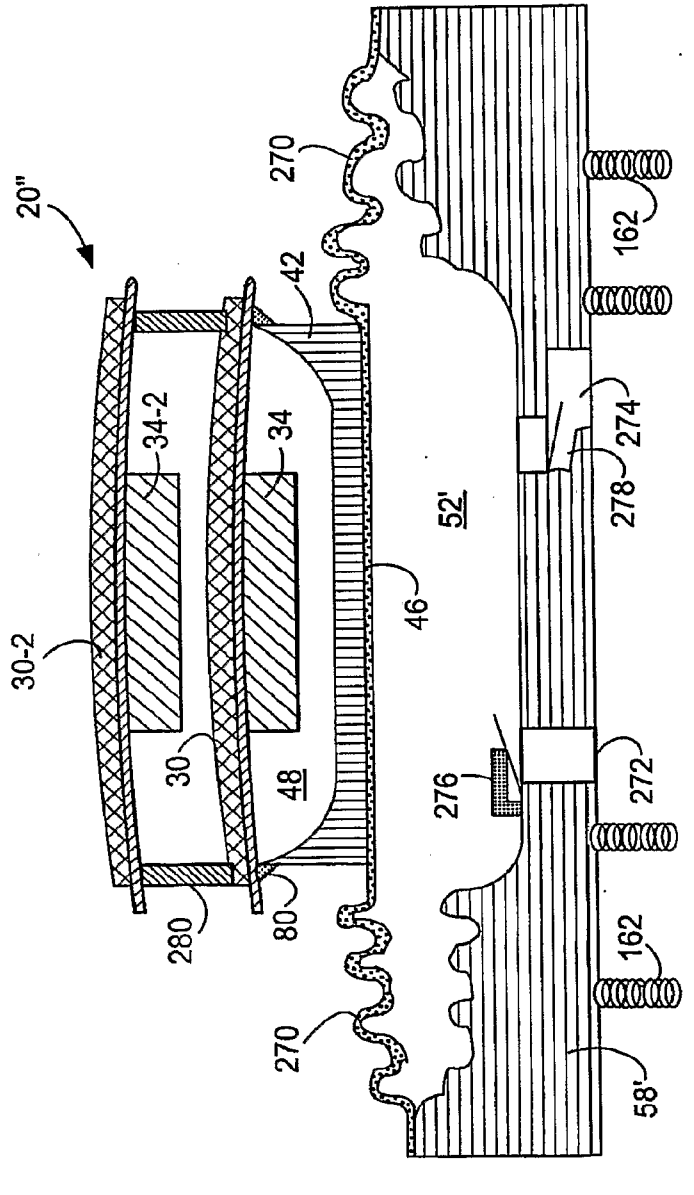


Fig. 26