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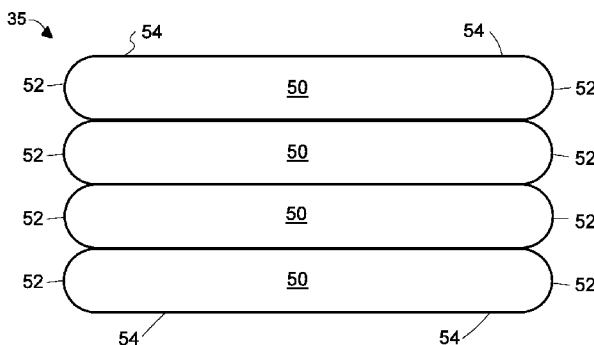


FIG. 1

(57) Abstract: The following description pertains to flexure structures, apparatuses comprising flexure structures, systems compris-
ing flexure structures, methods of using flexure structures, methods of using apparatuses comprising flexure structures, and methods
of using systems comprising flexure structures. The following description also pertains to methods, systems, and apparatuses for lin-
ear to rotary motion converters.

FLEXURE APPARATUSES, LINEAR ROTARY CONVERTERS, AND SYSTEMS

by

Russell F. JEWETT and Steven F. PUGH

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] The present application claims benefit of US Provisional Patent application Serial Number 62/016,766, entitled "FLEXURE APPARATUSES, FLEXURE SYSTEMS, FLEXURE METHODS, LINEAR ROTARY CONVERTERS, AND SYSTEMS WITH LINEAR ROTARY CONVERTERS," to Russell F. JEWETT and Steven F. PUGH, filed June 25, 2014. The content of US Provisional Patent application Serial Number 62/016,766 is incorporated herein in its entirety by this reference for all purposes.

BACKGROUND

[0002] One or more aspects of the present invention pertain to flexure structures, linear motion to rotary motion converters, and systems that include flexure structures and/or linear motion to rotary motion converters.

[0003] A wide variety of systems include and/or use mechanisms such as bellows structures, diaphragms, and piston/cylinder structures for handling, processing, moving, and using liquids and gases, i.e. fluids. For example, piston/cylinder structures are versatile and can be used for wide ranges of pressure and temperature for operation in numerous types of applications. These types of structures and their applications and uses are covered in the patent and scientific literature. Examples of such literature are US Patent 9,054,139, US Patent 8,431,855, US Patent 8,133,165, US Patent 7,866,953, US Patent 7,832,209, US Patent 7,556,065, US Patent 5,240,385, US Patent 4,655,690, US Patent 4,457,213,

US Patent 4,138,973, US Patent 3,131,563, US Patent 2,920,656, Yunus Cengel and Michael Boles, "Thermodynamics: An Engineering Approach," eight edition, McGraw-Hill, 2014 and Herbert Callen, "Thermodynamics and an Introduction to Thermostatistics," second edition, John Wiley & Sons, 1985. All of these references are incorporated herein by this reference in their entirety for all purposes.

[0004] The present inventors have recognized a need for alternatives to using structures such as bellows structures, diaphragms, piston/cylinder structures in apparatuses and systems in which they are currently used. Furthermore, the present inventors have made one or more discoveries which may overcome one or more deficiencies associated with the use of structures such as bellows structures, diaphragms, and piston/cylinder structures for one or more applications.

SUMMARY

[0005] One aspect of the present invention pertains to a flexure structure. Another aspect of the present invention pertains to systems comprising a flexure structure. Another aspect of the present invention pertains to methods of using flexure structures. Another aspect of the present invention pertains to linear motion to rotary motion converters. Another aspect of the present invention pertains to systems with linear motion to rotary motion converters. Another aspect of the present invention pertains to linear motion to rotary motion converters combined with flexure structures. Another aspect of the present invention pertains to systems with linear motion to rotary motion converters combined with flexure structures. Another aspect of the present invention pertains to linear motion to rotary motion converters combined with bellows structures. Another aspect of the present invention pertains to systems with linear motion to rotary motion converters combined with bellows structures.

[0006] It is to be understood that the invention is not limited in its application to the details of construction and to the arrangements of the components set forth in the following description. The invention is capable of other embodiments and of being practiced and carried out in various ways. In addition, it is to be understood

that the phraseology and terminology employed herein are for the purpose of description and should not be regarded as limiting.

BRIEF DESCRIPTION OF THE DRAWINGS

- [0007]** FIG. 1 is a side view of an embodiment of the present invention.
- [0008]** FIG. 2 is a top view of embodiment of the present invention.
- [0009]** FIG. 3 is a cross-section side view of an embodiment of the present invention.
- [0010]** FIG. 4 is a side view of an embodiment of the present invention.
- [0011]** FIG. 5 is a cross-section side view of an embodiment of the present invention.
- [0012]** FIG. 6 is a cross-section side view of an embodiment of the present invention.
- [0013]** FIG. 7 is a side view of an embodiment of the present invention.
- [0014]** FIG. 7-1 is a cross-section side view of an embodiment of the present invention.
- [0015]** FIG. 8 is a side view of an embodiment of the present invention.
- [0016]** FIG. 8-1 is a cross-section side view of an embodiment of the present invention.
- [0017]** FIG. 9 is a partial cross-section side view of an embodiment of the present invention.
- [0018]** FIG. 9-1 is a partial cross-section side view of an embodiment of the present invention.
- [0019]** FIG. 10 is a partial cross-section side view of an embodiment of the present invention.
- [0020]** FIG. 10-1 is a partial cross-section side view of an embodiment of the present invention.
- [0021]** FIG. 10-2 is a partial cross-section side view of an embodiment of the present invention.
- [0022]** FIG. 10-3 is a partial cross-section side view of an embodiment of the present invention.

[0023] FIG. 10-4 is a partial cross-section side view of an embodiment of the present invention.

[0024] FIG. 11 is a partial cross-section side view of an embodiment of the present invention.

[0025] FIG. 12 is a side view of an embodiment of the present invention.

[0026] FIG. 13 is a cross-section side view of an embodiment of the present invention.

[0027] FIG. 14 is a diagram of a system according to one embodiment of the present invention.

[0028] Skilled artisans appreciate that elements in the figures are illustrated for simplicity and clarity and have not necessarily been drawn to scale. For example, the dimensions of some of the elements in the figures may be exaggerated relative to other elements to help to improve understanding embodiments of the present invention.

DESCRIPTION

[0029] In the following description of the figures, identical reference numerals have been used when designating substantially identical elements or processes that are common to the figures.

[0030] Unless otherwise defined, all technical and scientific terms used herein have the same meaning as commonly understood by one of ordinary skill in the art to which this invention belongs. In case of conflict with publications, patent applications, patents, and other references mentioned incorporated herein by reference, the present specification, including definitions, will control.

[0031] For the following defined terms, these definitions shall be applied, unless a different definition is given in the claims or elsewhere in this specification. All numeric values are herein defined as being modified by the term "about," whether or not explicitly indicated. The term "about" generally refers to a range of numbers that a person of ordinary skill in the art would consider equivalent to the stated value to produce substantially the same properties, function, result, etc. A numerical range

indicated by a low value and a high value is defined to include all numbers subsumed within the numerical range and all subranges subsumed within the numerical range. As an example, the range 10 to 15 includes, but is not limited to, 10, 10.1, 10.47, 11, 11.75 to 12.2, 12.5, 13 to 13.8, 14, 14.025, and 15.

[0032] The term “horizontal” as used herein is defined as a plane parallel to the plane or surface of a reference surface, regardless of its orientation. The term “vertical” refers to a direction perpendicular to the horizontal as just defined. Terms, such as “above”, “below”, “bottom”, “top”, “side”, “higher”, “lower”, “upper”, “over”, and “under”, are defined with respect to the horizontal plane. The term “on” means there is direct contact among elements.

[0033] Various embodiments of the present invention may include any of the described features, alone or in combination. Other features and/or benefits of this disclosure will be apparent from the following description.

[0034] The order of execution or performance of the operations or the processes in embodiments of the invention illustrated and described herein is not essential, unless otherwise specified. That is, the operations or the processes may be performed in any order, unless otherwise specified, and embodiments of the invention may include additional or fewer operations or processes than those disclosed herein. For example, it is contemplated that executing or performing a particular operation or process before, contemporaneously with, or after another operation or process is within the scope of aspects of the invention.

[0035] Embodiments of the present invention will be discussed below primarily in the context of a class of flexure structures that have the fluid handling properties similar to bellows structures. In other words, these flexure structures can provide a gas or liquid seal, can provide containment of a fluid, can extend or contract along its axis, and can act on or be acted on by a fluid substantially the same as for bellows structures.

[0036] Flexure Structures

[0037] One or more aspects of the present invention pertain to flexure structures, apparatus comprising flexure structures, systems comprising flexure structures, methods of using apparatus comprising flexure structures, methods of using systems comprising flexure structures, and methods of designing flexure structures.

[0038] Numerous systems and apparatuses include and/or use mechanisms such as bellows structures, diaphragms, piston/cylinder structures and for handling and using fluids. These types of mechanisms may have various advantages and disadvantages for various applications. Piston/cylinder structures have the disadvantage of usually requiring lubrication or some other mechanism to reduce the amount of friction and wear between the piston and the walls of the cylinder. Typically, bellows structures and diaphragms require no lubrication, but they are not suitable for high differential pressure operation required for some applications. For high-pressure operations (such as those found in typical thermal cycle engines or fluid-cycle refrigeration systems), typical bellows structures and diaphragms are subjected to stresses that can exceed their elastic strain limit for even very strong and/or flexible materials. Exceeding the elastic strain limit can lead to plastic deformation and failure of the bellows structures and diaphragms.

[0039] One or more embodiments of the present invention pertain to a flexure structure that can withstand large pressure differences between the inside and outside of the flexure structure. More specifically, according to one or more embodiments of the present invention, the flexure structure does not require lubrication as required for piston/cylinder structures and is not subject to plastic deformation that can result from operating at differential pressures typical for the operation of engines and fluid cycle refrigeration systems which use piston/cylinder structures.

[0040] Reference is now made to Figure 1 where there is illustrated a side view of a flexure structure 35 according to one embodiment of the present invention. Flexure structure 35 comprises a plurality of hollow disk-like convolutions 50. Each of the hollow disk-like convolutions 50 has a periphery 52 that is curved. In other words, the outer edge of hollow disk-like convolutions 50 is curved. Hollow disk-like

convolutions 50 have sides 54 that have at least a substantially flat section. Sides 54 of the hollow disk-like convolutions 50 have a hole 56 (hole 56 is not shown in Figure 1). The plurality of hollow disk-like convolutions 50 are stacked substantially as though they are aligned about an axis. Adjacent hollow disk-like convolutions 50 are joined proximate or at the inner radius of the sides 54. In other words, the plurality of hollow disk-like convolutions are joined at or near the edge of holes 56. As an alternative, one or more embodiments of the present invention may be designed so that convolutions of the flexure structure are joined at or near the outer radius of the sides or at any location between the inner radius and the outer radius of sides 54. More generally, the convolutions are joined such as to form fluid tight seals.

[0041] Reference is now made to Figure 2 where there is shown a top view of a flexure structure 35, according to one embodiment of the present invention, that is substantially the same as that described in Figure 1. The top view of flexure structure 35 is substantially one side of hollow disk-like structure 50. More specifically, Figure 2 shows side 54 of hollow disk-like convolution 50 and a portion of periphery of hollow disk-like convolution 52 visible in top view. Side 54 of hollow disk-like convolution 50 has hole 56.

[0042] Reference is now made to Figure 3 where there is shown a cross-section side view of a flexure structure 35 according to one embodiment of the present invention. Flexure structure 35 comprises a plurality of hollow disk-like convolutions 50. Each of the hollow disk-like convolutions 50 has a periphery 52 that is curved; in other words, the outer edge of hollow disk-like convolutions 50 is curved. Hollow disk-like convolutions 50 have sides 54 that have at least a substantially flat section. Sides 54 of the hollow disk-like convolutions 50 have a hole 56. The plurality of hollow disk-like convolutions 50 are stacked substantially as though they are concentrically aligned. Adjacent hollow disk-like convolutions 50 have a connection 58 proximate or at the inner radius of sides 54. In other words, the plurality of hollow disk-like convolutions have a connection 58 at or near the edge of holes 56.

[0043] Connection 58 may be a connection such as, but not limited to, a connection formed by welding, formed by an adhesive, formed by fusing, or combinations thereof. Alternatively, connection 58 may be a connection formed by forming a bend in a substantially continuous portion of material of construction of the hollow disk-like convolutions. According to one or more embodiments of the present invention, adjacent hollow disk-like convolutions are arranged so that the sides 54 may be in contact during at least part of their movement for extension and/or contraction of flexure structure 35. In other words, connection 58 may exist while also having part of sides 54 in contact with adjacent sides 54 of hollow disk-like convolutions 50 while flexure structure 35 is relaxed, extended, and/or compressed. According to another embodiment of the present invention, flexure 35 has at least partial contact between adjacent sides 54 of hollow disk-like convolutions 50 while flexure structure 35 is relaxed, extended, and/or compressed.

[0044] Reference is now made to Figure 4 where there is illustrated a side view of a flexure structure 37 according to one embodiment of the present invention. Flexure structure 37 comprises a plurality of hollow disk-like convolutions 50. Each of the hollow disk-like convolutions 50 has a periphery 52 that is curved; in other words, the outer edge of hollow disk-like convolutions 50 is curved. Hollow disk-like convolutions 50 have sides 54 that have at least a substantially flat section. Sides 54 of the hollow disk-like convolutions 50 have a hole 56. The plurality of hollow disk-like convolutions 50 are stacked substantially as though they are concentrically aligned. Adjacent hollow disk-like convolutions 50 are joined proximate or at the inner radius of the sides. In other words, the plurality of hollow disk-like convolutions are joined at or near the edge of holes 56. Flexure structure 37 further comprises an end piece 59.

[0045] End piece 59, according to one or more embodiments of the present invention, is substantially rigid and joined at side 54 of one of the hollow disk-like convolutions 50 proximate or at the inner radius of side 54 at an end of the plurality of hollow disk-like convolutions 50. End piece 59 may be joined to side 54 using a connection such as, but not limited to, a connection formed by welding, formed by an adhesive, formed by fusing, and combinations thereof. As an option for one or more

embodiments of the present invention, end piece 59 may be shaped as a plate such as a metal plate which may or may not have one or more holes, or end piece 59 may be shaped as a substantially continuous ring. End piece 59 has dimensions so that it is not significantly deformed by the operating conditions for the flexure structure. For or more embodiments of the present invention, end piece 59 is made of a material compatible for joining with the material of the hollow disk-like convolutions and, optionally, may be the same material. Examples of some materials that can be used for end piece 59 include, but are not limited to, metals, metal alloys, steel, stainless steel, titanium, polymers, composite materials, materials used for the flexure structures, and combinations thereof.

[0046] Reference is now made to Figure 5 where there is shown a cross-section side view of a flexure structure 37 substantially the same as that shown in Figure 4. According to the embodiment of the present invention shown in Figure 5, end piece 59 is configured as a substantially continuous ring. Using a ring configuration for end piece 59 can permit fluids to enter or exit the plurality of hollow disk-like convolutions through end piece 59.

[0047] Reference is now made to Figure 6 where there is shown a cross-section side view of a flexure structure 37 substantially the same as that shown in Figure 5 with the exception that a second end piece 59 is attached to the other end of the plurality of hollow disk-like convolutions 50. More specifically, second end piece 59 is attached to side 54 of the plurality of disk-like convolutions. Second end piece 59 may be joined to side 54 using a connection such as, but not limited to, a connection formed by welding, formed by an adhesive, formed by fusing, and combinations thereof. According to the embodiment of the present invention shown in Figure 6, each end piece 59 is configured as a substantially continuous ring. Using a ring configuration for end piece 59 can permit fluids to enter or exit the plurality of hollow disk-like convolutions through end pieces 59.

[0048] The curvature of the periphery of the hollow disk-like convolutions may be varied for one or more embodiments of the present invention. According to one embodiment of the present invention, the curvature of the periphery corresponds to

the curvature of a partial circle such as a semi circular or a smaller portion of a circle. According to one embodiment of the present invention, the curvature of the periphery corresponds to the curvature of a partial ellipse such as a semi elliptical or a smaller portion of an ellipse. According to one embodiment of the present invention, the curvature of the periphery corresponds to the curvature of a partial parabola such as the closed end of a parabola.

[0049] The optimum curvature of the periphery of the hollow disk-like convolutions may depend on factors such as the material of construction of the flexure structure, the temperature range for use of the flexure structure, the pressure range for use of the flexure structure. In view of the present disclosure, persons of ordinary skill in the art will be able to derive suitable curvatures for flexure structures according to embodiments of the present invention using conventional optimization techniques.

[0050] Reference is now made to Figure 7 where there is shown a side view of the walls for a flexure structure 40 and Figure 7-1 where there is shown a cross-section side view of the walls for a flexure structure 40. Flexure structure 40 comprises a plurality of hollow disk-like convolutions 50. The periphery 52 of the hollow disk-like convolutions 50 is curved. Hollow disk-like convolutions 50 have sides 54 that comprise a substantially flat portion that connects with an inner curved portion 58 proximate the inner radius of the sides to join the adjacent hollow disk-like convolutions 50. According to one or more embodiments of the present invention, the plurality of hollow disk-like convolutions 50 are stacked. Flexure structure 40 further comprises a restriction ring (restriction ring not shown in Figure 7 and Figure 7-1) snugly disposed around each of the inner curved portion 58 of each of hollow disk-like convolutions 50.

[0051] Reference is now made to Figure 8 where there is shown a side view of a flexure structure 41 that is essentially the same as flexure structure 40 shown in Figure 7 with the exception of further including restriction rings 62 snugly disposed around each of the inner curved portion 58 of each of hollow disk-like convolutions 50. Figure 8-1 shows a cross-section side view of flexure structure 41.

[0052] According to one or more embodiments of the present invention, the dimensions of the inner curved portion 58 are a function of the difference between the maximum and minimum length variation desired for the flexure structure.

According to one or more embodiments of the present invention, the dimensions of the hollow disk-like convolutions 50 are a function of the operating pressure range and/or the operating temperature range of the flexure structure.

[0053] According to one or more embodiments of the present invention, restriction ring 62 has dimensions and a tensile strength to retard expansion of the flexure structure at the inner curved portion 58 of the flexure structure. More specifically, restriction ring 62 is constructed and placed so as to substantially retard or prevent radial plastic deformation of the flexure structure. A variety of materials may be used for restriction ring 62. Examples of some materials that can be used for restriction ring 62 include, but are not limited to, metals, metal alloys, steel, stainless steel, titanium, polymers, composite materials, materials used for the flexure structures, and combinations thereof.

[0054] It is to be noted that flexure structures illustrated in Figures 1 to 8-1 are merely exemplary. One or more embodiments of the present invention may use more than four hollow disk-like convolutions or may use fewer than four hollow disk-like convolutions for the flexure structure.

[0055] Flexure structures according to embodiments of the present invention such as, but not limited to, the embodiments shown in and described above for Figures 1 to 8-1, can be manufactured using a variety techniques. Manufacturing techniques such as those used for making conventional bellows structures such as, but not limited to, hydroforming, casting, metal plating, welding, injection molding, melting, chemical precipitation, fusing, chemically bonding, three-dimensional printing, and combinations thereof can be used to make one or more embodiments of flexure structures according to the present invention.

[0056] A variety of materials can be used for manufacturing flexure structures according to one or more embodiments of the present invention. According to one or more embodiments of the present invention, the flexure structures may comprise materials such as, but not limited to plastic or polymer sheet, rubber sheet, metallic sheet. According to one or more embodiments of the present invention, the plurality of hollow disk-like convolutions are formed from metal sheet or metal alloy sheet. According to one or more embodiments of the present invention, the plurality of hollow disk-like convolutions comprise steel or stainless steel. According to one or more embodiments of the present invention, the plurality of hollow disk-like convolutions comprise titanium alloy. According to one or more embodiments of the present invention, the plurality of hollow disk-like convolutions comprise aluminum, copper, chromium, cobalt, iridium, magnesium, molybdenum, nickel, osmium, rhodium, ruthenium, tantalum, zinc, metal alloys, or combinations thereof.

[0057] Computer Modeling Results

[0058] Computer models of one or more embodiments of the present invention have been developed. The software modeling was accomplished using one or more software programs such as SolidWorks made by Dassault Systems SolidWorks Corporation, 175 Wyman Street, Waltham, MA 02451. It is to be understood that the computer modeling could have been accomplished using software programs other than SolidWorks. Some details of the SolidWorks program can be found in "An Introduction to Stress Analysis Applications with Solid Works Simulation, Student Guide" which is available from Dassault Systems SolidWorks Corporation. The models were used to calculate the yield strength for flexure structures according to one or more embodiments of the present invention. For one or more embodiment of the invention, an appropriate flexure geometry for one or more configurations was determined by modeling the flexure structure by finite element analysis.

[0059] A model was created for a flexure structure according to an embodiment of the present invention such as flexure structure 37 shown in Figure 6. More specifically, a finite element analysis of the stresses experienced by the flexure structure was done to determine a stress profile for the flexure structure. The

modeling program was SolidWorks and the flexure structure material was selected to be stainless steel. A static von Mises profile was generated for a computer model image of a section of the flexure structure. The stress profile for the flexure structure was derived for the flexure structure having an internal pressure 45 atmospheres and +6 millimeter of extension along the axial length of the flexure structure. The flexure structure for the computer modeling can flex over a range exceeding -2.5% to +15% of its relaxed length without exceeding the yield limit for the stainless steel used for the modeling, all while maintaining the 45 atmospheres of differential pressure (i.e., difference between the pressure inside the flexure and the pressure outside the flexure). The yield strength of the stainless steel used for the modeling was 931 megapascals. The maximum stress for the flexure structure derived by the model was 757 megapascals which is well below the yield stress for the stainless steel.

[0060] Additional computer modeling of the flexure structure like that shown in Figure 6 was performed. The modeling shows that the flexure structure can be scaled up for use with a pressure differential of more than 350 atmospheres without exceeding the yield strength for stainless steel.

[0061] Reference is now made to Figures 9 and 9-1 where there is shown a static von Mises profile generated as a computer model image of a section of a flexure structure 41 according to one embodiment of the present invention. Flexure structure 41 is modeled as a material having a yield strength of 827 megapascals. Figure 9 models flexure structure 41 when it is not extended, in other words, in a relaxed state. Figure 9-1 shows a static von Mises profile generated as a computer model image of a section of a flexure structure 41 flexure structure 41 when it is in an extended state. The design and dimensions of flexure structure 41 are derived so that mechanical compression and expansion of flexure structure 41 can be sustained with a high differential pressure without exceeding the yield strength of the flexure structure. Figures 9 and 9-1 show the stresses in the flexure in the relaxed state and in the extended state of a mechanical cycle of flexure structure 41 with an internal pressure of 4.5 MPa.

[0062] Another aspect of the present invention comprises a method of obtaining a flexure structure design. According to one or more embodiments of the present invention, the method comprises specifying a material of construction and its yield strength data; specifying design parameters for a plurality of hollow disk-like convolutions of the material. The periphery of the hollow disk-like convolutions is curved. The sides of the hollow disk-like convolutions are substantially flat and have a hole. The adjacent hollow disk-like convolutions are joined proximate or at the inner radius of the sides. The method also includes iteratively adjusting one or more of the design parameters until all values of the stress profile for the plurality of hollow disk-like convolutions are less than the yield stress for the material of construction. According to one or more embodiments of the present invention, the method is carried out using a software-modeling program such as, but not limited to, a finite element analysis software program.

[0063] According to one or more embodiments of the present invention, the method comprises specifying an initial material of construction and acquiring yield stress data for the material. The method also includes specifying an initial shape, an initial size, and/or initial dimensions for a plurality of hollow disk-like convolutions of the material. The periphery of the hollow disk-like convolutions are curved. The sides of the hollow disk-like convolutions have at least a substantially flat section, and the sides of the hollow disk-like convolutions have a hole. The adjacent hollow disk-like convolutions are joined proximate or at the inner radius of the sides. The method also comprises specifying one or more operating conditions for the flexure structure. Examples of operating conditions that may be used include, but are not limited to, temperature, pressure, pressure differential, ambient or exposure gas composition, and combinations thereof. The method also includes specifying at least one performance parameter for the plurality of hollow disk-like convolutions of the material. Examples of performance parameters that might be used may include, but are not limited to, the amount of extension compared to the relaxed state, the amount of compression compared to the relaxed state, usable differential pressure range, and combinations thereof. The method further includes obtaining a stress profile for the plurality of hollow disk-like convolutions using one or more of the inputs the initial specified material of construction; the initial specified shape, initial size,

and/or initial dimensions for the plurality of hollow disk-like convolutions; the specified operating conditions; and/or the specified at least one performance parameter. The method includes determining if all values of the stress profile are less than the yield stress for the initial specified material, if so then using the initial specified material of construction; the initial specified shape, the initial size, and/or the initial dimensions for the plurality of hollow disk-like convolutions as the flexure structure design. If all values of the stress profile are not less than the yield stress for the initial specified material, then the method further includes iteratively adjusting one or more of the inputs, such as but not limited to, the specified material of construction; the specified shape, size, and/or dimensions for the plurality of hollow disk-like convolutions; the specified operating conditions; and the specified at least one performance parameter until all values of the stress profile for the plurality of hollow disk-like convolutions are less than the yield stress for the material of construction, then using the material of construction; the shape, size, and/or dimensions for the plurality of hollow disk-like convolutions that provide the stress profile with all values less than the yield stress as the flexure structure design.

[0064] Flexure structures according to one or more embodiments of the present invention have a stress profile, during operation at elevated differential pressure, that is below the yield strength of the material of construction of the flexure structure. For one or more embodiments of the present invention, the flexure structures have each value of their stress profile, during operation at elevated differential pressure, below the yield strength of the material of construction of the flexure structure. For one or more embodiments of the present invention, the flexure structures have each value of their stress profile for predetermined operating conditions of the flexure structure below the yield strength of the material of construction of the flexure structure at all points on the flexure structure. For one or more embodiments of the present invention, the flexure structures have each value of their stress profile during operation between 1% to 99% and all values, ranges, and subranges subsumed therein of the yield strength of the material of construction of the flexure structure. For one or more embodiments of the present invention, the flexure structures have a von Mises stress profile during operation below the yield strength of the material of construction of the flexure structure.

[0065] Another aspect of the present invention comprises a method of displacing a volume of fluid. According to one embodiment of the present invention, the method comprises providing one or more hollow disk-like convolutions. The periphery of the hollow disk-like convolutions is curved. The sides of the hollow disk-like convolutions are substantially flat and have a hole. The adjacent hollow disk-like convolutions are joined near or at the edge of the sides or may have portions of their sides in contact with adjacent sides. As an option, the method may use flexure structures substantially the same as those described above for Figures 1 to 6, 7, 7-1, 8, 8-1, 9, and 9-1. The method further includes cyclically increasing or decreasing the volume of the one or more hollow disk-like convolutions.

[0066] Another embodiment of the present invention comprises a linear actuator. The linear actuator comprises one or more hollow disk-like convolutions. The periphery of the hollow disk-like convolutions is curved. The sides of the hollow disk-like convolutions have a hole. When there is a plurality of hollow disk-like convolutions, they may be coaxially stacked such as axially aligned. The adjacent hollow disk-like convolutions are joined at the sides or have portions of their sides in contact with adjacent sides, whereby pressure differentials applied to the interior of the hollow disk-like convolutions produces motion substantially along the axis of the hollow disk-like convolutions.

[0067] Another aspect of the present invention pertains to systems that include flexure structures as taught in the present disclosure. One embodiment of the present invention is a fluid pump comprising a flexure structure such as the flexure structures described supra and shown in Figures 1-6. According to one or more embodiments of the present invention, the flexure structure replaces one or more piston/cylinder structures, bellows structures, or diaphragms of standard technology fluid pumps.

[0068] One embodiment of the present invention is a fluid meter comprising a flexure structure such as the flexure structures described supra and shown in Figures 1 to 6, 7, 7-1, 8, 8-1, 9, and 9-1.

[0069] One embodiment of the present invention is a fluid dispenser comprising a flexure structure such as the flexure structures described supra and shown in Figures 1 to 6, 7, 7-1, 8, 8-1, 9, and 9-1.

[0070] One embodiment of the present invention is a fluid flow controller comprising a flexure structure such as the flexure structures described supra and shown in Figures 1 to 6, 7, 7-1, 8, 8-1, 9, and 9-1. The fluid flow controller further comprises a pressure sensor to measure the pressure of the fluid, and a temperature sensor to measure the temperature of the fluid.

[0071] One embodiment of the present invention is an internal combustion engine comprising a flexure structure such as the flexure structures described supra and shown in Figures 1 to 6, 7, 7-1, 8, 8-1, 9, and 9-1. According to one embodiment of the present invention, the generation of pressure differentials in the bellows such as by the internal combustion process produces linear motion.

[0072] One embodiment of the present invention is a heat engine comprising a flexure structure such as the flexure structures described supra and shown in Figures 1 to 6, 7, 7-1, 8, 8-1, 9, and 9-1. According to one embodiment of the present invention, alternately heating and cooling a gas causes the flexure structure to expand or contract to produce linear motion.

[0073] One embodiment of the present invention is a heat engine comprising a flexure structure such as the flexure structures described supra and shown in Figures 1 to 6, 7, 7-1, 8, 8-1, 9, and 9-1. According to one embodiment of the present invention, the heat engine further comprises components to effect energy conversion using a Brayton cycle, a Rankine cycle, or a Stirling cycle to convert thermal energy into mechanical energy.

[0074] One embodiment of the present invention is a heat pump comprising a flexure structure such as the flexure structures described supra and shown in Figures 1 to 6, 7, 7-1, 8, 8-1, 9, and 9-1. According to one embodiment of the present invention, the heat pump further comprises components to effect heating or

cooling of a load through application of mechanical energy in a Brayton cycle, a Rankine cycle, or a Stirling cycle.

[0075] One embodiment of the present invention is a heat pump comprising a flexure structure such as the flexure structures described supra and shown in Figures 1 to 6, 7, 7-1, 8, 8-1, 9, and 9-1. According to one embodiment of the present invention, the heat pump further comprises components to effect heating or cooling of a load through application of mechanical energy in a gas cycle or a gas/liquid cycle. One or more embodiments of the present invention comprise a heat pump in which flexure structures such as those described above and in Figures 1 to 6, 7, 7-1, 8, 8-1, 9, and 9-1 are used to replace bellows, diaphragms, piston/cylinder structures used in conventional heat pumps.

[0076] One embodiment of the present invention is a vacuum pump comprising a flexure structure such as the flexure structures described supra and shown in Figures 1 to 6, 7, 7-1, 8, 8-1, 9, and 9-1. According to one embodiment of the present invention, the vacuum pump further comprises components to effect expulsion of fluid from a chamber through application of mechanical energy to the flexure structure. One or more embodiments of the present invention comprise a vacuum pump in which flexure structures such as those described above and in Figures 1 to 6, 7, 7-1, 8, 8-1, 9, and 9-1 are used to replace bellows, diaphragms, piston/cylinder structures used in conventional vacuum pumps.

[0077] Another embodiment of the present invention comprises using a flexure structure such as the flexure structures described supra and shown in Figures 1 to 6, 7, 7-1, 8, 8-1, 9, and 9-1 with fuel/oxidizer mixtures (such as gasoline and air) to derive power from the energy released during ignition comparable to a 4-cycle internal combustion piston engine. One or more embodiments of the present invention comprise a 4 cycle internal combustion engine in which flexure structures such as those described above and in Figures 1 to 6, 7, 7-1, 8, 8-1, 9, and 9-1 are used to replace piston/cylinder structures used in conventional 4-cycle internal combustion engines.

[0078] Another embodiment of the present invention comprises using a flexure structure such as the flexure structures described supra and shown in Figures 1 to 6, 7, 7-1, 8, 8-1,9, and 9-1 with a fuel/oxidizer mixture (such as gasoline and air) to derive power from the energy released during ignition comparable to a 2-cycle internal combustion piston engine. One or more embodiments of the present invention comprise a 2 cycle internal combustion engine in which flexure structures such as those described above and in Figures 1 to 6, 7, 7-1, 8, 8-1,9, and 9-1 are used to replace piston/cylinder structures used in conventional 2-cycle internal combustion engines.

[0079] Another embodiment of the present invention comprises using a flexure structure such as the flexure structures described supra and shown in Figures 1 to 6, 7, 7-1, 8, 8-1,9, and 9-1 with fuel/oxidizer mixture (such as diesel fuel and air) to derive power from the energy released during ignition comparable to a diesel internal combustion piston engine. One or more embodiments of the present invention comprise a diesel internal combustion piston engine in which flexure structures such as those described above and in Figures 1 to 6, 7, 7-1, 8, 8-1,9, and 9-1 are used to replace piston/cylinder structures used in conventional diesel internal combustion piston engine.

[0080] Another embodiment of the present invention comprises using a flexure structure such as the flexure structures described supra and shown in Figures 1 to 6, 7, 7-1, 8, 8-1, 9, and 9-1 with a heat source (fuel/oxidizer mixture, the sun or other available external heat source) to derive power from the heat transfer to a cold sink using substantially a Brayton cycle. One or more embodiments of the present invention comprise a system that uses the Brayton cycle in which flexure structures such as those described above and in Figures 1 to 6, 7, 7-1, 8, 8-1, 9, and 9-1 are used to replace bellows structures, diaphragms, and/or piston/cylinder structures used in conventional Brayton cycle systems.

[0081] Another embodiment of the present invention comprises using a flexure structure such as the flexure structures described supra and shown in Figures 1 to 6, 7, 7-1, 8, 8-1, 9, and 9-1 with a heat source (fuel/oxidizer mixture, the sun or

available external heat source) to derive power from the heat transfer to a cold sink using substantially a Stirling cycle. One or more embodiments of the present invention comprise a system that uses the Stirling cycle in which flexure structures such as those described above and in Figures 1 to 6, 7, 7-1, 8, 8-1, 9, and 9-1 are used to replace bellows structures, diaphragms, and/or piston/cylinder structures used in conventional Stirling cycle systems.

[0082] Another embodiment of the present invention comprises using a flexure structure such as the flexure structures described supra and shown in Figures 1 to 6, 7, 7-1, 8, 8-1, 9, and 9-1 with a heat source (fuel/oxidizer mixture, the sun or available external heat source) to derive power from the heat transfer to a cold sink using substantially a Rankine cycle. One or more embodiments of the present invention comprise a system that uses the Rankine cycle in which flexure structures such as those described above and in Figures 1 to 6, 7, 7-1, 8, 8-1, 9, and 9-1 are used to replace bellows structures, diaphragms, and/or piston/cylinder structures used in conventional Rankine cycle systems.

[0083] Another embodiment of the present invention comprises using a flexure structure such as the flexure structures described supra and shown in Figures 1 to 6, 7, 7-1, 8, 8-1, 9, and 9-1 with a heat source (fuel/oxidizer mixture, the sun or available external heat source) to derive power from the heat transfer to a cold sink using a gas cycle or a gas/liquid cycle (including a phase change).

[0084] Another embodiment of the present invention comprises using a flexure structure such as the flexure structures described supra and shown in Figures 1 to 6, 7, 7-1, 8, 8-1, 9, and 9-1 with a rotary source of power to pump heat from a cold source to a warm sink using a Rankine cycle.

[0085] Another embodiment of the present invention comprises using a flexure structure such as the flexure structures described supra and shown in Figures 1 to 6, 7, 7-1, 8, 8-1, 9, and 9-1 with a rotary source of power to pump heat from a cold source to a warm sink using a Stirling cycle.

[0086] Another embodiment of the present invention comprises using a flexure structure such as the flexure structures described supra and shown in Figures 1 to 6, 7, 7-1, 8, 8-1, 9, and 9-1 with a rotary source of power to pump heat from a cold source to a warm sink using a Brayton cycle.

[0087] Another embodiment of the present invention comprises using a flexure structure such as the flexure structures described supra and shown in Figures 1 to 6, 7, 7-1, 8, 8-1, 9, and 9-1 with a rotary source of power to pump heat from a cold source to a warm sink using a gas cycle or a gas/liquid cycle.

[0088] Additional background information about systems and/or the operation of systems such as fluid pumps, fluid dispensers, fluid flow controllers, vacuum pumps, linear actuators, internal combustion engines, heat pumps, refrigeration, gas cycles, gas/liquid cycles, Brayton cycle, Rankine cycle, and/or Stirling cycle can be found in the scientific and patent literature. Examples of references containing relevant background information include Yunus Cengel and Michael Boles, "Thermodynamics: An Engineering Approach," eight edition, McGraw-Hill, 2014 and Herbert Callen, "Thermodynamics and an Introduction to Thermostatistics," second edition, John Wiley & Sons, 1985. All of these references are incorporated herein by this reference in their entirety for all purposes.

[0089] Linear – Rotary Motion Conversion

[0090] Another aspect of the present invention pertains to an apparatus that produces rotary motion from the expansion and contraction of flexure structures and/or uses rotary motion for expansion and contraction of flexure structures.

[0091] Reference is now made to Figure 10 where there is shown a diagram of a linear rotary converter 100 according to one or more embodiments of the present invention. Linear rotary converter 100 comprises at least one flexure structure 130 such as any of the embodiments of flexure structures described above, a first port plate 140 which has an opening 142, a nutation rig 150, and a nutation coupling 160 connected with nutation rig 150 through opening 142. The at least one flexure

structure 130 is coupled between first port plate 140 and nutation rig 150. The embodiment shown in Figure 10 also includes a nutation shaft 152. A first end of nutation shaft 152 is connected proximate the center of nutation rig 150; the second end of nutation shaft 152 is connected with nutation coupling 160.

[0092] According to one or more embodiments of the present invention, first port plate 140 is substantially rigid and has an area to which one end of flexure structure 130 can be attached so as to form a substantially fluid tight seal such as by welding, soldering, brazing, bolting, adhesive attachment, clamping, or other attachment method or attachment mechanism. Optionally, the fluid tight seal may be accomplished by use of an O-ring, a gasket, or other sealing apparatus. Optionally, the least one flexure structure 130 may include an end piece, such as those described above, for attachment of the least one flexure structure 130 to first port plate 140. According to one or more embodiments of the present invention, first port plate 140 includes one or more ports disposed to allow fluids to enter and/or exit the interior of the at least one flexure structure 130. Optionally, first port plate 140 has one or more ports disposed so as to allow fluid to enter the interior of the least one flexure structure 130 and has one or more ports disposed so as to allow fluid to exit the interior of the least one flexure structure 130.

[0093] According to one or more embodiments of the present invention, at least a portion of nutation rig 150 has a substantially planar surface and nutation rig 150 is a substantially rigid. Optionally, nutation rig 150 may be shaped in the form of a plate; optionally the plate may be round or of some other shape. Optionally, nutation rig 150 may be a frame with open areas between the substantially planar surface. The substantially planar surface includes an area to which one end of the least one flexure structure 130 can be attached so as to form a substantially fluid tight seal such as by welding, soldering, brazing, bolting, adhesive attachment, clamping or other attachment method or attachment mechanism. Optionally, the fluid tight seal may be accomplished by use of an O-ring, a gasket, or other sealing apparatus. Optionally, the least one flexure structure 130 may include an end piece, such as those described above, for attachment of the least one flexure structure 130 to nutation rig 150.

[0094] The attachment of flexure structure 130 between first port plate 140 and nutation rig 150 prevents rotation of nutation rig 150 while accommodating the nutating oscillations of nutation rig 150 during operation.

[0095] According to one or more embodiments of the present invention, nutation coupling 160 comprises a drive shaft 162 having a bore 165 axially offset from the axis of driveshaft 162, and a rotary assembly 168 held in bore 165 arranged so that the second end of nutation shaft 152 is connected with one end of drive shaft 162 by rotary union 168 at an off axis angle. Optionally, rotary assembly 168 may comprise bearings, ball bearings, or other types of rotary mechanisms. According to one embodiment of the present invention the off axis angle is from 1 to 30 degrees. According to one embodiment of the present invention the off axis angle is from 2 to 10 degrees. According to one embodiment of the present invention the off axis angle is 4 degrees.

[0096] Alternatively, other types of nutation couplings can be used in one or more embodiments of the present invention. As examples, nutation couplings such as those used to achieve nutation of wobble plates and/or swash plates may be used directly or modified for use in one or more embodiments of the present invention.

[0097] Figure 10 shows an embodiment of the present invention that includes one flexure structure 130. It is to be understood that other embodiments of the present invention may include more than one flexure structure 130 such as two or more flexure structures disposed around the nutation coupling such as shown in Figure 10-1.

[0098] Reference is now made to Figure 10-2 where there is illustrated a system 112 according to one or more embodiments of the present invention. Figure 10-2 shows system 112 as a cross-section side view of a partial linear rotary converter substantially the same as linear rotary converter 100 described above coupled with an engine, a motor, or an electricity generator 176. Linear rotary converter 110 shown in Figure 10-2 includes two or more flexure structures 130 coupled between

first port plate 140 and nutation rig 150. Drive shaft 162 of linear rotary converter 100 is coupled with engine, motor, or electricity generator 176. More specifically, drive shaft 162 may be coupled to an engine or coupled to a motor or coupled to an electricity generator according to one or more embodiments of the present invention. The coupling between linear rotary converter 100 and engine, motor, or electricity generator 176 is accomplished so as to allow rotation of drive shaft 162. Figure 10-2 shows drive shaft 162 disposed so that nutation rig 150 is tilted because of the nutation arrangement. The tilting of nutation rig 150 causes extension or compression of flexure structures 130 depending on their location.

[0099] As an option for one embodiment of system 112, the expansion and contraction of flexure structures 130 acting on nutation rig 150 can be used to produce rotation of drive shaft 162 through nutation coupling 160. The expansion and contraction of flexure structures 130 may be accomplished by processes such as, but not limited to, internal combustion processes, cyclical applications of heated gas and cooled gas, and/or cyclical heating and cooling of gas. The rotation of drive shaft 162 may be used to generate electricity when connected with an electricity generator or for other applications that need rotary motion or a rotary drive.

[0100] As another option for one embodiment of system 112, the expansion and contraction of flexure structures 130 by way of action from nutation rig 150 can be produced from rotation of drive shaft 162 through nutation coupling 160 when drive shaft 162 is coupled with an engine or electric motor 176. The rotation of drive shaft 162 by engine or electric motor 176 may be accomplished by processes such as, but not limited to, internal combustion processes, electric power, and/or other sources of power provided by or provided to engine or electric motor 176. The expansion and contraction of flexure structures 130 may be used in configurations such as, but not limited to, to pump fluids, to operate fluid-based refrigeration cycles, to compress gases, to evacuate fluids, and to meter fluids.

[0101] Alternative embodiments of systems such as system 112 include, but are not limited to: A fluid pump comprising a linear rotary converter as described above. A fluid meter comprising a linear rotary converter as described above. A fluid

dispenser comprising a linear rotary converter as described above. A fluid flow controller comprising a linear rotary converter as described above. An internal combustion engine comprising a linear rotary converter as described above. A heat engine comprising a linear rotary converter as described above. A heat pump comprising a linear rotary converter as described above. A vacuum pump comprising a linear rotary converter as described above.

[0102] Reference is now made to Figure 10-3 where there is shown a diagram of a linear rotary converter 100 substantially the same as shown in Figure 10 and Figure 10-1 with the exception of having a modified nutation rig and modified nutation coupling replacing the nutation rig and nutation coupling shown in Figure 10 and Figure 10-1. More specifically, Figure 10-3 shows linear rotary converter 100 having a nutation coupling 170 which includes a substantially rigid shell 171 having an axial bore. A drive shaft 162 is disposed through the bore and is held by a rotary coupling 178 having an off-axis axial bore which receives drive shaft 162. Optionally, a second rotary coupling 179 may be disposed around rotary coupling 178. Nutation coupling 170 is configured so that rotation of drive shaft 162 causes nutation of nutation rig 150 to cause compression and expansion of flexure structures 130. Similarly, compression and expansion of flexure structures 130 cause nutation rig 150 and nutation coupling 170 to rotate drive shaft 162.

[0103] Reference is now made to Figure 10-4 where there is shown a diagram of a system 112 substantially the same as shown in Figure 10-2 with the exception of having a modified nutation rig and modified nutation coupling replacing the nutation rig and nutation coupling shown in Figure 10-2. More specifically, Figure 10-4 shows system 112 having a nutation coupling 170 which includes a substantially rigid shell 171 having an axial bore. A drive shaft 162 is disposed through the bore and is held by a rotary coupling 178 having an off-axis axial bore which receives drive shaft 162. Optionally, a second rotary coupling 179 may be disposed around rotary coupling 178. Nutation coupling 170 is configured so that rotation of drive shaft 162 causes nutation of nutation rig 150 to cause compression and expansion of flexure structures 130. Similarly, compression and expansion of flexure structures 130 cause nutation rig 150 and nutation coupling 170 to rotate drive shaft 162.

[0104] Reference is now made to Figure 11 where there is shown a cross section side view diagram of a linear rotary converter 110 according to one or more embodiments of the present invention. Linear rotary converter 110 comprises at least one flexure structure 130 such as any of the embodiments of flexure structures described above, a first port plate 140 which has an opening 142, a nutation rig 150, and a nutation coupling 160 connected with nutation rig 150 through opening 142. The at least one flexure structure 130 is coupled between first port plate 140 and nutation rig 150. The embodiment shown in Figure 11 also includes a nutation shaft 152. A first end of nutation shaft 152 is connected proximate the center of nutation rig 150; the second end of nutation shaft 152 is connected with nutation coupling 160. Rotary converter 110 is essentially the same as rotary converter 100 shown in Figure 10 but also comprises a second port plate 180, at least one second level flexure structure 185, and one or more port plate connectors 190. The one or more port plate connectors 190 are substantially rigid and are disposed so as to hold second port plate 180 opposite first port plate 140 so as to have nutation rig 150 therebetween. The at least one second level flexure structure 185 is connected between nutation rig 150 and second port plate 180.

[0105] According to one or more embodiments of the present invention, second port plate 180 is essentially the same as first port plate 140 described above with the exception that second port plate 180 does not require center hole 142 described for first port plate 140, although a center hole may be present as an option. The at least one second level flexure structure 185 is essentially the same as flexure structure 130 described above. Second level flexure structure 185 is connected between nutation rig 150 and second port plate 180 so that the ends of second level flexure structure 185 have a fluid tight seal to nutation rig 150 on one end and a fluid tight seal to second port plate 180 on the other end. The connection of the at least one second level flexure structure 185 may be accomplished as described above for the connection of the least one flexure structure 130 above.

[0106] According to one or more embodiments of the present invention, second port plate 180 includes one or more ports disposed to allow fluids to enter and/or exit

the interior of the at least one second level flexure structure 185. Optionally, second port plate 180 has one or more ports disposed so as to allow fluid to enter the interior of the least one-second level flexure structure 185 and has one or more ports disposed so as to allow fluid to exit the interior of the least one-second level flexure structure 185.

[0107] Reference is now made to Figure 12, where there is illustrated a system 115 according to one or more embodiments of the present invention. Figure 12 shows system 115 as a cross-section side view of a partial linear rotary converter substantially the same as linear rotary converter 110 described above coupled with an engine, a motor, or an electricity generator. Drive shaft 162 of linear rotary converter 110 is coupled with engine, motor, or electricity generator 196. More specifically, drive shaft 162 may be coupled to an engine, coupled to a motor, or coupled to an electricity generator according to one or more embodiments of the present invention. The coupling between linear rotary converter 110 and engine, motor, or electricity generator 196 is accomplished so as to enable rotation of drive shaft 162. Figure 12 shows drive shaft 162 disposed so that nutation rig 150 is tilted because of the nutation arrangement. The tilting of nutation rig 150 causes extension or compression of flexure structures 185 and 130 depending on their location.

[0108] As an option for one or more embodiments of system 115, the expansion and contraction of flexure structures 185 and 130 acting on nutation rig 150 can be used to produce rotation of drive shaft 162 through nutation coupling 160. The expansion and contraction of flexure structures 185 and 130 may be accomplished by processes such as, but not limited to, internal combustion processes, cyclical applications of heated gas and cooled gas, and/or cyclical heating and cooling of gas. The rotation of drive shaft 162 may be used to generate electricity when connected with an electricity generator or for other applications that need rotary motion or a rotary drive.

[0109] As another option for one or more embodiments of system 115, the expansion and contraction of flexure structures 185 and 130 by way of action from

nutration rig 150 can be produced from rotation of drive shaft 162 through nutation coupling 160 when drive shaft 162 is coupled with an engine or electric motor 196. The rotation of drive shaft 162 by engine or electric motor 196 may be accomplished by processes such as, but not limited to, internal combustion processes, electric power, and/or other sources of power provided by or provided to engine or electric motor 196. The expansion and contraction of flexure structures 185 to 130 may be used in configurations such as, but not limited to, to pump fluids, to operate fluid-based refrigeration cycles, to compress gases, to evacuate fluids, and to meter fluids.

[0110] Alternative embodiments of the present invention include, but are not limited to: A fluid pump comprising a linear rotary converter as described above. A fluid meter comprising a linear rotary converter as described above. A fluid dispenser comprising a linear rotary converter as described above. A fluid flow controller comprising a linear rotary converter as described above. An internal combustion engine comprising a linear rotary converter as described above. A heat engine comprising a linear rotary converter as described above. A heat pump comprising a linear rotary converter as described above. A vacuum pump comprising a linear rotary converter as described above.

[0111] Another embodiment of the present invention includes a method comprising providing a flexure structure such as any of the flexure structures described above and in Figures 1-6, 8, 8-1, 9, and 9-1. The method further comprises providing a fluid to the interior of the flexure structure and cyclically creating a differential pressure exceeding 200 kPa (2 Bar) between the interior and exterior of the flexure structure so as to elongate the flexure structure without exceeding the yield strength of the flexure structure and reducing the pressure within the flexure structure so that the flexure structure contracts. The method may further comprise using the expansion and contraction motion of the flexure structure to create rotary motion. Optionally, the method may comprise using the expansion and contraction motion of the flexure structure to actuate a nutation rig or a wobble plate to create rotary motion.

[0112] Another embodiment of the present invention includes a method comprising providing a flexure structure such as flexure structures described above and in Figures 1-6, 8, 8-1, 9, and 9-1, providing a fluid to the interior of the flexure structure, and using rotary motion to compress the flexure structure so as to produce a differential pressure between the interior and exterior of the flexure structure exceeding 200 kPa (2 Bar) without exceeding the yield strength of the flexure structure. The method may further comprise expelling the fluid from the flexure structure at a higher pressure. Optionally, the method may comprise using rotary motion to compress the flexure structure by using a nutation rig or a wobble plate to actuate the flexure structure.

[0113] Another embodiment of the present invention includes a flexure structure, such as flexure structures described above and in Figures 1-6, 8, 8-1, 9, and 9-1, comprising a sidewall that at least partially encloses a volume. The sidewall is shaped so as to operate with a differential pressure exceeding 200 kPa (2 Bar) between the interior and exterior of the volume. The volume is changeable with time so as to interact with a fluid or gas.

[0114] One or more embodiments of the present invention include a flexure structure comprising a plurality of hollow disk-like convolutions of a material. The hollow disk-like convolutions have a periphery and two oppositely disposed sides joined by the periphery. The periphery of the hollow disk-like convolutions have a curvature and a portion of the sides of the hollow disk-like convolutions is a substantially flat area. The sides of the hollow disk-like convolutions have a hole defined by an inner radius. The adjacent hollow disk-like convolutions are joined proximate or at the edge of the holes so as to form a fluid tight seal. The flat areas between adjacent hollow disk-like convolutions are in contact.

[0115] According to a further embodiment of the present invention, the thickness of the sides of the hollow disk-like convolutions, the yield strength of the material, and/or the size of the flat areas of the sides of the hollow disk-like convolutions are effective to retard or prevent radial plastic deformation of the plurality of hollow disk-like convolutions for operating pressure differentials such as, but not limited to, fluid

based refrigeration cycle operating pressure differentials, fluid based thermal engine operating pressure differentials, fluid pump operating pressure differentials, fluid compressors, fluid flow meter operating pressure differentials, internal combustion engine operating pressure differentials, four- stroke gasoline engine operating pressure differentials, two-stroke gasoline engine operating pressure differentials, and diesel engine operating pressure differentials.

[0116] According to a further embodiment of the present invention, the thickness of the sides of the hollow disk-like convolutions, the yield strength of the material, and/or the size of the flat areas of the sides of the hollow disk-like convolutions are effective to prevent radial plastic deformation of the plurality of hollow disk-like convolutions for operating pressure differentials of greater than or equal to 200 kPa (2 Bar).

[0117] One or more embodiments of the present invention comprise a linear rotary converter substantially as described above with the exception of replacing the flexure structures described above with a bellows structure such as commercially available bellows. According to one embodiment, the linear rotary converter comprises at least one bellows and a first port plate, the first port plate being substantially rigid, the first port plate having an opening. The linear rotary converter further comprises a nutation rig, the nutation rig having a substantially planar surface, the nutation rig being substantially rigid, and a nutation coupling connected with the nutation rig through the opening. The at least one bellows is coupled between the base and the nutation rig substantially as described above for the flexure structure embodiments of the present invention. Optionally, the linear rotary converter may further comprise a second port plate, one or more port plate connectors, and at least one second level bellows, the one or more port plate connectors are substantially rigid, the one or more port plate connectors are disposed so as to hold the second port plate opposite the first port plate having the nutation rig therebetween. The at least one second bellows is connected between the nutation rig and the second port plate.

[0118] Reference is now made to Figure 13 where there is illustrated a cross-section side view of a linear rotary converter 210 according to one or more embodiments of the present invention. Linear rotary converter 210 is substantially the same as linear rotary converter 110 shown in Figure 11 with the exception that linear rotary converter 210 has at least one bellows 215 instead of the at least one flexure structure 130 and has at least one second level bellows 220 instead of the at least one second level flexure structure 185.

[0119] A variety of materials can be used for manufacturing linear rotary converters according to one or more embodiments of the present invention. According to one or more embodiments of the present invention, the linear rotary converters comprise steel or stainless steel. According to one or more embodiments of the present invention, the linear rotary converters comprise titanium or titanium alloy. According to one or more embodiments of the present invention, the linear rotary converters comprise aluminum, copper, chromium, cobalt, iridium, magnesium, molybdenum, nickel, osmium, rhodium, ruthenium, tantalum, zinc, metal alloys, or combinations thereof.

[0120] Reference is now made to Figure 14 which shows a diagram of a system 300 according to one or more embodiments of the present invention. System 300 comprises a flexure structure 310 such as any of the flexure structures described above and in Figures 1-6, 8, 8-1, 9, and 9-1 and/or a linear rotary converter 320 such as any of the linear rotary converters described above and in Figures 10, 10-1, 10-2, 10-3, 10-4, 11, 12, and 13. System 300 is further characterized as being or having components for a fluid based refrigeration cycle, fluid based thermal engine, fluid pump, fluid compressors, fluid flow meter, internal combustion engine, four- stroke gasoline engine, two-stroke gasoline engine, diesel engine, or electricity generator.

[0121] In the foregoing specification, the invention has been described with reference to specific embodiments; however, one of ordinary skill in the art appreciates that various modifications and changes can be made without departing from the scope of the present invention as set forth in the claims below. Accordingly, the specification is to be regarded in an illustrative, rather than a restrictive sense,

and all such modifications are intended to be included within the scope of the present invention.

[0122] Benefits, other advantages, and solutions to problems have been described above with regard to specific embodiments; however, the benefits, advantages, solutions to problems, and any element(s) that may cause any benefit, advantage, or solution to occur or become more pronounced are not to be construed as a critical, required, or essential feature or element of any or all the claims.

[0123] As used herein, the terms "comprises," "comprising," "includes," "including," "has," "having," "at least one of," or any other variation thereof, are intended to cover a non-exclusive inclusion. For example, a process, method, article, or apparatus that comprises a list of elements is not necessarily limited only to those elements, but may include other elements not expressly listed or inherent to such process, method, article, or apparatus. Further, unless expressly stated to the contrary, "or" refers to an inclusive or and not to an exclusive or. For example, a condition A or B is satisfied by any one of the following: A is true (or present) and B is false (or not present), A is false (or not present) and B is true (or present), and both A and B are true (or present) .

CLAIMS

What is claimed is:

1. A flexure structure comprising:

a plurality of hollow disk-like convolutions, the periphery of the hollow disk-like convolutions being curved, the sides of the hollow disk-like convolutions being substantially flat, the sides of the hollow disk-like convolutions having a hole, the adjacent hollow disk-like convolutions being joined.

2. A flexure structure comprising:

a plurality of hollow disk-like convolutions of a material, the periphery of the hollow disk-like convolutions being curved, the sides of the hollow disk-like convolutions being substantially flat, the sides of the hollow disk-like convolutions having a hole, the adjacent hollow disk-like convolutions being joined proximate or at the inner radius of the sides.

3. A flexure structure comprising:

a plurality of hollow disk-like convolutions of a material, the hollow disk-like convolutions comprising a periphery and two oppositely disposed sides joined by the periphery, the periphery of the hollow disk-like convolutions having a curvature, the sides of the hollow disk-like convolutions comprising a substantially flat area, the sides of the hollow disk-like convolutions having a hole defined by an inner radius, the adjacent hollow disk-like convolutions being joined proximate or at the edge of the holes to form a fluid tight seal, the flat areas between adjacent hollow disk-like convolutions being in at least partial contact when the flexure structure is extended.

4. The flexure structure of claim 2, further comprising an end piece, the end piece being substantially rigid and joined at the sides of the hollow disk-like convolutions proximate or at the inner radius of one of the sides at an end of the plurality of hollow disk-like convolutions.

5. The flexure structure of claim 2, wherein the periphery of the hollow disk-like convolutions are partially circular, partially elliptical, or partially parabolic.
6. The flexure structure of claim 2, wherein adjacent hollow disk-like convolutions have sides that may be in contact on a portion of their sides during part of a cycle of motion.
7. The flexure structure of claim 2, wherein the plurality of hollow disk-like convolutions comprise plastic or polymer sheet.
8. The flexure structure of claim 2, wherein the plurality of hollow disk-like convolutions comprise rubber sheet.
9. The flexure structure of claim 2, wherein the plurality of hollow disk-like convolutions comprise metallic sheet.
10. The flexure structure of claim 2, wherein the plurality of hollow disk-like convolutions are formed from metal sheet or metal alloy sheet.
11. The flexure structure of claim 2, wherein the plurality of hollow disk-like convolutions comprise stainless steel.
12. The flexure structure of claim 2, wherein the plurality of hollow disk-like convolutions comprise titanium alloy.
13. The flexure structure of claim 2, wherein the plurality of hollow disk-like convolutions comprise aluminum, copper, chromium, cobalt, iridium, magnesium, molybdenum, nickel, osmium, rhodium, ruthenium, tantalum, zinc, or combinations thereof.
14. The flexure structure of claim 2, further comprising an end piece, the end piece being substantially rigid and joined at the sides of the hollow disk-like convolutions

proximate or at the inner radius of one of the sides at an end of the plurality of hollow disk-like convolutions wherein each of the end piece is shaped as a continuous ring.

15. The flexure structure of claim 2, wherein one of the pair of end pieces is shaped as a continuous ring and the other one of the pair of end pieces shaped as a plate and are attached to form opposite ends of the flexure structure.

16. A flexure structure comprising:

a plurality of hollow disk-like convolutions, the periphery of the hollow disk-like convolutions being curved, the sides of the hollow disk-like convolutions having a substantially flat portion connecting an inner curved portion proximate the inner radius of the sides to join the adjacent hollow disk-like convolution; and

a restriction ring snugly disposed around each of the inner curved portions of each of the hollow disk-like convolutions.

17. The flexure structure of claim 16, wherein the dimensions of the are to retard expansion of the flexure structure at the inner curved portion.

18. The flexure structure of claim 16, wherein the restriction ring has a tensile strength to retard expansion of the flexure structure at the inner curved portion.

19. A fluid pump comprising a flexure structure according to any one of claims 1-17.

20. A fluid meter comprising a flexure structure according to any one of claims 1-17.

21. A fluid dispenser comprising a flexure structure according to any one of claims 1-17.

22. A fluid flow controller comprising a flexure structure according to any one of claims 1-17, a pressure sensor to measure the pressure of the fluid, and a temperature sensor to measure the temperature of the fluid.

23. An internal combustion engine comprising a flexure structure according to any one of claims 1-17, wherein generation of pressure differentials in the flexure structure produces linear motion.
24. A heat engine comprising a flexure structure according to any one of claims 1-17 wherein alternately heating and cooling a gas causes the flexure structure to expand or contract to produce linear motion.
25. A heat engine comprising a flexure structure according to any one of claims 1-17 and components to effect energy conversion using a Brayton cycle, a Rankine cycle, or a Stirling cycle to convert thermal energy into mechanical energy.
26. A heat pump comprising a flexure structure according to any one of claims 1-17 and components to effect heating or cooling of a load through application of mechanical energy in a Brayton cycle, a Rankine cycle, or a Stirling cycle.
27. A heat pump comprising a flexure structure according to any one of claims 1-17 and components to effect heating or cooling of a load through application of mechanical energy in a gas cycle or a gas/liquid cycle.
28. A vacuum pump comprising a flexure structure according to any one of 1-17 and components to effect expulsion of fluid from a chamber through application of mechanical energy to the flexure structure.
29. A system comprising:
- at least one flexure structure according to any one of claims 1-17;
 - a first port plate, the first port plate being substantially rigid, the first port plate having a hole;
 - a nutation rig, the nutation rig having a substantially planar surface, the nutation rig being substantially rigid;
 - a nutation coupling connected with the nutation rig through the hole; and
- the at least one flexure structure being coupled between the ~~base~~ first port plate and the nutation rig.

30. The system of claim 29, wherein the at least one flexure structure comprises two or more flexure structures disposed around the nutation coupling.
31. The system of claim 29, wherein the first port plate has one or more ports disposed so as to allow fluid to enter or exit the interior of the at least one flexure structure.
32. The system of claim 29, wherein the first port plate has one or more ports disposed so as to allow fluid to enter the interior of the flexure structure and has one or more ports disposed so as to allow fluid to exit the interior of the flexure structure.
33. The system of claim 29, wherein the nutation coupling comprises a nutation shaft with a first end connected proximate the center of the nutation rig, a drive shaft, and a rotary union arranged so that the second end of the nutation shaft is connected with one end of the drive shaft by the rotary union at an off axis angle.
34. The system of claim 33, wherein the off axis angle is from 1 to 30 degrees.
35. The system of claim 33, wherein the off axis angle is from 2 to 10 degrees.
36. The system of claim 33, wherein the off axis angle is 4 degrees.
37. The system of claim 29, further comprising a second port plate, one or more port plate connectors, and at least one second level flexure structure, the one or more port plate connectors being substantially rigid, the one or more port plate connectors being disposed so as to hold the second port plate opposite the first port plate having the nutation rig therebetween; the at least one second level flexure structure being connected between the nutation rig and the second port plate.
38. The system of claim 33, further comprising an engine, a motor, or an electricity generator coupled to the drive shaft.
39. A fluid pump comprising the system of claim 29.

40. A fluid meter comprising the system of claim 29.
41. A fluid dispenser comprising the system of claim 29.
42. A fluid flow controller comprising the system of claim 29.
43. An internal combustion engine comprising the system of claim 29.
44. A heat engine comprising the system of claim 29.
45. A heat pump comprising the system of claim 29.
46. A vacuum pump comprising the system of claim 29.
47. A linear actuator comprising:
a plurality of hollow disk-like convolutions, the periphery of the hollow disk-like convolutions being curved, the sides of the hollow disk-like convolutions being substantially flat, the sides of the hollow disk-like convolutions having a hole, the plurality of hollow disk-like convolutions being coaxially stacked, the adjacent hollow disk-like convolutions being joined at the sides or having a portion of their sides in contact, whereby pressure differentials applied to the interior of the hollow disk-like convolutions produces motion substantially along the axis of the hollow disk-like convolutions.
48. A method of displacing a volume of fluid, the method comprising:
providing one or more hollow disk-like convolutions, the periphery of the hollow disk-like convolutions being curved, the sides of the hollow disk-like convolutions being substantially flat, the sides of the hollow disk-like convolutions having a hole, the plurality of hollow disk-like convolutions being stacked, the adjacent hollow disk-like convolutions being joined near or at the edge of the sides or having a portion of the sides in contact; and
cyclically increasing or decreasing the volume of the one or more hollow disk-like convolutions.

49. A method comprising:
- providing a flexure structure;
 - providing a fluid to the interior of the flexure structure;
 - cyclically creating a differential pressure exceeding 200 kPa (2 Bar) between the interior and exterior of the flexure structure so as to elongate the flexure structure without exceeding the yield strength of the flexure structure and reducing the pressure within the flexure structure so that the flexure structure contracts.
50. The method of claim 49, further comprising using the expansion and contraction motion of the flexure structure to create rotary motion.
51. The method of claim 49, further comprising using the expansion and contraction motion of the flexure structure to actuate a nutation rig or a wobble plate to create rotary motion.
52. A method comprising:
- providing a flexure structure;
 - providing a fluid to the interior of the flexure structure; and
 - using rotary motion to compress the flexure structure so as to produce a differential pressure between the interior and exterior of the flexure structure exceeding 200 kPa (2 Bar) without exceeding the yield strength of the flexure structure.
53. The method of claim 52, further comprising expelling the fluid from the flexure structure at a higher pressure.
54. The method of claim 52, wherein the using rotary motion to compress the flexure structure comprises using a nutation rig or a wobble plate.
55. A flexure structure comprising a sidewall that at least partially encloses a volume, the sidewall being shaped so as to operate with a differential pressure

exceeding 200 kPa (2 Bar) between the interior and exterior of the volume, the volume being changeable with time so as to interact with a fluid or gas.

56. A method of obtaining a flexure structure design, the method comprising:

- specifying an initial material of construction and acquiring yield stress data for the material;

- specifying an initial shape, an initial size, and/or initial dimensions for a plurality of hollow disk-like convolutions of the material, the periphery of the hollow disk-like convolutions being curved, the sides of the hollow disk-like convolutions having a substantially flat section, the sides of the hollow disk-like convolutions having a hole, the adjacent hollow disk-like convolutions being joined proximate or at the inner radius of the sides;

- specifying one or more operating conditions for the flexure structure;

- specifying at least one performance parameter for the plurality of hollow disk-like convolutions of the material;

- obtaining a stress profile for the plurality of hollow disk-like convolutions using one or more of the inputs:.

- the initial specified material of construction;

- the initial specified shape, initial size, and/or initial dimensions for the plurality of hollow disk-like convolutions;

- the specified operating conditions; and/or

- the specified at least one performance parameter; and

- if all values of the stress profile are less than the yield stress for the initial specified material, then using the initial specified material of construction; the initial specified shape, the initial size, and/or the initial dimensions for the plurality of hollow disk-like convolutions as the flexure structure design;

- if all values of the stress profile are not less than the yield stress for the initial specified material, then iteratively adjust one or more of the inputs:

- the specified material of construction;

- the specified shape, size, and/or dimensions for the plurality of hollow disk-like convolutions;

- the specified operating conditions; and

- the specified at least one performance parameter

until all values of the stress profile for the plurality of hollow disk-like convolutions are less than the yield stress for the material of construction, then using the material of construction; the shape, size, and/or dimensions for the plurality of hollow disk-like convolutions that provide the stress profile with all values less than the yield stress as the flexure structure design.

57. In a combination:

- at least one bellows;

- a first port plate, the first port plate being substantially rigid, the base having an opening;

- a nutation rig, the nutation rig having a substantially planar surface, the nutation rig being substantially rigid;

- a nutation coupling connected with the nutation rig through the opening; and the at least one bellows being coupled between the base and the nutation rig.

58. The combination of claim 57, further comprising a second port plate, one or more port plate connectors, and at least one second level bellows, the one or more port plate connectors being substantially rigid, the one or more port plate connectors being disposed so as to hold the second port plate opposite the first port plate having the nutation rig therebetween; the at least one second bellows being connected between the nutation rig and the second port plate.

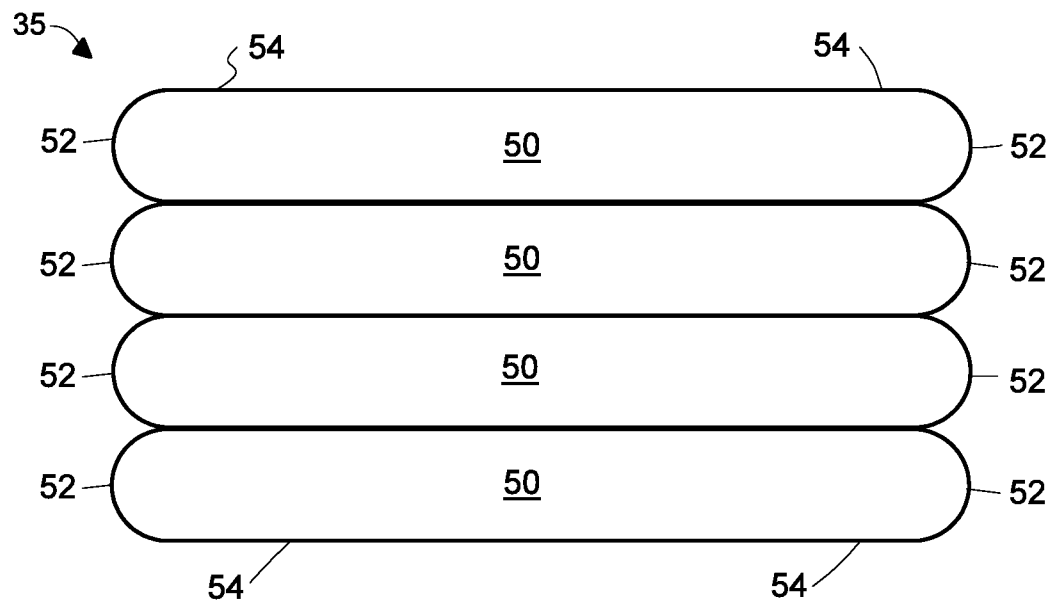


FIG. 1

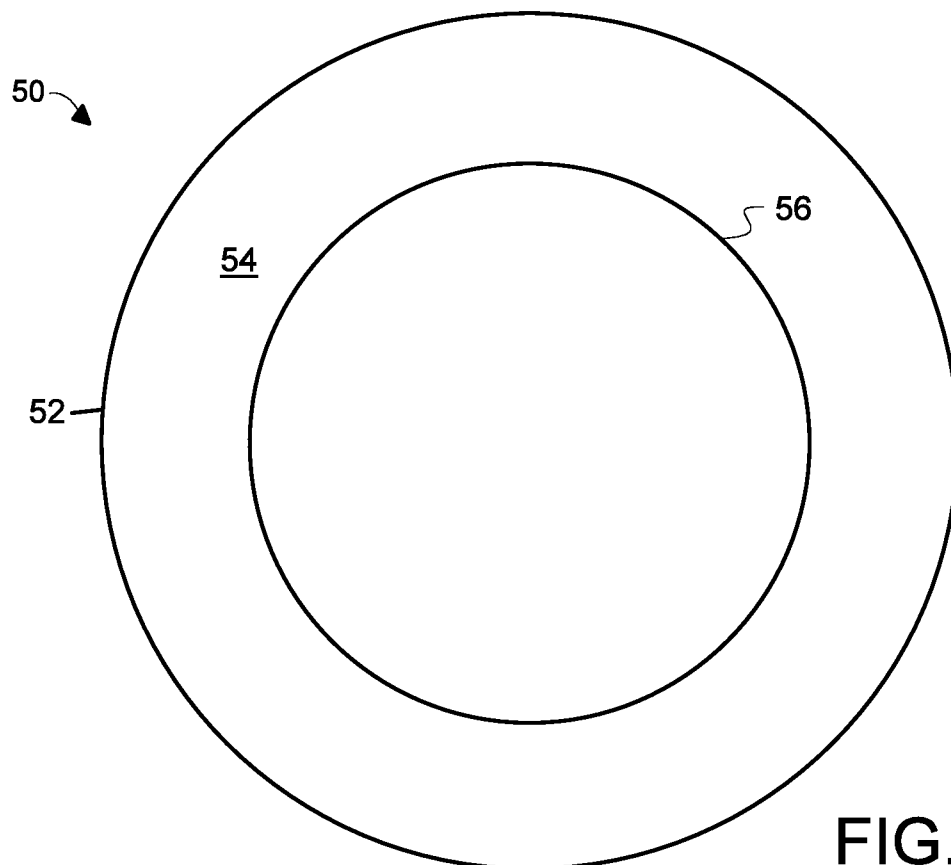


FIG. 2

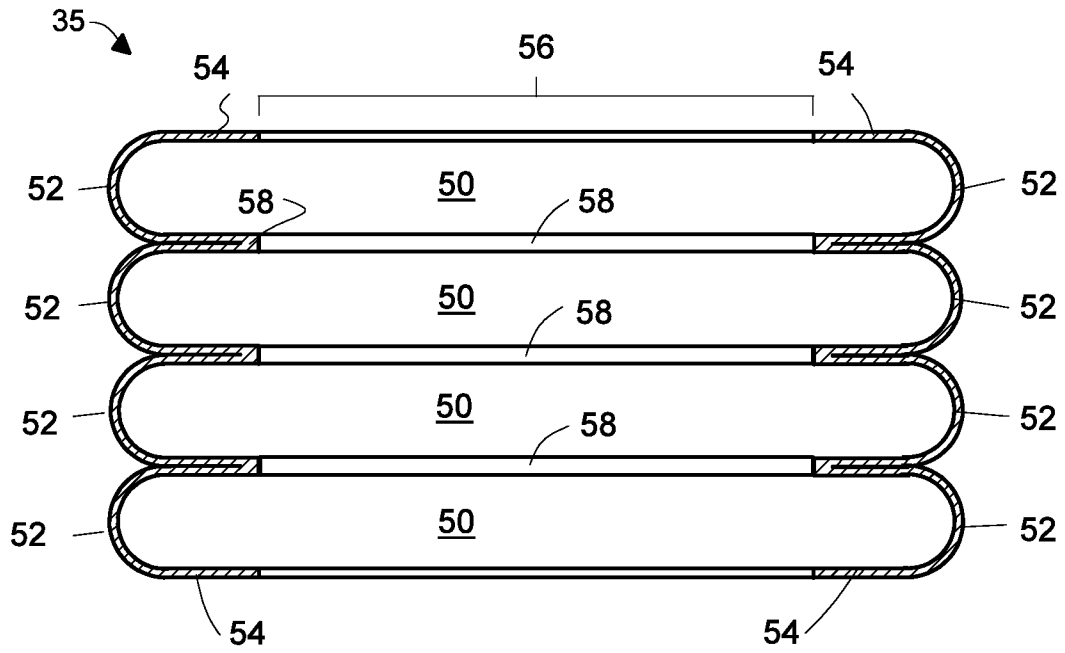


FIG. 3

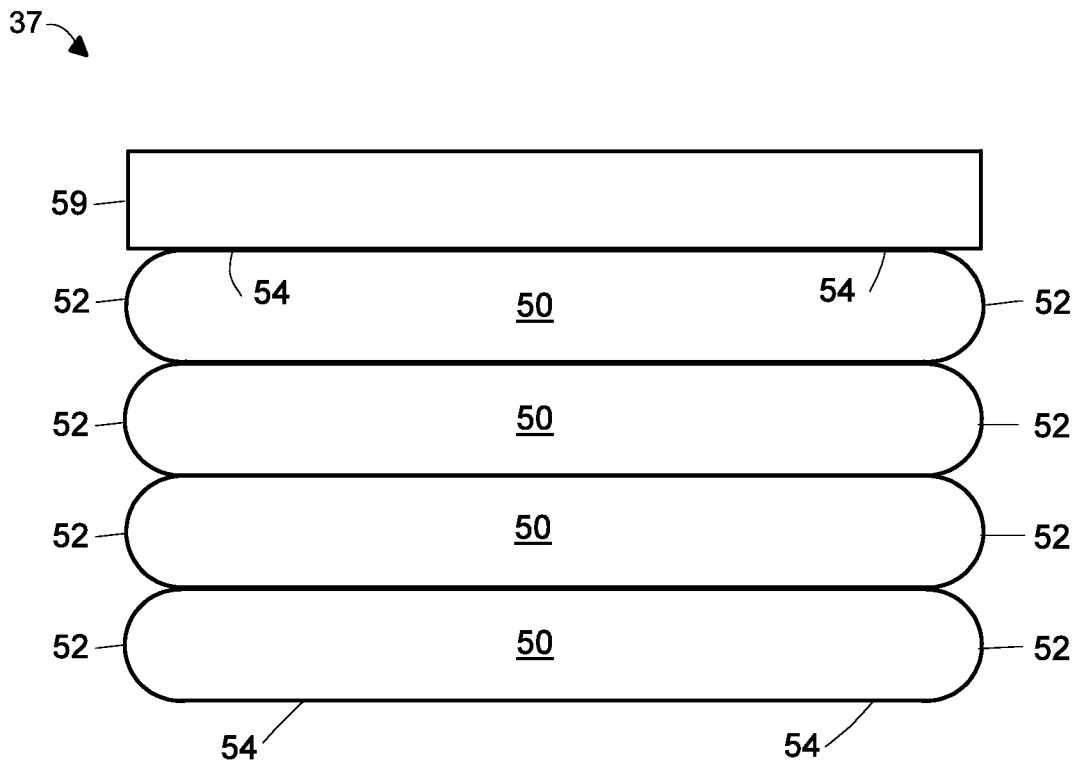


FIG. 4

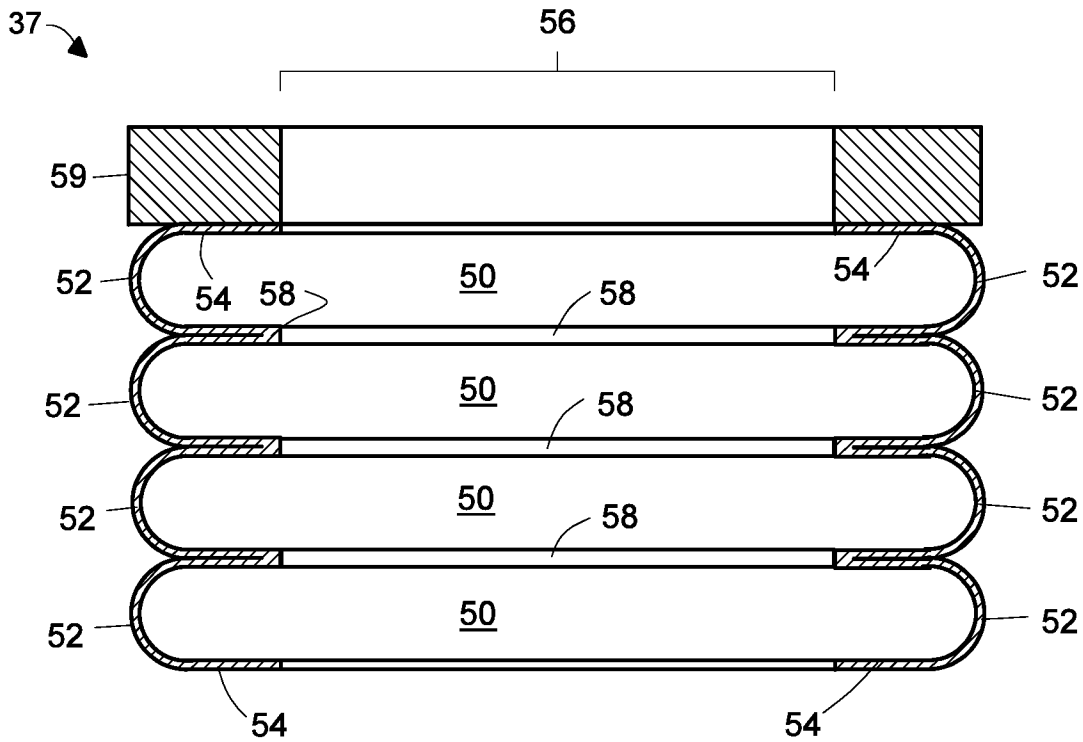


FIG. 5

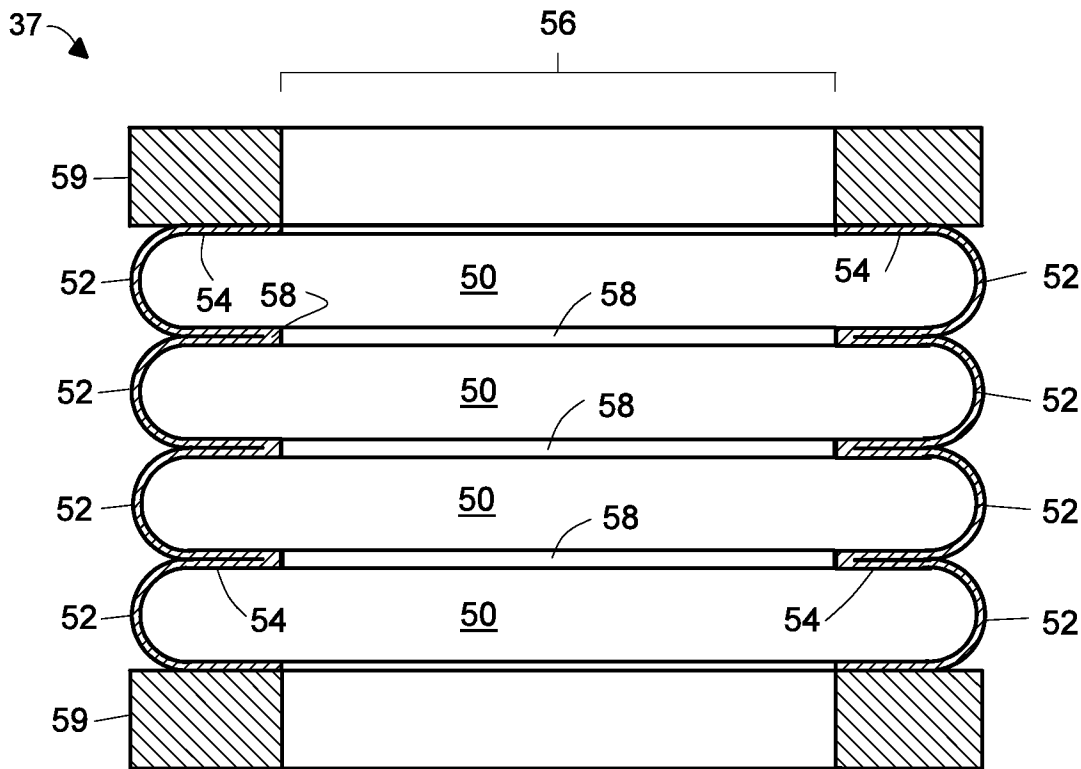
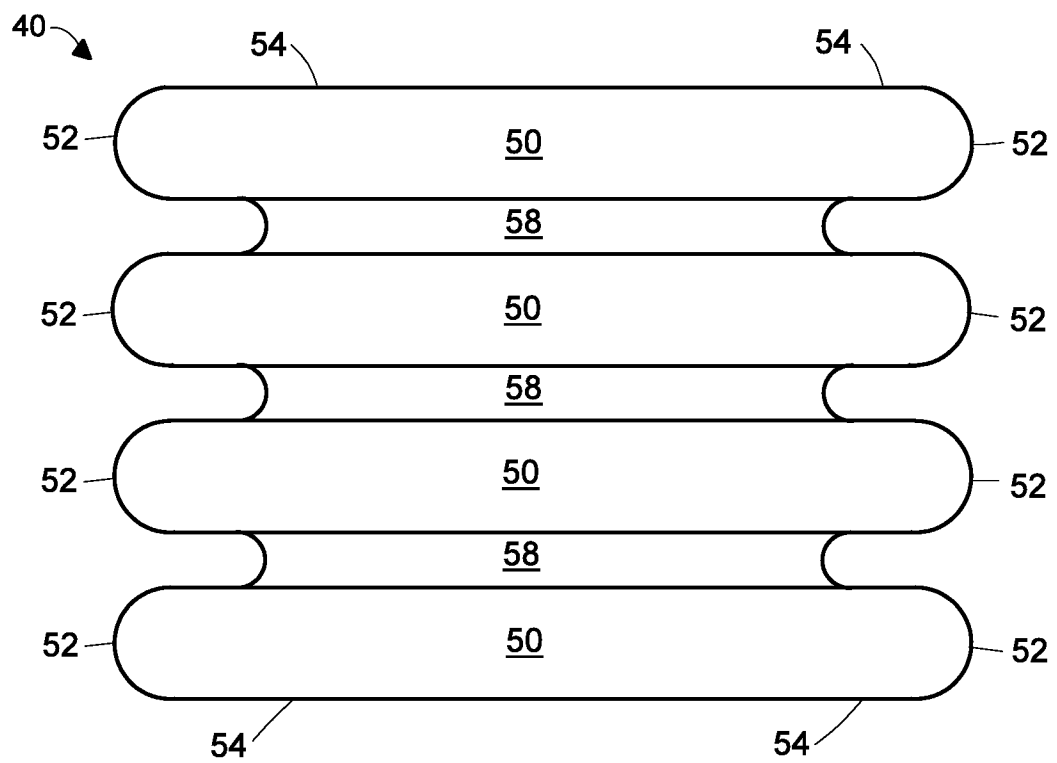


FIG. 6

**FIG. 7**

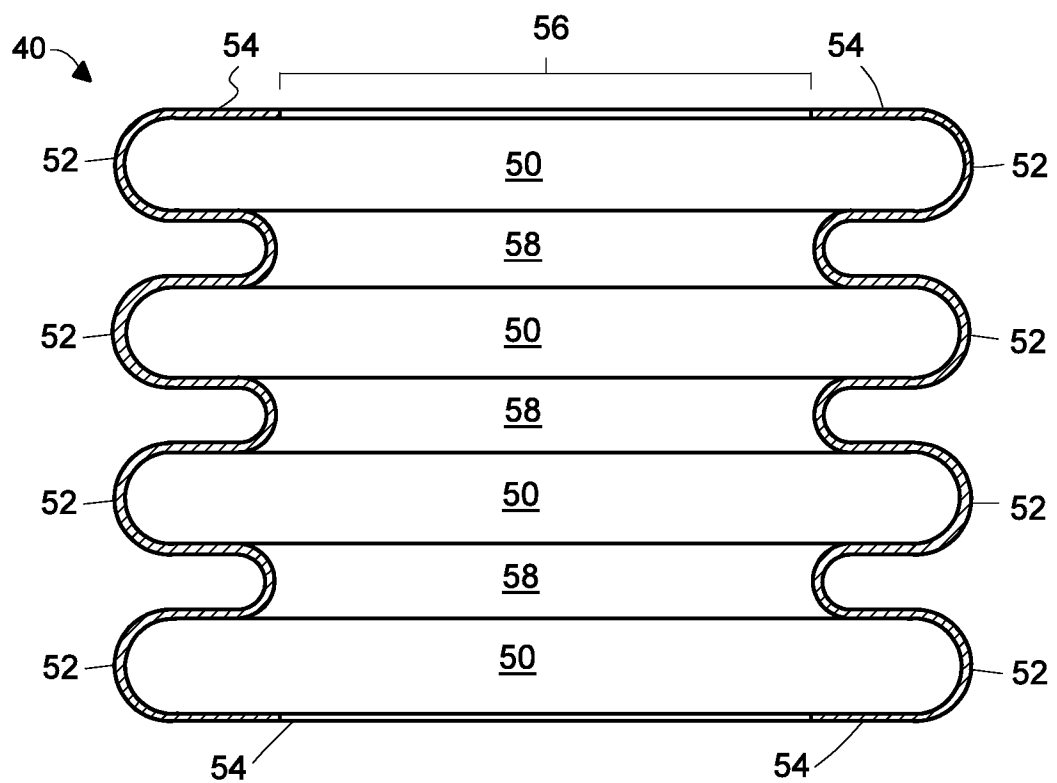
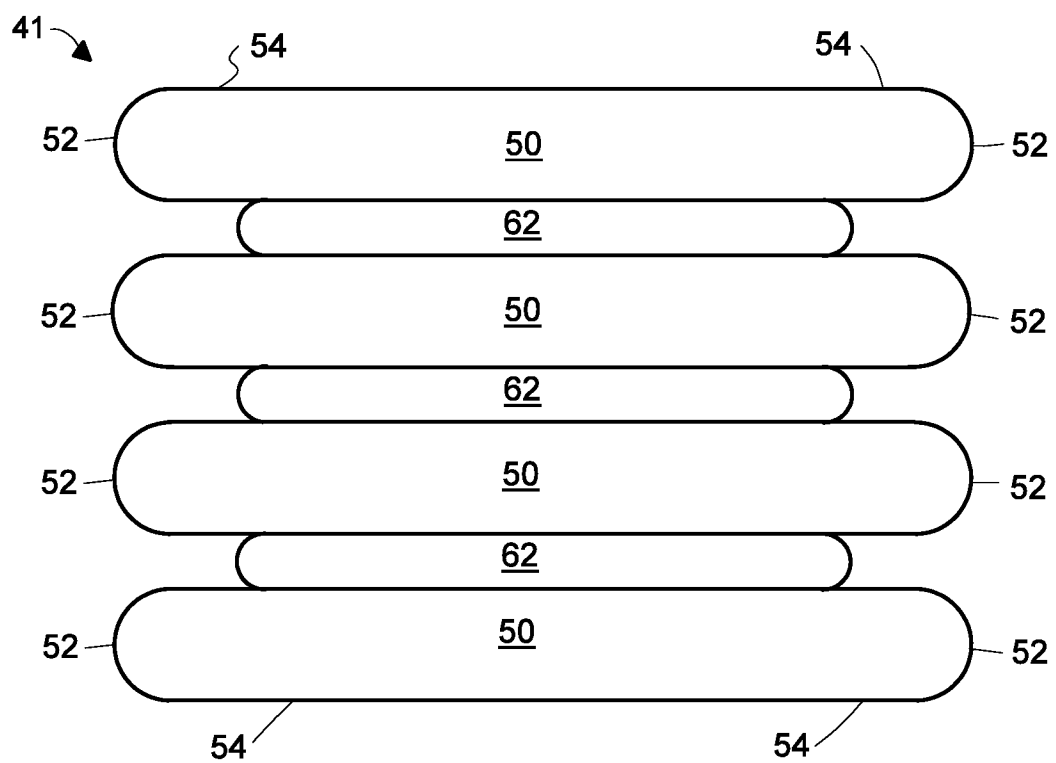


FIG. 7-1

**FIG. 8**

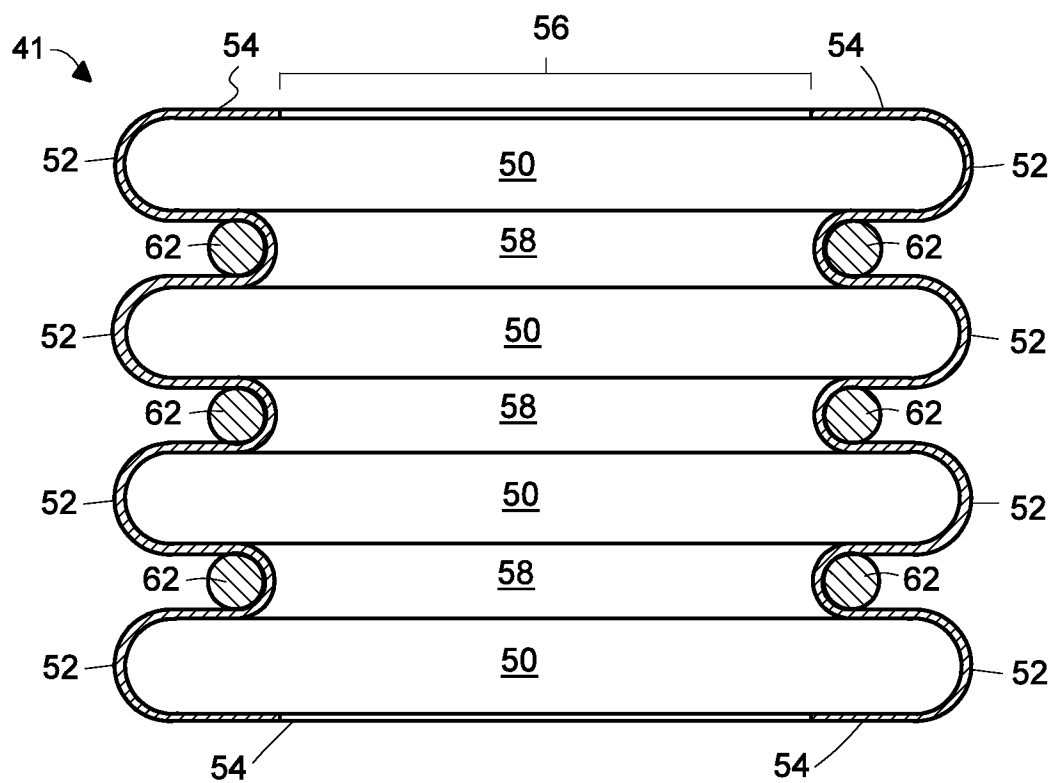


FIG. 8-1

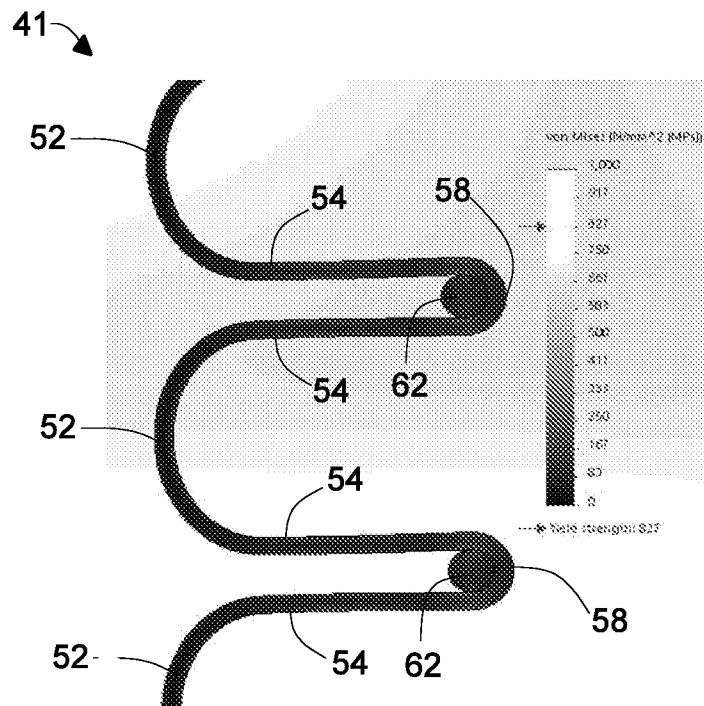


FIG. 9

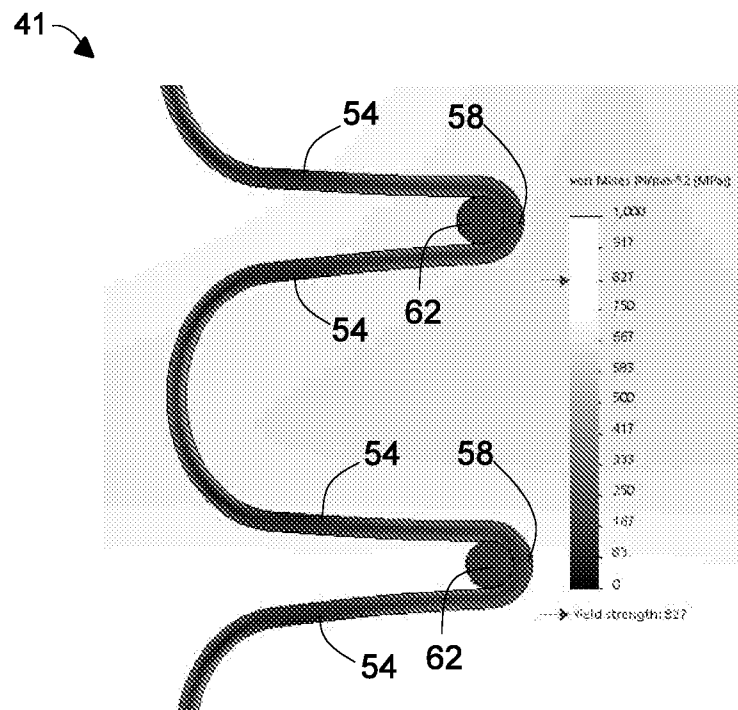


FIG. 9-1

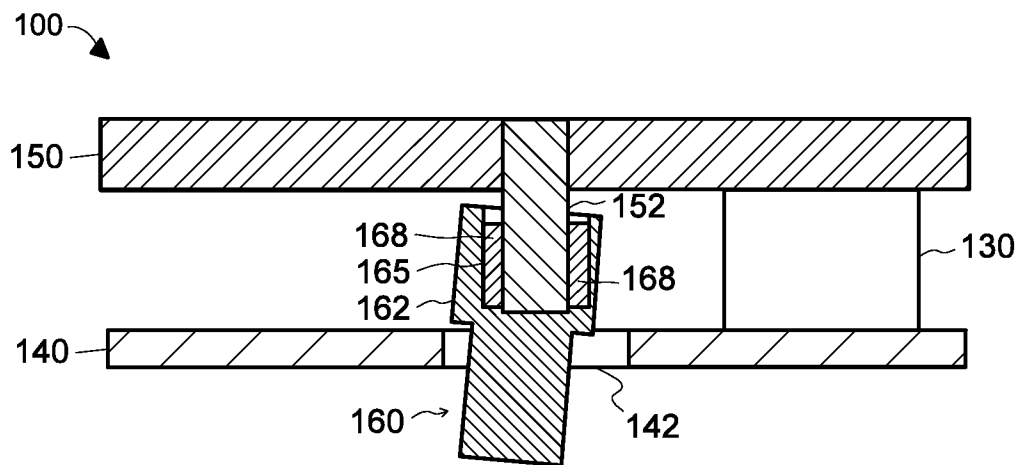


FIG. 10

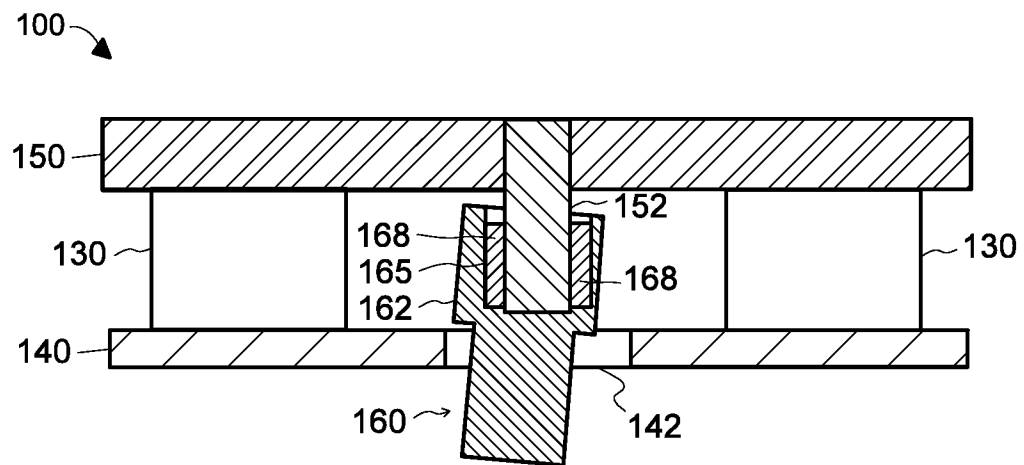


FIG. 10-1

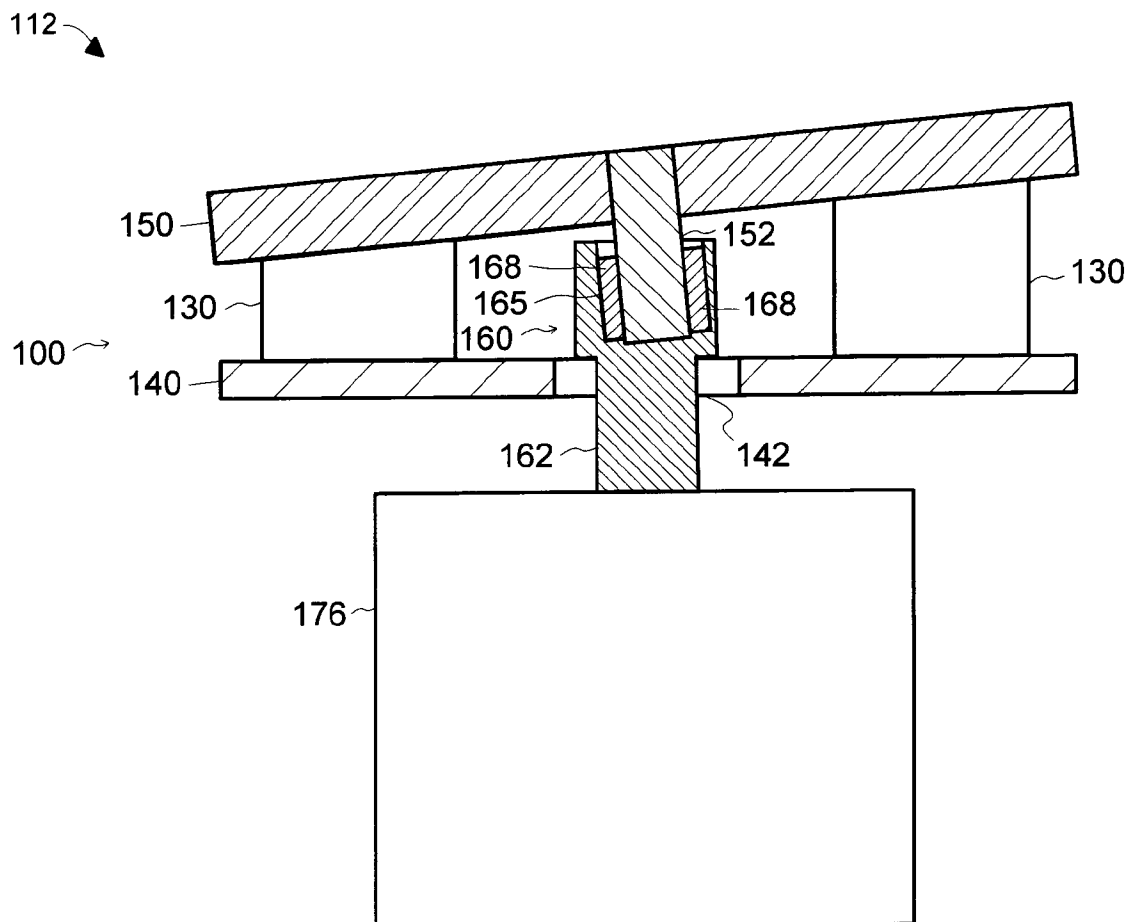


FIG. 10-2

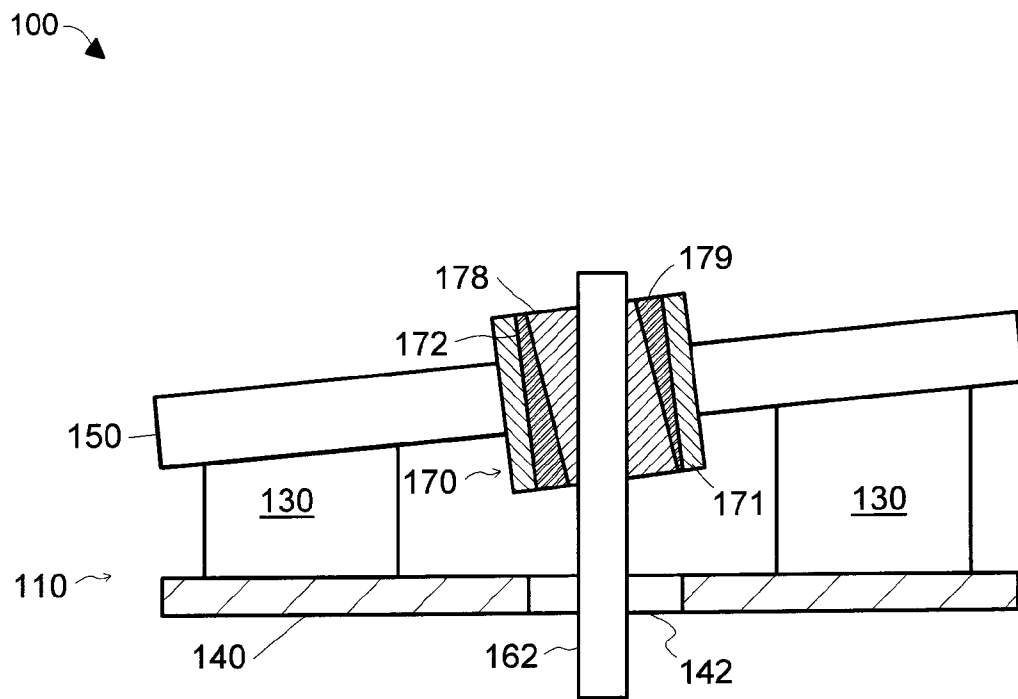


FIG. 10-3

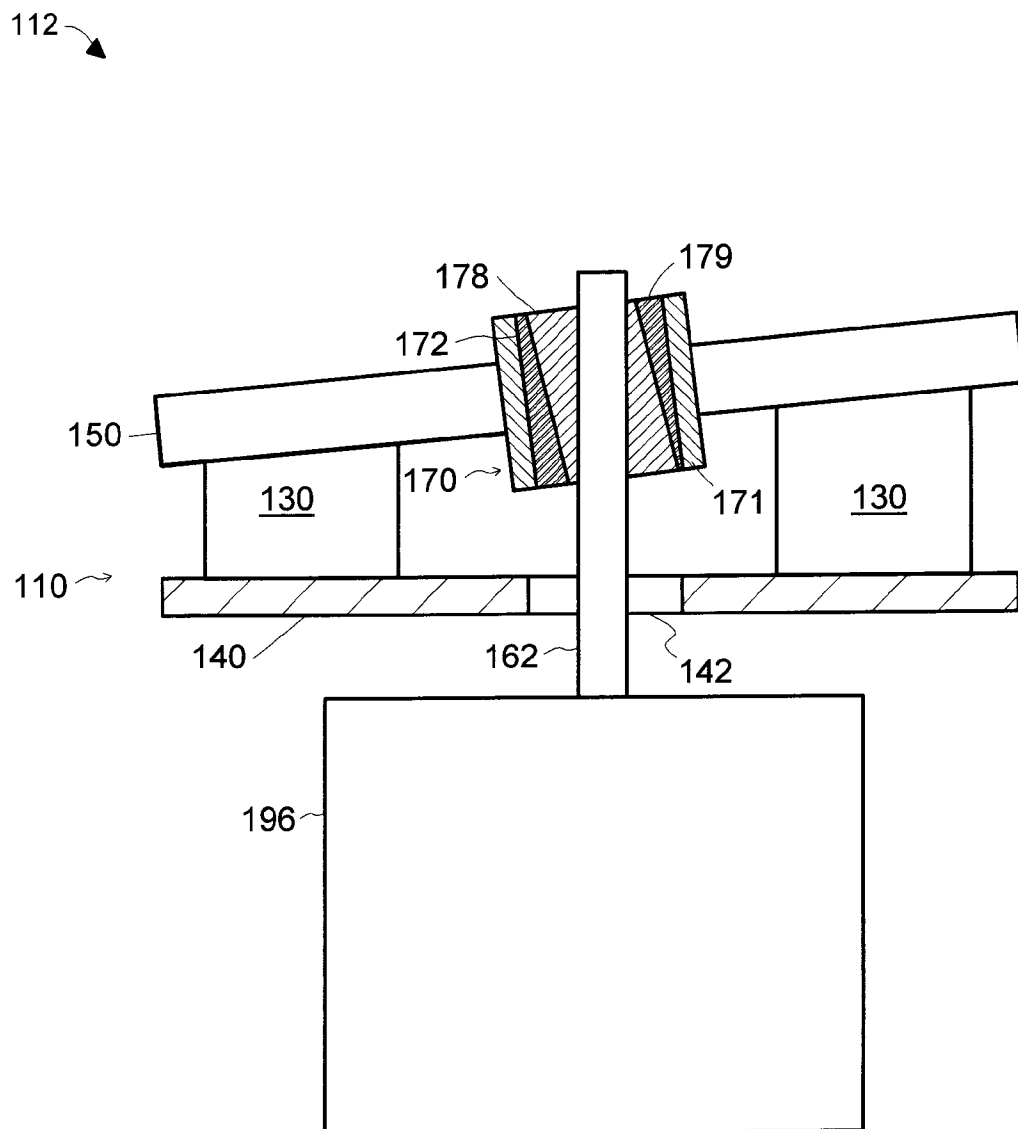


FIG. 10-4

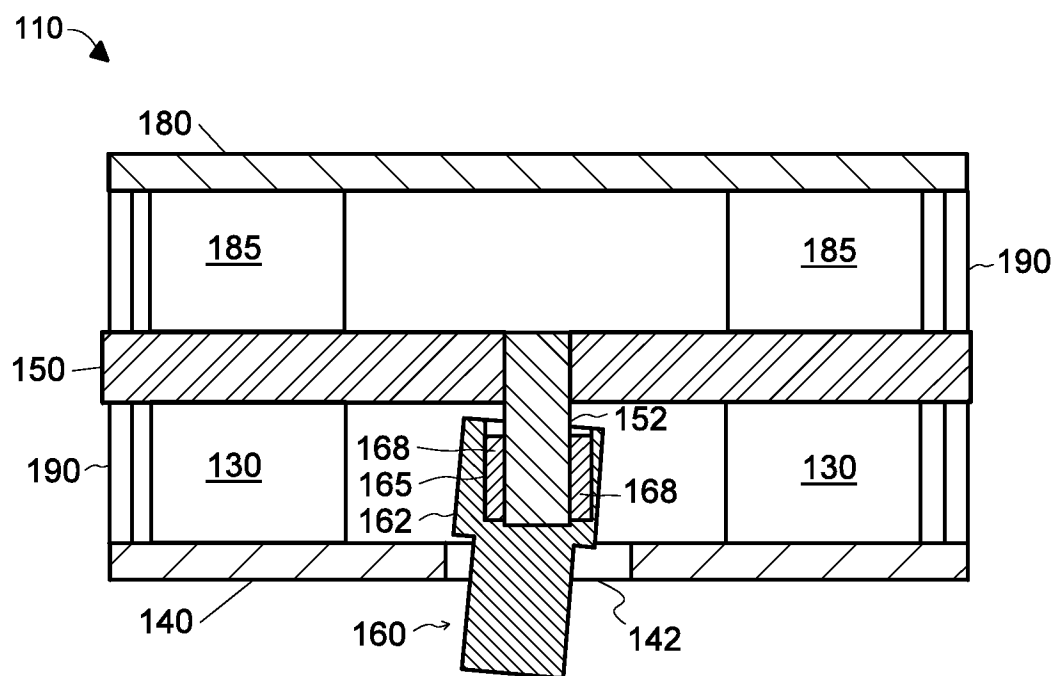


FIG. 11

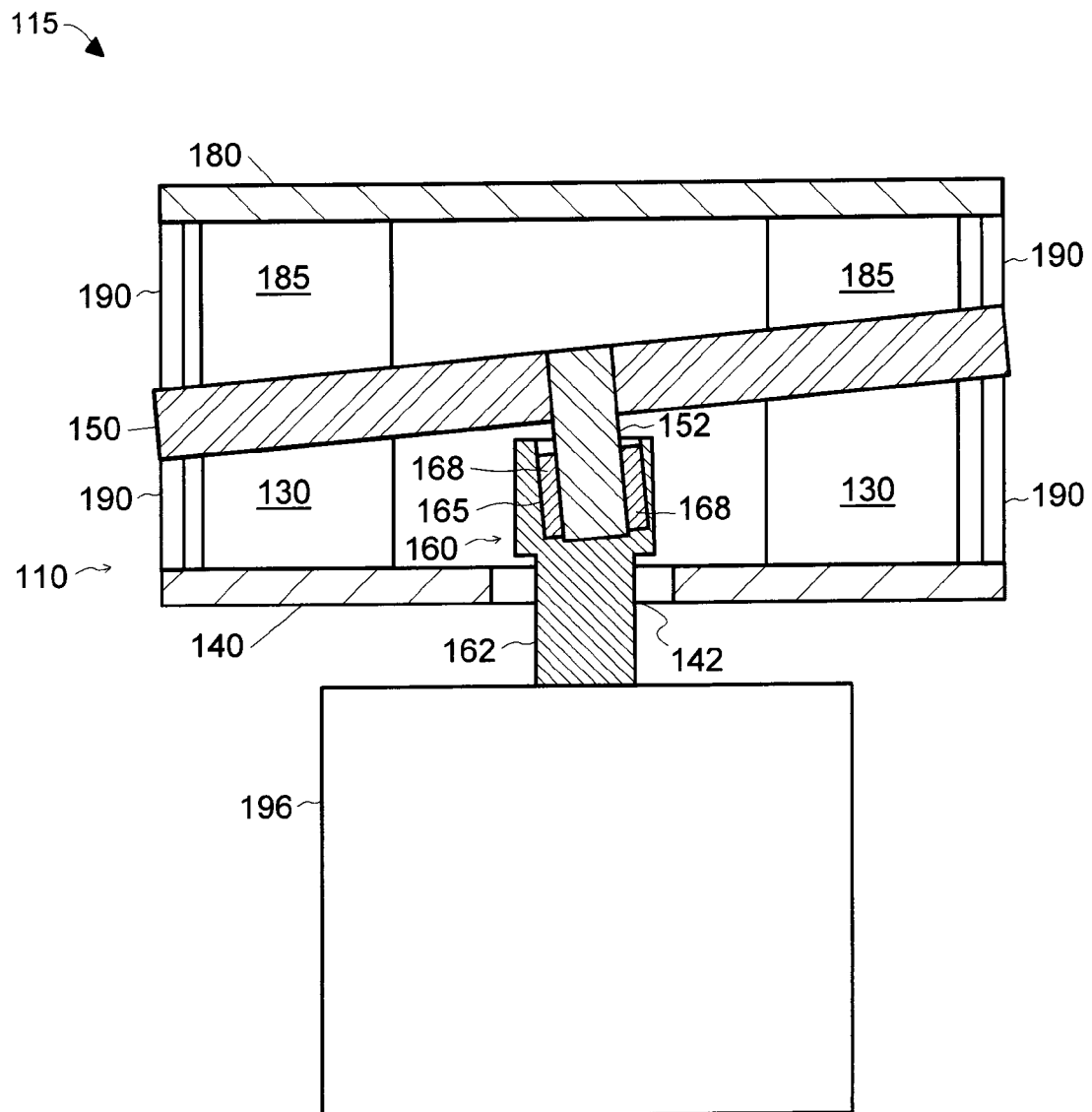


FIG. 12

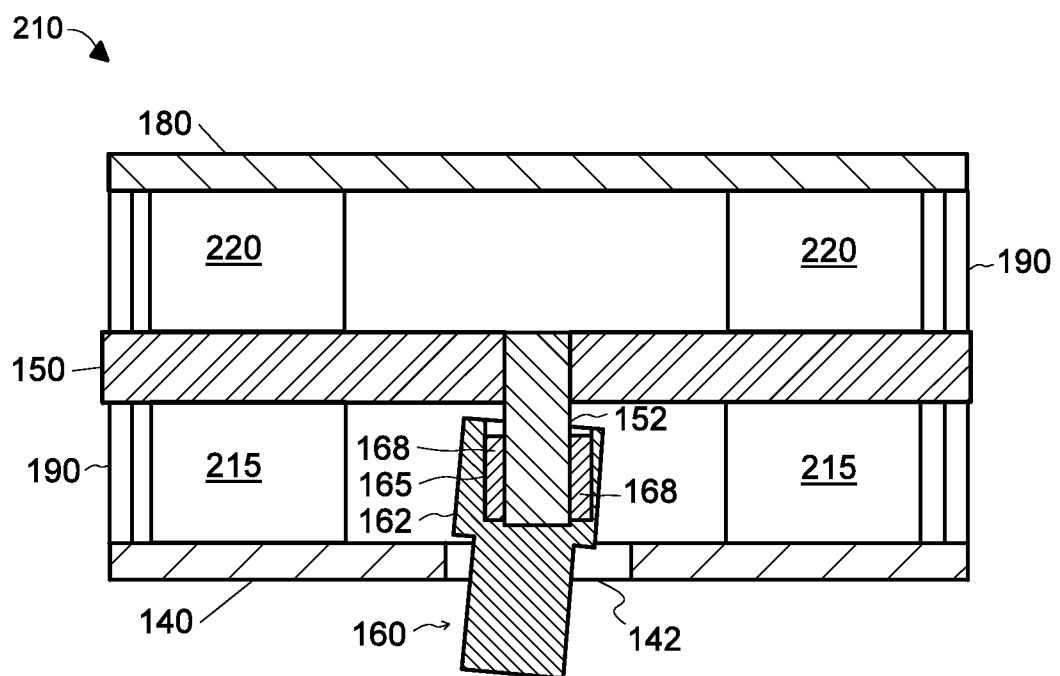


FIG. 13

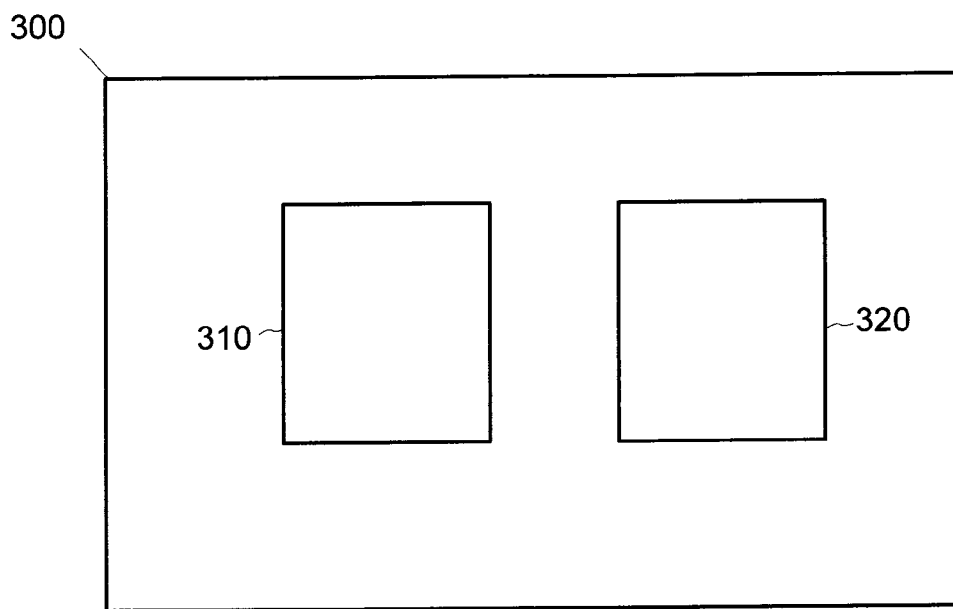


FIG. 14

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US 15/37839

A. CLASSIFICATION OF SUBJECT MATTER

IPC(8) - F04B 43/08, 45/02; F15B 15/10; F16J 3/04, 3/06 (2015.01)

CPC - F16J 3/04, 3/041

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC(8) - F04B 43/08, 45/02; F15B 15/10; F16J 3/04, 3/06 (2015.01)

CPC - F16J 3/04, 3/041

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
CPC - F16J 3/06; F04B 43/08, 43/088, 43/0054, 43/0063, 43/0072, 45/02; B29L 2031/703; F15B 15/10

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

Patbase; Google Patents; Google Scholar; Google Web; Espacenet; Search Terms: aperture*, axial*, band*, bellow*, circular*, combust*, controller*, convert*, cool*, diaphragm*, disc*, disk*, dispense*, expan*, fluid*, edge*, elipt*, heat*, hole*, hollow*, inflat*, linear*, meter*, multi*, nuta*, opening*, periph*, plastic*, plural*, polymer*, pressur

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X --- Y --- A	US 3,442,005 A (Langlet et al.) 06 May 1969 (06.05.1969), Figs. 3, 4c, col. 3, ln. 69-70, col. 4, ln. 3-74	1-6, 9-15 and 47 --- 7-8, 16-18, 19/(1-17), 20/(1-17), 21/(1-17), 22/(1-17), 23/(1-17), 24/(1-17), 25/(1-17), 26/(1-17), 27/(1-17), 28/(1-17), 48 --- 29-46 and 56 7-8, 16-18, 19/(7-8, 16-17), 20/(7-8, 16-17), 21/(7-8, 16-17), 22/(7-8, 16-17), 23/(7-8, 16-17), 24/(7-8, 16-17), 25/(7-8, 16-17), 26/(7-8, 16-17), 27/(7-8, 16-17), 28/(7-8, 16-17) --- 29-46 and 56 19/(1-17), 48
Y ----- A	US 6,076,557 A (Carney) 20 June 2000 (20.06.2000), Fig. 3c(1), col. 3, ln. 8-26, col. 5, ln. 51-52	
Y	GB 2166496 A (Stoll) 08 May 1986 (08.05.1986), Fig. 9, pg. 5, ln. 110-113	

☒ Further documents are listed in the continuation of Box C.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

22 October 2015 (22.10.2015)

Date of mailing of the international search report

12 JAN 2016

Name and mailing address of the ISA/US

Mail Stop PCT, Attn: ISA/US, Commissioner for Patents
P.O. Box 1450, Alexandria, Virginia 22313-1450

Facsimile No. 571-273-8300

Authorized officer:

Lee W. Young

PCT Helpdesk: 571-272-4300
PCT OSP: 571-272-7774

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US 15/37839

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☐ Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:
--- See supplemental box ---

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.
2. ☐ As all searchable claims could be searched without effort justifying additional fees, this Authority did not invite payment of additional fees.
3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:
4. ☒ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:
1-48 and 56

Remark on Protest

- ☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.
- ☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.
- ☐ No protest accompanied the payment of additional search fees.

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US 15/37839

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 5,061,156 A (Kuehne et al.) 29 October 1991 (29.10.1991), col. 1, ln. 6-10	20/(1-17), 21/(1-17)
Y	US 2004/0011411 A1 (Thordarson et al.) 22 January 2004 (22.01.2004), para [0147], [0163]	22/(1-17)
Y	US 2003/0136358 A1 (Galvin) 24 July 2003 (24.07.2003), Figs. 5-6, para [0043]	23/(1-17)
Y	GB 480850 A (Frederick), 01 March 1938 (01.03.1938), Figs. 1-2, pg. 2, ln. 25-40	24/(1-17)
Y	US 6,263,671 B1 (Bliesner) 24 July 2001 (24.07.2001), col. 5, ln. 10-11, col. 8, ln. 34-40	25/(1-17), 26/(1-17), 27/(1-17)
Y	US 2008/0199335 A1 (Melatti) 21 August 2008 (21.08.2008), Fig. 4, para [0021]	28/(1-17)
A	US 1,736,974 A (King) 26 November 1929 (26.11.1929), Fig. 2, pg. 3, ln. 83-101	29-46
A	US 3,861,277 A (Wagner et al.) 21 January 1975 (21.01.1975), Figs. 1-8, col. 2, ln. 19-67	1-48 and 56
A	US 2,323,985 A (Fausek et al.) 13 July 1943 (13.07.1943), Figs. 6-7, pg. 2, col. 2, ln. 3-28	1-48 and 56

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US 15/37839

Continuation of Box No. III - Observations where unity of invention is lacking

This application contains the following inventions or groups of inventions which are not so linked as to form a single general inventive concept under PCT Rule 13.1. In order for all inventions to be examined, the appropriate additional examination fees must be paid.

Group I: Claims 1-48 and 56, directed to a flexure structure including a plurality of hollow disk-like convolutions and method of using such a structure, and method of obtaining such a flexure structure design.

Group II: Claims 49-55, directed to a method of providing fluid to a flexure structure at a differential pressure exceeding 200 kPa (2 Bar) between the interior and exterior.

Group III: Claims 57-58, directed to a bellows in combination with a port plate and nutation rig.

The inventions listed as Groups I-III do not relate to a single inventive concept under PCT Rule 13.1 because under PCT Rule 13.2 they lack the same or corresponding technical features for the following reasons:

Special Technical Features

Group I includes the special technical features of a plurality of hollow disk-like convolutions, the periphery of the hollow disk-like convolutions being curved, the sides of the hollow disk-like convolutions being substantially flat, the sides of the hollow disk-like convolutions having a hole, the adjacent hollow disk-like convolutions being joined that are not required by Groups II-III.

Group II includes the special technical features of creating a differential pressure exceeding 200 kPa (2 Bar) between an interior and exterior of a flexure structure that are not required by Groups I and III.

Group III includes the special technical features of a first port plate, the first port plate being substantially rigid, the base having an opening; a nutation rig, the nutation rig having a substantially planar surface, the nutation rig being substantially rigid; a nutation coupling connected with the nutation rig through the opening; and an at least one bellows being coupled between the base and the nutation rig that are not required by Groups I-II.

Common Technical Features

Groups I-III share the common technical feature of a flexure structure / bellows. However, this shared technical feature does not represent a contribution over the prior art as being anticipated by US 4,464,980 A (Yoshida) which discloses a flexure structure / bellows (Fig. 16).

Therefore, Groups I-III lack unity under PCT Rule 13 because they do not share a same or corresponding technical feature.