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United States Patent Application Publication	20250260288
Kind Code	A1
Publication Date	August 14, 2025
Inventor(s)	Lawler; John et al.

SYSTEMS AND METHODS FOR FLEXURE-BASED BEARING MOUNTING

Abstract

A bearing assembly for a linear electromagnetic machine includes a sleeve having a surface configured to provide a bearing between the surface and a translator, a front plate coupled to the sleeve, a support block, and a plurality of flexures coupled to the support block. Each flexure is coupled between the support block and one of the front plate or a stator. For example, a load path extends from a stator to the support block via a first set of flexures of the plurality of flexures, from the support block to the front plate via a second set of flexures of the plurality of flexures, and from the front plate to the sleeve. In the example of four flexures, two flexures are affixed to the support block and front plate, while two other flexures are affixed to the support block and the stator.

Inventors: **Lawler; John (Portland, OR), Watters; Neil (Redwood City, CA), Sherman; Samuel (San Francisco, CA), Svrcek; Matthew (Redwood City, CA), DeGraaff; David (Mountain View, CA)**

Applicant: **Mainspring Energy, Inc.** (Menlo Park, CA)

Family ID: **1000008563507**

Appl. No.: **19/058787**

Filed: **February 20, 2025**

Related U.S. Application Data

parent US continuation 17876992 20220729 parent-grant-document US 12255514 child US 19058787
us-provisional-application US 63227780 20210730

Publication Classification

Int. Cl.: **H02K5/167** (20060101); **F16C32/06** (20060101); **H02K7/18** (20060101)

U.S. Cl.:

CPC **H02K5/167** (20130101); **F16C32/0614** (20130101); **H02K7/1884** (20130101);

Background/Summary

CROSS-REFERENCE TO RELATED APPLICATIONS [0001] This application is a continuation of U.S. patent application Ser. No. 17/876,992 filed Jul. 29, 2022 (now allowed), which claims the benefit of U.S. Provisional Patent Application No. 63/227,780 filed Jul. 30, 2021, the disclosure of which is hereby incorporated by reference herein in its entirety.

[0002] The present disclosure is directed to bearing structures for forming gas bearings, and more particularly, to bearing structures for controlling or otherwise limiting the trajectory of a translator of a linear generator.
SUMMARY
[0003] In some embodiments, the present disclosure is directed to bearing structures. In some embodiments, the present disclosure is directed to systems for constraining translator displacement. In some embodiments, the present disclosure is directed to methods for constraining translator displacement.
[0004] In some embodiments, the present disclosure is directed to a bearing assembly for a linear electromagnetic machine (LEM). The bearing structure includes a sleeve having a surface configured to provide a bearing between the surface and a translator, a front plate coupled to the sleeve, a support block, and a plurality of flexures coupled to the support block. Each flexure is coupled between the support block and one of the front plate or a stator. In some embodiments, the bearing structure includes at least one hub affixing the sleeve to the front plate. In some embodiments, the surface is configured to provide a gas bearing between the surface and the translator during operation. In some embodiments, the sleeve is an inner sleeve, and the bearing structure includes an outer sleeve that forms one or more gas passages for providing gas to a gas bearing adjacent to the surface.
[0005] In some embodiments, the plurality of flexures includes (i) first flexures arranged at a first azimuthal position and a second azimuthal position of the bearing assembly and affixed to the support block and to the front plate, and (ii) second flexures arranged at a third azimuthal position and a fourth azimuthal position of the bearing structure and affixed to the support block and the stator. For example, in some embodiments, the bearing structure includes two first flexures and two second flexures.
[0006] In some embodiments, a load path extends from the stator to the support block via a first set of flexures of the plurality of flexures, from the support block to the front plate via a second set of flexures of the plurality of flexures, and from the front plate to the sleeve.
[0007] In some embodiments, the present disclosure is directed to a stator assembly of a linear generator. The stator assembly includes a stator configured to electromagnetically interact with a translator, at least one bearing assembly (e.g., each being a bearing structure) coupled to the stator, each bearing assembly including a plurality of flexures that couple a sleeve to the stator. Each flexure is configured to allow pitch or yaw of the sleeve, and the sleeve (e.g., a surface thereof) interfaces with the translator. In some embodiments, the surface provides a gas bearing with the translator during operation. In some embodiments, the bearing assembly includes an outer sleeve that forms one or more gas passages for providing gas to a gas bearing adjacent to a surface of the sleeve.
[0008] In some embodiments, the present disclosure is directed to a linear electromagnetic machine (LEM) that includes a stator comprising a plurality of phases, a translator that moves along the

stator and electromagnetically interacts with the plurality of phases, and at least one bearing assembly coupled to the stator. Each bearing assembly includes a plurality of flexures that couple a sleeve, interfacing with the translator, to the stator. Each flexure allows pitch or yaw. In some embodiments, the at least one bearing assembly includes a first bearing assembly and a second bearing assembly, where the first bearing assembly is arranged at a first axial end of the stator, and the second bearing assembly is arranged at a second axial end of the stator.
[0009] In some embodiments, the present disclosure is directed to a method for operating a linear generator. The method includes providing stiffness against pitch and yaw using a plurality of flexures that couple a stator assembly to a sleeve having a surface configured to provide a bearing between the surface and a translator, providing gas to a bearing surface of the sleeve to form a gas bearing between the surface and a surface of a translator, and maintaining a motor air gap using the gas bearing. In some embodiments, the method includes providing current to phases of the stator assembly along which the translator is configured to move. In some embodiments, the method includes monitoring a pressure of the gas during operation. In some embodiments, the method includes causing the translator to move axially along the gas bearing.

Description

BRIEF DESCRIPTION OF THE DRAWINGS
[0010] The present disclosure, in accordance with one or more various embodiments, is described in detail with reference to the following figures. The drawings are provided for purposes of illustration only and merely depict typical or example embodiments. These drawings are provided to facilitate an understanding of the concepts disclosed herein and shall not be considered limiting of the breadth, scope, or applicability of these concepts. It should be noted that for clarity and case of illustration these drawings are not necessarily made to scale.
[0011] FIG. **1** shows a cross-sectional view of an illustrative linear electromagnetic machine, in accordance with some embodiments of the present disclosure;
[0012] FIG. **2** shows a perspective view of an illustrative bearing structure, in accordance with some embodiments of the present disclosure;
[0013] FIG. **3** shows a portion of the bearing structure of FIG. **2** illustrating a yaw flexure (e.g., one of two) that mounts rigidly to (i) the front side of the support block (e.g., illustrated as transparent for clarity) and, (ii) at another end bolts to the stator structure, in accordance with some embodiments of the present disclosure;
[0014] FIG. **4** shows a portion of the bearing structure of FIG. **2** illustrating a pitch flexure (e.g., one of two) that mounts rigidly to the rear of the support block, and then bolts rigidly to the front plate, in accordance with some embodiments of the present disclosure;
[0015] FIG. **5** shows a portion of the bearing structure of FIG. **2** arranged as part of a linear generator, in accordance with some embodiments of the present disclosure;
[0016] FIG. **6** shows a perspective view of some components of the bearing structure of FIG. **2**, in accordance with some embodiments of the present disclosure;
[0017] FIG. **7** shows another perspective view of some components of the bearing structure of FIG. **2**, in accordance with some embodiments of the present disclosure;
[0018] FIG. **8** shows a perspective view of some components of the bearing structure of FIG. **2**, centered on one flexure, in accordance with some embodiments of the present disclosure;
[0019] FIG. **9** shows a side view of some components of the bearing structure of FIG. **2**, in accordance with some embodiments of the present disclosure;
[0020] FIG. **10** shows a side view of a portion of the bearing structure of FIG. **2** arranged as part of a stator assembly, in accordance with some embodiments of the present disclosure;
[0021] FIG. **11** shows a side view of a portion of the bearing structure of FIG. **2** arranged as part of

a stator assembly, with a load path indicated, in accordance with some embodiments of the present disclosure;

[0022] FIG. **12** shows a perspective view of an illustrative bearing housing, in accordance with some embodiments of the present disclosure;

[0023] FIG. **13** shows a cross-sectional view of an illustrative translator and bearing housing, in accordance with some embodiments of the present disclosure;

[0024] FIG. **14** shows a block diagram of an illustrative LEM system, in accordance with some embodiments of the present disclosure;

[0025] FIG. **15** shows a cross-sectional side view of an illustrative generator assembly, in accordance with some embodiments of the present disclosure;

[0026] FIG. **16** is a flowchart showing an illustrative process for operating a linear generator having gas bearings, in accordance with some embodiments of the present disclosure; and

[0027] FIG. **17** shows a side cross-sectional side view of a portion of an illustrative generator assembly having a bearing structure, in accordance with some embodiments of the present disclosure.

DETAILED DESCRIPTION

[0028] The present disclosure is applicable towards bearing mounting structures for linear generators. Linear generators may include stators, translators, cylinders, manifolds, pistons, sealing ring assemblies, bearings, sensors, any other suitable components, or any suitable combination thereof. For example, a linear generator may include one or more linear electromagnetic machines (LEMs) formed by respective translator/stator pairs, which are aligned using the bearing structures of the present disclosure. For example, in some embodiments, the bearing mounting structures are configured to: [0029] (i) be axially stiff enough to avoid resonance from high axial excitation; [0030] (ii) be radially stiff enough to securely align a translator to a cylinder and a stator (e.g., overcoming magnetic forces); [0031] (iii) provide enough compliance (e.g., in yaw and pitch) to allow a relatively low-stiffness air film (e.g., a gas bearing) to align the bearing housing to the translator tube axis without consuming too much of the bearing housing's load-carrying capacity; [0032] (iv) permit the bearing sleeve (e.g., of a bearing housing) to thermally expand and contract without distorting the bearing bore (e.g., an outer bearing surface) in a way that could lead to reduced air film capacity (e.g., gas bearing capacity) or binding of the translator tube; [0033] (v) permit the bearing sleeve (e.g., of the bearing housing) to be removed and replaced in the field (e.g., should a failure occur or a replacement sleeve design be installed); [0034] (vi) keep the overall structure lightweight enough to not have axial or rotational excitation modes that can be significantly excited by the shaking of the linear generator (e.g., during operation); [0035] or a combination thereof (e.g., any or all of (i)-(vi)).

[0036] FIG. **1** shows a cross-sectional view of illustrative LEM **100**, in accordance with some embodiments of the present disclosure. LEM **100** includes translator **160**, stator **150**, bearing housings **102** and **104**, mounting assemblies **103** and **105** (e.g., flexures including hinges, plates, hubs, and/or any other suitable components), features **123-126** (e.g., tubes, ports, fittings, or a combination thereof to receive bearing gas from a gas supply), and bearing interfaces **112** and **114**. Translator **160** includes tube **162** and section **163** configured to interact electromagnetically with stator **150**. For example, section **163** (also referred to as an "electromagnet section" or "magnet section") may include a magnet section having permanent magnets, electromagnets, an induction section, or a combination thereof. Although referred to as a tube, tube **162** may have any suitable cross-sectional shape, and accordingly bearing interfaces **112** and **114** may have a corresponding shape. For example, in some embodiments, tube **162** may have a rectangular cross section, and accordingly bearing interfaces **112** and **114** may be flat rather than annular. In a further example, in some embodiments, tube **162** may have at least one circular cross section for a first longitudinal distance (i.e., axial distance) and at least one rectangular cross section for a second longitudinal distance, where the first and second longitudinal distances may be equal or different.

[0037] To illustrate, stator **150** is configured to electromagnetically interact with translator **160**. At least one bearing assembly is coupled to stator **150** (e.g., LEM includes two bearing assemblies), with each bearing assembly having a plurality of flexures (e.g., of mounting assemblies **103** and **105**) that couple a sleeve (e.g., of bearing housings **102** and **104**) to stator **150**. For example, each flexure is configured to allow pitch or yaw of the sleeve, and the sleeve interfaces with translator **160**.

[0038] Stator **150** and section **163** interact electromagnetically to cause motion of translator **160**, affect motion of translator **160**, convert kinetic energy of translator **160** (e.g., based on the mass and velocity of translator **160**) to electrical energy (e.g., in windings of phases of stator **150** and, if desired, power electronics coupled thereto), convert electrical energy (e.g., in windings of phases of stator **150** and, if desired, power electronics coupled thereto) into kinetic energy of translator **160**, or a combination thereof. Motor gap **151** (as referred to as "motor air gap") between stator **150** (e.g., laminated ferrous teeth thereof) and section **163** (e.g., permanent magnets thereof) affects reluctance of the electromagnet magnetic interaction between stator **150** and translator **160**. For example, the smaller the motor gap **151** is, the larger the motor force constant (e.g., larger magnetic flux) that can be achieved between stator **150** and translator **160**. However, if motor gap **151** nears zero (e.g., at one or more locations), translator **160** may contact stator **150** causing friction, impact, deformation, electrical shorts, reduced performance, failure, or any combination thereof. Accordingly, bearings are used to maintain the lateral alignment of stator **150** and translator **160** (e.g., to maintain motor gap **151** in an operable range).

[0039] In some embodiments, as illustrated, bearing housings **102** and **104** are affixed to stator **150** by mounting assemblies **103** and **105**. For example, rigidly affixing bearing housings **102** and **104** to stator **150** may help in counteracting lateral (e.g., radial) loads on translator **160**. In some embodiments, one or both of bearing housings **102** and **104** may be coupled to stator **150** by mounting assemblies **103** and **105**, having flexures with prescribed stiffness or compliance in one or more directions. In some embodiments, mounting assemblies **103** and **105** may be affixed to stator **150** or a stator frame thereof. In some embodiments, one or both bearing housings **102** and **104** need not be affixed to stator **150** and may be affixed to any other suitable stationary component (e.g., an external frame). In some embodiments, only one bearing housing (e.g., bearing housing **102** or bearing housing **104**) is needed. To illustrate, the cantilever mounting of the bearing housing to support the translator may provide minimal constraints on the translator, which provides more tolerance to misalignments.

[0040] In some embodiments, one or both bearing interfaces **112** and **114** are configured as contact bearings. In some embodiments, one or both bearing interfaces **112** and **114** are configured as non-contact bearings. In some embodiments, one or both bearing interfaces **112** and **114** are configured as gas bearings (e.g., a type of non-contact bearing). In some such embodiments, one or both bearing housings **102** and **104** are configured to receive bearing gas from features **123-126**, which may include respective ports for receiving respective bearing gas supplies. For example, referencing a tubular geometry, each of bearing housings **102** and **104** may include a bearing surface arranged at a radially inward surface, configured to interface with respective annular gas bearings in bearing interfaces **112** and **114**. Tube **162** may include a cylindrical bearing surface configured to interface with annular bearing interfaces **112** and **114**. During operation, bearing interfaces **112** and **114** allow translator **160** to move along axis **190** with low or near-zero friction, and prevent substantial lateral (e.g., radial) motion off from axis **190**. For example, bearing interfaces **112** and **114** may be configured to maintain motor air gap **151** between stator **150** (e.g., iron stator teeth and copper windings thereof) and section **163** during operation. It will be understood that bearing interfaces **112** and **114**, and motor air gap **151** may respectively have any suitable thickness. For example, in general the thicknesses are preferred to be as thin as possible while ensuring reliable operation. In some embodiments, bearing interfaces **112** and **114** are configured to be 20-150 microns thick and motor air gap **151** is configured to be 20-40 mm thick.

[0041] In an illustrative example, in which bearing interfaces **112** and **114** are configured as gas bearings, bearing gas is configured to exit bearing housings **102** and **104** (e.g., to form respective gas bearings in bearing interfaces **112** and **114**) in a substantially radially inward direction (i.e., streamlines directed towards axis **190**). Bearing gas may flow through porous sections of bearing housings **102** and **104**, ducts and orifices within bearing housings **102** and **104**, or a combination thereof, to reach respective bearing interfaces **112** and **114**.

[0042] In some embodiments, bearing housings **102** and **104** may include a coating, a consumable layer, a dry film lubricant, an abradable coating, or a combination thereof, at corresponding bearing surfaces to accommodate, for example, contact with translator **160** while limiting or avoiding damage to the translator, bearing housing, or both. In some embodiments, translator **160** may include a coating, a consumable layer, a dry film lubricant, an abradable coating, or a combination thereof, to accommodate, for example, contact with bearing housings **102** and **104** while limiting or avoiding damage to the translator, bearing housing, or both. In some embodiments, a bearing housing extends fully and continuously (e.g., 360° azimuthally) around a translator. In some embodiments, a bearing housing includes one or more bearing segments that extend for an azimuthal range around a translator that is less than 360°. For example, a bearing housing may include four bearing segments, each extending about 90° around the translator, with azimuthal gaps in between the bearing segments. A bearing housing may include any suitable number of bearing segments having any suitable number of gaps, and arranged in any suitable configuration, around a translator.

[0043] In some embodiments, translator **160** may include one or more pistons or end caps (not shown in FIG. **1**) affixed to axial ends of tube **162**. For example, tube **162** may act as a rigid body coupling the pistons and other components to form a rigid translator. In a further example, LEM **100** may be included as part of a linear generator (e.g., as illustrated in FIG. **15**), in which one piston is configured to contact a reaction section and the other piston is configured to contact a gas spring. Although section **163** is illustrated in FIG. **1** as being axially shorter than stator **150**, section **163** may be axially shorter, longer, or the same length as stator **150**, in accordance with some embodiments of the present disclosure. In some embodiments, whether section **163** is longer, shorter, or the same length as stator **150**, section **163** or portions thereof may be capable of being positioned axially outside of stator **150** (e.g., axially beyond ends of stator **150**).

[0044] In an illustrative example, the bearing structures (e.g., mounting assemblies **103** and **105**, and bearing housings **102** and **104** thereof) must be axially stiff enough such that large axial vibrations do not excite the bearing structure's axial mode, which may lead to unstable air films and contact between the translator and the opposing bearing surface. In some embodiments, an axially stiff bearing structure allows an encoder to be mounted directly to the bearing structure. For example, in some embodiments, the bearing structure provides a preferred location to best control the radial distance between a translator encoder tape and an encoder read head (e.g., an optical or magnetic linear encoder read head coupled to control circuitry).

[0045] In a further illustrative example, the bearing structures must be radially stiff in order to hold the translator securely in alignment to the stator (e.g., a primary function of the bearing structure), power cylinder, air spring cylinder, or a combination thereof. To illustrate, magnets mounted around the outer diameter of the translator provide a radial force on the translator toward the stator, adding to forces caused by the mass of the translator, forces due to vibration, and the cyclic radial component of force due to power cylinder reaction and air spring pressure, or a combination thereof.

[0046] In a further illustrative example, manufacturing tolerances within LEM components can result in conditions wherein two bearings need to operate in conditions where they are not perfectly perpendicular to their mounting faces or each other. To illustrate, this circumstance may occur under static conditions due to part and assembly tolerances, and under dynamic conditions (e.g., during operation) due to translator straightness (e.g., or deviations thereof). In some embodiments, the bearing structures include hinges that allow the bearing structures to adjust in yaw and pitch and accommodate tolerances, yet remain stiff in radial and axial positioning to maintain proper system alignment.

[0047] In some embodiments, the bearing structures of the present disclosure are configured to operate at temperatures between −40° C. and 120° C. (e.g., during operation). To illustrate, this relatively large range of operating temperature means the mounting components of the bearing structure must allow for thermal expansion without constraining the inner sleeve of the bearing housing in a way that the inner diameter size or shape is significantly affected (e.g., the bearing surface is not significantly affected).

[0048] In addition to the hinges of the present disclosure, other approaches may be combined or included to form a bearing structure for a gas bearing. In some embodiments, for example, alternative bearing structures may include a flexible disc to allow for yaw and pitch through flex on the disc, a pad with a ball joint to allow the pad to pivot into proper alignment position or if radial load is light, O-rings used as a flexible mounting system, any other suitable component, or any combination thereof. To illustrate, a flexible disc design may create a two-point constraint on the bearing during thermal expansion, which may cause the bearing to ovalize significantly as it warms up and may lead to contact between the translator and bearing surface as the air film (e.g., the gas bearing) becomes unstable. To illustrate further, some flexible disc designs exhibit relatively low axial stiffness, which may cause the bearing structure to resonate axially and may lead to contact between the translator and the outer bearing surface as well as cause control issues (e.g., if an encoder is mounted directly to the bearing). In a further example, ball joints and O-rings may structurally degrade, bind up, or creep in a high-load, extreme temperature-dynamic environment and might not provide a robust and service-free solution, in addition to having a greater likelihood of imposing a radial thermal constraint on the bearing sleeve as it heats up.

[0049] FIGS. **2-11** illustrate an illustrative assembly configured to provide a bearing structure, in accordance with some embodiments of the present disclosure. As illustrated, bearing structure **200** includes front plate **202**, support block **204**, flexures **211-214** (e.g., each including a hinge and mounting features), hubs **221-224**, sleeve **230** (e.g., an inner sleeve, having surface **235** and holes **236**), and sleeve **231** (e.g., an outer sleeve). It will be understood that a flexure as referred to herein refers to a component having a hinge and mounting features such as flanges.

[0050] FIG. **2** shows a perspective view of illustrative bearing structure **200**, in accordance with some embodiments of the present disclosure. Bearing structure **200** is shown separated from a LEM structure. In some embodiments, bearing structure **200** is connected to the LEM structure through the rear of either of the yaw flexures (e.g., flexures **211** and **213**) or the pitch flexures (e.g., flexures **212** and **214**), with the other set of flexures connected to front plate **202**. Axis **299** corresponds to the axial direction in polar coordinates, with the radial direction extending outward normal from axis **299**, and the azimuthal direction extending around axis **299** (i.e., normal to the axial and radial directions).

[0051] FIG. **3** shows a portion of bearing structure **200** of FIG. **2** illustrating a yaw hinge (e.g., of either flexure **211** or **213**) that mounts rigidly to (i) the front side of support block **204** (e.g., illustrated as transparent for clarity) and, (ii) at another end bolts to a stator structure (not illustrated in FIG. **3**), in accordance with some embodiments of the present disclosure. As illustrated, for each yaw flexure (e.g., flexures **211** and **213**), one axial end mounts rigidly to the front side of support block **204** (e.g., axially outboard relative to the stator), while the other axial end bolts to the stator structure (e.g., axially inboard relative to the stator). As illustrated, flexure **211** includes mounting features **270** and **272** (e.g., flanges with holes for affixing), and hinge **271** configured to exhibit a predetermined stiffness against displacement accordingly to various degrees freedom, with a reduced stiffness corresponding to at least one degree of freedom. The view of FIG. **3** is taken along direction **298** shown in FIG. **2**. Gap **273** exists between flexure **211** and front plate **202**, as flexures **211** and **213** (i.e. comprising the yaw hinge) are not affixed to front plate **202** but rather to the stator assembly (e.g., and support block **204**).

[0052] FIG. **4** shows a portion of the bearing structure of FIG. **2** illustrating a pitch hinge (e.g., of either flexure **212** or **214**) that mounts rigidly to the rear of support block **204**, and then bolts rigidly to front plate **202**, in accordance with some embodiments of the present disclosure. To illustrate, flexures **212** and **214** include respective pitch hinges that are mounted rigidly to the rear of support block **204**, and also rigidly affixed (e.g., by bolts) to front plate **202**. To illustrate, hubs **221-224** (e.g., L-shaped hub sections) extend (e.g., axially at least) through support block **204** without touching support block **204**, and mount rigidly to front plate **202** (e.g., through features thereof to accommodate the hub sections) and also mount to sleeve **230** (e.g., by bolts, as illustrated). Only hub **222** is shown in the view of FIG. **4**. As illustrated, flexure **212** includes mounting features **280** and **282** (e.g., flanges with holes for affixing), and hinge **281** configured to exhibit a predetermined stiffness against displacement accordingly to various degrees freedom, with a reduced stiffness corresponding to at least one degree of freedom. The view of FIG. **4** is taken along direction **297** shown in FIG. **2**. Flexures **212** and **214** are affixed to front plate **202** (e.g., and support block **204**) rather than to the stator assembly, forming pitch hinges. Note that each of flexures **211-214** may include a hinge such as hinge **271** or **281**, which may be the same. Similarly, each of flexures **211-214** may include mounting features such as mounting features **270** and **272**, or **280** and **282**, which may be the same.

[0053] FIG. **5** shows a portion of bearing structure **200** of FIGS. **2-4** arranged as part of a linear generator (e.g., with some components hidden for purposes of illustration), in accordance with some embodiments of the present disclosure. The stator assembly includes stator **250**, stator mounts (e.g., stator mounts **251** and **252**, which may be features of a single component **259** or separate components), and stator couplings (e.g., stator couplings **255** and **256**).

[0054] As illustrated in aspects of FIGS. **2-5**, four individual hubs **221-224** (e.g., L-shaped hub sections also referred to herein as “hubs”) mount to one axial end of sleeve **230** using eight fasteners as illustrated (e.g., fasteners **225**). The “L” shape allows for compliance as bearing structure **200** expands diametrically but provides a rigid connection to axial and radial loads (e.g., for axial and radial loading). Since hubs **221-224** are four individual pieces, they provide a minimal or otherwise reduced amount of constraint when compared to a single-piece part. In some embodiments, hubs **221-224** may behave similarly to “expansion” hinges (e.g., axial expansion, lateral or radial expansion), while still providing sufficient radial stiffness. Hubs **221-224** extend through support block **204** and mount to front plate **202**, providing them more length (e.g., axial length) to enable this expansion compliance.

[0055] Two pairs of flexures **211-214** are mounted around sleeve **230** (e.g., azimuthally spaced) to provide yaw and pitch compliance and allow bearing structures to accommodate fixed manufacturing and assembly tolerances without over-constraining the assembly. As illustrated in FIGS. **2-5**, the top and bottom flexures (e.g., flexures **211** and **213**) provide yaw compliance between the bearing sleeve and the stator, while the left and right flexures (e.g., flexures **212** and **214**) provide pitch compliance. Flexures **211-214** also allow the bearing assembly (e.g., bearing structure **200**) to accommodate changing straightness (e.g., of an imperfect translator **260**, which may arise from machining or thermal variations). In some embodiments, each of flexures **211-214** includes a hinge that provides flex (e.g., reduced stiffness in at least one degree of freedom) without significant wear or maintenance. The shape and assembly position of each flexure is such that the part provides significant radial and axial stiffness while providing a low bending stiffness. In an illustrative example, a bearing structure may include four flexures that include two pitch hinges (e.g., arranged at the right and left), and two yaw hinges (e.g., arranged at the top and bottom). To illustrate, in some embodiments, the pitch hinges couple the front plate and the support block, while the yaw hinges couple the support block and the stator assembly. In a further example, a bearing structure may include N flexures (e.g., where N is an integer two or greater), arranged azimuthally about a sleeve, and configured to provide compliance in a degree of freedom (e.g., which may be, but need not be, pitch and yaw). For example, flexures can be arranged clocked 45° from that illustrated, or a non-multiple of four may be included (e.g., six flexures).

[0056] Support block **204** and front plate **202** provide radial stiffness to the assembly, while still permitting the hinge elements (i.e., of flexures **211-214**) to pitch, yaw, expand, or a combination thereof. The yaw flexures (e.g., flexures **211** and **213** located at top and bottom in FIG. **2**) may mount directly to the stator structure (e.g., to stator mounts **251** and **252** of FIG. **5**), as well as the support block **204**. As shown in FIG. **5**, a linear generator may include translator **260** and stator **250**, which form a LEM, and bearing structure **200** may be coupled to stator **250** (e.g., using a stator mount thereof such as stator mounts **251** and **252**) to maintain alignment of translator **260**, provide stiffness against off-axis displacement, allow some displacement in some degrees of freedom, resist forces, maintain a motor air gap, prevent contact of translator **260** with other components, or a combination thereof. In some embodiments, component **259** is coupled to stator **250** by stator couplings **255** and **256**, and component **259** includes stator mounts **251** and **252**. For example, component **259** may be a single assembly or component that includes stator mounts **251** and **252** and is bolted or otherwise affixed to stator **250** by one or more stator couplings (e.g., stator couplings **255** and **256**). Bearing housing **239** includes sleeves **230** and **231**, which may seal together using O-rings, gaskets, sealant, any other suitable seal, or any combination thereof. It will be understood that in some embodiments, a bearing structure may be included at each axial end of stator **250** (e.g., two bearing structures coupled to the stator), to constrain a trajectory of translator **260** (e.g., as illustrated in FIG. **1**).

[0057] FIG. **6** shows a perspective view of some components of bearing structure **200**, in accordance with some embodiments of the present disclosure. FIG. **7** shows another perspective view of some components of bearing structure **200**, in accordance with some embodiments of the present disclosure. The partial assembly of FIG. **6** shows hubs **221-224**, sleeve **230**, and flexures **211**, **213**, and **214** (e.g., flexure **212** is not visible in FIG. **6**). Sleeve **230** mounts to hubs **221-224**, which may be capable of flexing (e.g., are cantilevered) to allow thermal expansion but can be considered as rigid bodies in comparison to the hinges. Hubs **221-224** (e.g., L-shaped expansion hubs), in turn, bolt onto or are otherwise affixed to front plate **202**. To illustrate, this assembly (except the hinges) can be thought of as a rigid body that articulates in pitch and yaw via the hinges. In some embodiments, sleeve **231** (e.g., an outer sleeve, not shown in FIG. **6**) forms one or more gas passages **237** for providing gas to a gas bearing adjacent to surface **235** of sleeve **230**.

[0058] The pitch hinge(s) (e.g., flexures **212** and **214**) mounts directly to front plate **202** at its front (e.g., axially farther from stator **250**) and to support block **204** (not shown in FIGS. **6-7**) at its rear (e.g., proximal to stator **250**). Accordingly, pitch of front plate **202**, and hence sleeve **230**, occurs relative to support block **204** (not shown in FIGS. **6-7**). To illustrate, front plate **202** can pitch relative to support block **204**. However, if support block **204** rotates in yaw, front plate **202**, and hence sleeve **230**, may move with it. As shown in FIG. **6**, flexures **211-214** are I-shaped such that they flex in bending to allow articulation of the bearing assembly in pitch or yaw. Notably, the pitch flexures (e.g., flexures **212** and **214**) are stiff enough to hold the bearing assembly against gravity without appreciable deflection, as in some embodiments, the pitch flexures (e.g., flexures **212** and **214** that are diametrically opposed) support the entire weight of the bearing assembly.

[0059] FIG. **8** shows a perspective view of some components of bearing structure **200**, centered on flexure **214**, in accordance with some embodiments of the present disclosure. The partial assembly of FIG. **8** shows front plate **202**, support block **204**, flexure **214** only (e.g., a pitch hinge), hub **221** only, and sleeve **230**. Flexure **214** (e.g., having a pitch hinge) mounts directly and rigidly to front plate **202** and to support block **204**. As illustrated, the pitch hinge(s) passes through the axial front (e.g., axially away from stator **250**) of support block **204** and mounts to front plate **202** (e.g., but not the stator assembly).

[0060] FIG. **9** shows a side view of some components of bearing structure **200**, in accordance with some embodiments of the present disclosure. As illustrated, unlike flexure **214** (e.g., having the pitch hinge), flexure **211** (e.g., having the yaw hinge(s)) does not itself connect to front plate **202** (e.g., gap **273** is at the interface).

[0061] FIG. **10** shows a side view of a portion of bearing structure **200** arranged as part of a stator assembly, in accordance with some embodiments of the present disclosure. As illustrated, flexures **211** and **213** (e.g., designated as yaw hinges) mount (i) to the end bell of stator mount **251** (e.g., of component **259**), which is hard mounted to stator **250** at an axial inboard side (e.g., a rear side) and also (ii) to support block **204** at its (axially) front end. Flexures **211** and **213** (e.g., having yaw hinges) do not mount to front plate **202** because this would over-constrain pitch. To illustrate, front plate **202** can pitch independent of support block **204**. Flexures **211** and **213** (e.g., having yaw hinges) pass through the back of support block **204** (e.g., with clearance for flexing) and also mount to the front of support block **204**.

[0062] FIG. **11** shows a side view of a portion of bearing structure **200** arranged as part of a stator assembly, with a load path indicated to illustrate the connectivity of the various components, in accordance with some embodiments of the present disclosure. As illustrated by the dashed line in FIG. **10**, the load path from the stator to the sleeve **230** (bearing) includes: [0063] A-B: stator mount **251** (e.g., an end bell of the LEM) to flexure **211** (e.g., a yaw flexure); [0064] B-C: flexure **211** to front of support block **204**; [0065] C-D: support block **204** to rear of flexure **214** (e.g., a pitch flexure); [0066] D-E: flexure **214** to front plate **202**; [0067] E-F: front plate **202** to the front of hub **221**; [0068] F-G: within hub **221** front to rear (axially); and [0069] G-H: rear of hub **221** to sleeve **230**.

[0070] The deflection of the arrangement of FIGS. **2-11** may be further described with reference to three states of deflection: (i) yaw-only, (ii) pitch-only and (iii) combined pitch and yaw. In yaw-only deflection, for example, support block **204** rotates in yaw relative to stator mount **251** based on bending deflection of flexures **211** and **213** (e.g., yaw flexures), which is are attached between stator mount **251** and the front of support block **204**. The front plate **202**, being attached to support block **204** via the pitch flexures **212** and **214**, articulates along with the support block **204** (e.g., staying parallel to support block **204**) because, in this illustrative scenario, the pitch flexures are not in bending deflection. As such, sleeve **230**, being attached to the front plate **202** via relatively rigid hub **221**, articulates to the same degree of yaw as support block **204**.

[0071] In pitch-only deflection, for example, support block **204** remains in plane, that is, flexures **211** and **213** (e.g., yaw flexures) are not in bending deformation. However, front plate **202** may articulate in pitch based on deflection of flexures **212** and **214** (e.g., yaw flexures), which attach between front plate **202** and support block **204**, and which, in this scenario, is not deflected. As such, sleeve **230**, being attached to front plate **202** via relatively rigid hub **221**, articulates to the same degree of pitch as front plate **202**.

[0072] In combined pitch and yaw deformation, for example, support block **204** articulates in yaw as described above, that is, via deformation of flexures **211** and **213**, while front plate **202** articulates in pitch, also as described above, via deformation of flexures **212** and **214**. The result is that the pitch deflection of front plate **202** is superimposed on the yaw deflection of support block **204**, resulting in a combined deflection of pitch and yaw for sleeve **230**, enabling sleeve **230** to deflect to any suitable combined angle of pitch and yaw within the elastic limits of the flexures.

[0073] FIG. **12** shows a perspective view of illustrative bearing housing **1200**, in accordance with some embodiments of the present disclosure. For example, bearing housing **1200** may be formed by one or more sleeves (e.g., sleeves **230** and **231**), which may be sealed together by O-rings, gaskets, sealant, or any other suitable seals. As illustrated, bearing housing **1200** is configured to extend azimuthally around a translator having a circular bearing surface. In some embodiments, bearing housing **1200** may include one or more azimuthal, radial, or axial pieces that may be assembled to form a complete bearing housing. As illustrated, bearing housing **1200** is configured to accommodate a gas bearing, and includes passages **1210** and flow restrictions **1220**. Passages **1210** direct and distribute flow of bearing gas within bearing housing **1200** to flow restrictions

1220. Passages **1210** may include, for example, plenums, channels, manifolds, filters, drilled holes, machines recesses, flow control features, ports for sensors (e.g., to sense bearing gas pressure, flow or temperature), ports for receiving a supply of bearing gas, ports for removing condensate (e.g., condensed water, oil, or other condensed fluids), any other suitable features, or any combination thereof. Flow restrictions **1220** are configured to provide the bearing gas to the bearing interface (e.g., a bearing gap) at bearing bore **1230**. Flow restrictions **1220** provide bearing gas at a desired pressure and flow rate to the gas bearing, which provides lateral stiffness to off-axis motion of the translator. Flow restriction **1220** may include, for example, orifices, porous sections, or both, or any other suitable flow-restricting features. For example, in some embodiments, flow restrictions **1220** include an array of orifices along bearing bore **1230**. In some embodiments, flow restrictions **1220** include a thickness of porous material along bearing bore **1230**. In some embodiments, bearing housing **1200** may include a coating, a consumable layer, a dry film lubricant, an abradable coating, or a combination thereof, at bearing bore **1230** to accommodate, for example, contact with a translator.

[0074] Although bearing housing **1200** is shown in FIG. **12** as having a cylindrical bearing bore **1230**, a bearing housing may include any suitable surface for creating a bearing interface. For example, a bearing housing may include a semi-circular surface, a flat surface, a non-circular curved surface, a piecewise flat or curved surface, any other suitable continuous, piecewise, or segmented surface, or any combination thereof. For example, a bearing housing may include more than one cylindrical surfaces, separated axially, for forming respective bearing interfaces. In a further example, a LEM may include, at a particular axial region, a set of three, four, or more bearing housings having flat surfaces and forming respective bearing interfaces with corresponding flat surfaces of a translator (e.g., a translator having a triangular, rectangular, or other polygonal cross-section). In some embodiments, a bearing housing need not include passages **1210** or flow restrictions **1220**. For example, a bearing housing may be configured as a contact slide bearing, with a low-friction coating applied at bearing bore **1230**.

[0075] FIG. **13** shows cross-sectional view of translator **1300** and bearing housing **1350**, in accordance with some embodiments of the present disclosure. In some embodiments, bearing housing **1350** may include one or more reliefs **1304** to accommodate rail **1316** during axial motion of translator **1300** (e.g., when rail **1316** is axially coincident or otherwise overlapping with bearing housing **1350**). As shown in FIG. **13**, gas bearing **1301** arranged radially between bearing housing **1350** and translator **1300** does not extend into one or more reliefs **1304**. In some embodiments (not shown), a gas bearing arranged radially between bearing housing **1350** and translator **1300** does extend into one or more reliefs **1304**. In some embodiments, bearing housing **1350** is of clamshell-type construction, as illustrated, wherein two components mate together to form the complete bearing housing **1350**, as shown in FIG. **13**. In some embodiments, a bearing housing may be constructed of a single azimuthally continuous housing (e.g., as illustrated in FIG. **12**). It should be noted that for clarity and case of illustration the drawings of the present patent application are not necessarily drawn to scale and do not reflect the actual or relative size of each feature. A bearing housing may be any suitable shape such as, for example, round, rectangular, polygonal, curved, or any other shape including a single segment or more than one segment. Although shown as cylindrical in the present disclosure, a translator “tube” may include any suitable cross-sectional shape or cross-sectional shape profile along its axial length. For example, a translator tube may include an outer surface that is a bearing surface, and the bearing surface may be flat, round, curved, segmented, or any other suitable profile at which a bearing gap may be formed to contain a gas bearing.

[0076] FIG. **14** shows a block diagram of illustrative LEM system **1400**, in accordance with some embodiments of the present disclosure. LEM system **1400**, as illustrated, includes control system **1410**, power electronics **1420**, cooling system **1421**, sensors **1411**, stator **1450**, translator **1460**, bearing housings **1430** and **1431**, bearing gas management system **1480**, and bearing gas supply

1490. Components of LEM system **1400** are coupled, as illustrated, by a gap interface, signal interface, flow interface, mechanical interface, phase lead interface, or a combination thereof. For example, translator **1460** is coupled to stator **1450** by a gap interface (e.g., a motor air gap), bearing housing **1430** by a gap interface (e.g., a bearing interface such as a gas bearing), and bearing housing **1431** by a gap interface (e.g., a bearing interface such as a gas bearing).

[0077] Control system **1410** is configured to interface with (e.g., provide control signals to, receive feedback from) power electronics **1420** to control currents in phases of stator **1450**. Power electronics **1420** is coupled to stator **1450** by a plurality of phase leads, which may include lengths of electrically conductive material, electrical terminals and terminations, connectors, sensors (e.g., current sensors), any other suitable components, or any combination thereof. Control system **1410** is configured to interface with (e.g., provide control signals to, receive feedback from) cooling system **1421** to control cooling of stator **1450** (e.g., to remove heat from windings, stator teeth, hoops, or a combination thereof). For example, cooling system **1421** may include one or more cooling jackets, plenums, manifolds, pumps, compressors, filters, sensors, any other suitable components, or any combination thereof. In a further example, cooling system **1421** may exchange heat and fluid with a reservoir (e.g., the environment provides cooling air and accepts heated air). In a further example, control system **1410** may be communicatively coupled to cooling system **1421** and is configured to provide a control signal to cooling system **1421** to cause heat removal from a plurality of windings of stator **1450**. Control system **1410** is configured to interface with (e.g., provide control signals to, receive sensor signals from) sensors **1411**, which may include, for example, temperature sensors, pressure sensors, vibration sensors, position sensors, current sensors, voltage sensors, any other suitable sensors, or any combination thereof.

[0078] Bearing housings **1430** and **1431** may include any suitable number and type of bearing housing, in accordance with the present disclosure. As illustrated, bearing housings **1430** and **1431** are configured for gas bearings (e.g., using bearing gas management system **1480** and bearing gas supply **1490**), although a LEM system may include any suitable type of bearing (e.g., contact or non-contact). In some embodiments, one or more sensors are coupled to each of bearing housings **1430** and **1431**, configured to sense, for example, bearing gas pressure, bearing gas temperature, bearing gas flow rate, bearing housing acceleration (e.g., an accelerometer may be affixed to a bearing housing to measure vibration), bearing housing temperature, any other suitable property or behavior, or any combination thereof.

[0079] Bearing gas management system **1480** is configured to control at least one aspect of respective bearing gas provided to bearing housings **1430** and **1431**. For example, bearing gas management system **1480** may include one or more filters, compressors, pumps, pressure regulators, valves, sensors, any other suitable components, or any combination thereof for providing bearing gas to bearing housings **1430** and **1431**. For example, control system **1410** is configured to interface with (e.g., provide control signals to, receive feedback from) bearing gas management system **1480** for controlling at least one property of the bearing gas. In a further example, control system **1410** is configured to interface with (e.g., provide control signals to, receive feedback from) bearing gas management system **1480** for controlling a stiffness of the bearing interface (e.g., to lateral displacement of translator **1460**) between translator **1460** and bearing housings **1430** and **1431**. Bearing gas supply **1490** may include one or more filters, compressors, pumps, pressure regulators, valves, sensors, any other suitable components, or any combination thereof for providing bearing gas to bearing gas management system **1480**. In some embodiments, bearing gas management system **1480** and bearing gas supply **1490** may be combined as a single system. In some embodiments, bearing gas supply **1490** need not be included (e.g., bearing gas management system **1480** may intake atmospheric air).

[0080] In some embodiments, stator **1450** includes a plurality of coils and an axis; translator **1460** is arranged to move axially along the axis; and bearing housing **1430**, bearing housing **1431**, or both are coupled to stator **1450** to constrain lateral motion of translator **1460**. For example, the coils include windings that interface with a plurality of stator teeth that define an axis (e.g., an axis of a stator bore). In some such embodiments, control system **1410** is configured to control axial displacement of translator **1460**, and control lateral displacement of translator **1460**. For example, bearing housing **1430**, bearing housing **1431**, or both, and translator **1460** form a bearing interface, and control system **1410** is configured to control a stiffness of the bearing interface against the lateral displacement of translator **1460**. In an illustrative example, the bearing interface may include a gas bearing interface configured for oil-less operation (e.g., without the use of liquid lubricant).

[0081] In some embodiments, bearing gas management system **1480** is configured to provide a pressurized gas to the bearing interface. In some such embodiments, control system **1410** is communicatively coupled to bearing gas management system **1480** and is configured to provide a control signal to bearing gas management system **1480** to cause the pressurized gas to be provided to the bearing interface. For example, control system **1410** may cause bearing gas management system **1480** to control a property of the pressurized gas to control the lateral stiffness to lateral displacement of the translator. To illustrate, bearing gas management system **1480** may provide a pressurized gas to the bearing gap by opening a valve. To further illustrate, bearing gas management system **1480** may provide pressurized gas by controlling a valve, a pressure regulator, or both. Bearing gas may be provided by a compressor, a driver section, any other suitable source of pressurized gas, or any combination thereof.

[0082] In some embodiments, power electronics **1420** are coupled to a plurality of windings of stator **1450**. Control system **1410** is communicatively coupled to power electronics **1420** and is configured to provide a control signal to power electronics **1420** to cause electrical current to flow in at least one winding of the plurality of windings to control the axial displacement of translator **1460**.

[0083] In some embodiments, one or more sensors of LEM system **1400** include a position sensor that senses an axial position of translator **1460** relative to stator **1450**. In some such embodiments, control system **1410** is communicatively coupled to the sensor (e.g., of sensors **1411**) and is configured to cause electrical current to flow in the plurality of windings of stator **1450** based on the axial position of translator **1460**. In some embodiments, control system **1410** is configured to estimate an axial position of translator **1460** relative to stator **1450** and cause electrical current to flow in the plurality of windings of stator **1450** based on the axial position of translator **1460**.

[0084] In some embodiments, translator **1460** includes at least one rail having a rail surface. System **1400** may optionally include at least one anti-clocking bearing housing (e.g., bearing housing **1432**) coupled to stator **1450** and configured to constrain azimuthal motion of translator **1460**, wherein anti-clocking bearing housing **1432** and the rail surface form a rail interface. For example, control system **1410** is configured to cause the rail interface to achieve a stiffness against azimuthal motion of the translator.

[0085] In some embodiments, bearing housing **1430** is arranged on a first longitudinal side of stator **1450** to constrain the lateral motion of translator **1460** at the first longitudinal side of stator **1450**, and bearing housing **1431** is arranged on a second longitudinal side of stator **1450** to constrain the lateral motion of translator **1460** at the second longitudinal side of stator **1450**.

[0086] In some embodiments, control system **1410** is configured to control a LEM by causing electric current to flow in at least one winding of a plurality of windings of a stator to apply a force on a translator along a longitudinal axis of the stator, and controlling lateral stiffness to lateral displacement of the translator arranged to move along a longitudinal axis of the stator. For example, the translator and the stator may form a motor air gap, and the lateral stiffness provided by the bearings is capable of maintaining the motor air gap in an operable range. For example, causing electric current to flow in at least one winding may include providing a control signal to power electronics **1420** that are electrically coupled to the plurality of windings.

[0087] In some embodiments, control system **1410** is configured to monitor a property of the bearing gas, bearing housing, or both, for a fault condition and, in response to an identification of the fault condition, brake translator **1460**. For example, control system **1410** may brake translator **1460** by causing power electronics **1420** to apply currents to phases of stator **1450** that cause a force on translator **1460** that oppose motion of translator **1460** (e.g., thus reducing a velocity of, or even stopping, translator **1460**). To illustrate, control system **1410** may monitor a mass flowrate of bearing gas, a pressure of bearing gas, a temperature of bearing gas, a temperature of a bearing housing, a vibration of a bearing housing, a force load on a bearing housing, a translator position trajectory, or a combination thereof.

[0088] FIG. **15** shows a cross-sectional view of illustrative generator assembly **1500**, in accordance with some embodiments of the present disclosure. Generator assembly **1500** is configured as an opposed, free-piston generator. Generator assembly **1500** includes translators **1510** and **1520**, which are configured to move along axis **1506** (e.g., translate linearly along axis **1506**). Translators **1510** and **1520** are configured to move within cylinders **1502**, **1504** and **1505**, thus forming expansion and compression volumes **1597**, **1598**, and **1599** for performing boundary work (e.g., determined using the integral ∫ PdV over a suitable range such as a stroke or cycle). For clarity, the spatial arrangement of the systems and assemblies described herein will generally be referred to in the context of cylindrical coordinates, having axial, radial, and azimuthal directions. It will be understood that any suitable coordinate system may be used (e.g., cylindrical coordinates may be mapped to any suitable coordinate system), in accordance with the present disclosure. Note that axis **1506** is directed in the axial direction, and the radial direction is defined as being perpendicular to axis **1506** (e.g., directed away from axis **1506**). The azimuthal direction is defined as the angular direction around axis **1506** (e.g., orthogonal to both axis **1506** and the radial direction, and directed around axis **1506**). As illustrated, generator assembly **1500** includes driver sections **1550** and **1558**, linear motors (e.g., LEMs) **1552** and **1556**, and central cylinder region **1554**. Axis **1507** corresponds to the center of generator assembly **1500**, about which translators **1510** and **1520** translate (e.g., in equal and opposite motions).

[0089] In some embodiments, the stationary components of generator assembly **1500** include cylinder **1502**, cylinder **1504**, cylinder **1505**, stator **1518**, stator **1528**, bearing housing **1516**, bearing housing **1517**, bearing housing **1526**, and bearing housing **1527**. In some embodiments, bearing housings **1516** and **1517** are coupled to stator **1518** (e.g., either directly connected, or coupled by an intermediate component such as a hinge, mount, or both). For example, bearing housings **1516** and **1517** may be aligned to (e.g., laterally or axially aligned), and affixed to, stator **1518** to maintain a radial air gap between magnet assembly **1513** and stator **1518**. Similarly, in some embodiments, bearing housings **1526** and **1527** are rigidly coupled to stator **1528**. In a further example, in some embodiments, bearing housing **1526** and **1527** are aligned to stator **1518**, but affixed to another portion of a generator assembly or components thereof. Each of the bearing housings may be part of bearing structure **200** or any other suitable bearing structure, and may be coupled to stators **1518** and **1528** in accordance with any of the bearing structures of the present disclosure (e.g., bearing structure **200** of FIGS. **2-11**).

[0090] Translator **1510** includes tube **1512**, piston **1511**, piston **1514**, and magnet assembly **1513**, all substantially rigidly coupled to move as a substantially rigid body along axis **1506**, relative to the stationary components. Translator **1520** includes tube **1522**, piston **1521**, piston **1524**, and magnet assembly **1523**, all substantially rigidly coupled to move as a substantially rigid body along axis **1506**. In some embodiments, magnet assemblies **1513** and **1523** may be a region of tubes **1512** and **1522**, respectively. In some embodiments, magnet assemblies **1513** and **1523** may include separate components affixed to tubes **1512** and **1522**, respectively. Reaction section **1597** is bounded by pistons **1511** and **1521**, as well as bore **1503** of cylinder **1502**. Gas springs **1598** and **1599** are bounded by respective pistons **1514** and **1524**, as well as respective cylinders **1504** and **1505**. Accordingly, as translators **1510** and **1520** move along axis **1506**, the volumes of reaction section **1597**, gas spring **1598**, and gas spring **1599** expand and contract. Further, for example, pressures within those volumes decrease or increase as the volume increases or decreases, respectively. Each of bearing housings **1516**, **1517**, **1526**, and **1527** is configured to provide a gas bearing between itself and the corresponding translator (e.g., tubes **1512** and **1522**). For example, each of bearing housings **1516**, **1517**, **1526**, and **1527** may be configured to direct pressurized gas to the gas bearing (e.g., via a flow system). In an illustrative example, each of bearing housings **1516**, **1517**, **1526**, and **1527** may be configured to direct pressurized gas having an absolute pressure greater than ambient pressure (e.g., 1 atm at sea level) to the gas bearing such that the bearing gas has sufficient pressure to flow through the gas bearing and into the environment (e.g., directly or via other ducting). In some embodiments, bearing gas may be pressurized relative to the environment (e.g., about 1 atm), a pressure in a breathing system (e.g., a boost pressure, or a gas pressure in an exhaust system that may be greater than or less than 1 atm), or any other suitable pressure reference. In some embodiments, generator assembly **1500** is configured for oil-less operation (e.g., without the use of lubricating liquids or without the use of solid-to-solid contact bearings), with bearing housings **1516**, **1517**, **1526**, and **1527** forming gas bearings against translators **1510** and **1520**. Cylinder **1502** includes bore **1503**, which houses compression section **1597**. Cylinder **1502** also includes illustrative ports **1519** and **1529**, which couple bore **1503** to the outside of cylinder **1502** to allow fluid exchange.

[0091] Stator **1518**, magnet assembly **1513**, tube **1512**, and bearing housings **1516** and **1517** form linear electromagnetic machine (LEM) **1556**. Similarly, stator **1528**, magnet assembly **1523**, tube **1522**, and bearing housings **1526** and **1528** form LEM **1552**. Further, a LEM may optionally include one or more pistons affixed to the translator. For example, a LEM may be defined to include stator **1518**, translator **1510**, and bearing housings **1516** and **1517**. In a further example, a LEM may be defined to include stator **1528**, translator **1520**, and bearing housings **1526** and **1527**. A LEM includes a stationary assembly (e.g., a stator and bearing housings) and a translating assembly (e.g., a translator) that is constrained to move along an axis, wherein the stator is capable of applying an electromagnetic force on the translator to cause and/or effect motion along the axis. The bearing housings of a LEM may be, but need not be, affixed to the stator. For example, the bearings housings may be coupled to the stator, a structural frame, a cylinder, either directly or by one or more intervening components, or any combination thereof. Stators **1518** and **1528** may include a plurality of phase windings, which form a plurality of phases. The current in each of the phases may be controlled by a control system (e.g., which may include corresponding power electronics and processing equipment) to affect the position of translators **1510** and **1520** or motion of translators **1510** and **1520** or work interactions with translators **1510** and **1520**, or any combination thereof. In some embodiments, magnet assemblies **1513** and **1523** include permanent magnets arranged in an array (e.g., of alternating North and South poles). Because translators **1510** and **1520** move as substantially rigid assemblies, electromagnetic forces applied to respective magnet assemblies **1513** and **1523** accelerate and decelerate translators **1510** and **1520**. In some embodiments, stators **1518** and **1528** may be air-cooled (e.g., by an air cooling system), liquid-cooled (e.g., by a liquid cooling system), or both. In some embodiments, stators **1518** and **1528** are arranged around respective translators **1510** and **1520**, or respective magnet assemblies **1513** and **1523** thereof (e.g., the motor air gap is arcuate with a thickness profile). For example, stators **1518** and **1528** may extend fully around (e.g., 360° azimuthally around) or partially around (e.g., having azimuthally arranged segments and azimuthally arranged gaps between windings of a phase) respective translators **1510** and **1520**. In some embodiments, stators **1518** and **1528** are arranged axially along respective translators **1510** and **1520**, or respective magnet assemblies **1513** and **1523** thereof. For example, magnet assemblies **1513** and **1523** may include flat magnet sections, and stators **1518** and **1528** may include flat surfaces that correspond to the magnet sections (e.g., the motor air gap is planar with a thickness profile). In some embodiments, stators **1518** and **1528** extend axially along respective translators **1510** and **1520**, or respective magnet assemblies **1513** and **1523** thereof.

[0092] FIG. **16** is a flowchart showing illustrative process **1600** for operating a linear generator having gas bearings, in accordance with some embodiments of the present disclosure.

[0093] Step **1602** may include providing stiffness against pitch using a plurality of flexures, having hinges, that couple a stator assembly to a bearing sleeve, which provides gas to a bearing surface of the bearing sleeve to form a gas bearing between the bearing surface and a surface of a translator, and maintaining a motor air gap using the gas bearing.

[0094] Step **1604** may include providing stiffness against yaw using a plurality of flexure(s) that couple a stator assembly to a bearing sleeve. In some embodiments, a linear generator, or LEM thereof may include two bearing structures, each having a plurality of flexures for managing pitch and yaw stiffness.

[0095] Step **1606** may include providing gas (e.g., bearing gas such as air) to each bearing structure (e.g., by providing the gas to passages formed by the bearing sleeve and an outer sleeve) to form a gas bearing between respective bearing surfaces and the translator.

[0096] Step **1608** may include maintaining a motor air gap. For example, the bearing structure provides a surface to form a gas bearing, which applies force on the translator to in the lateral plane (e.g., to constrain lateral displacement, thus maintaining the motor air gap).

[0097] Step **1610** may include operating a linear generator or other suitable linear device. For example, step **1610** may include applying current to one or more phases of a stator (e.g., to apply force on a translator), providing pressurized bearing gas to a gas bearing, sensing one or more operating characteristics (e.g., translator position, bearing gas pressure, any other suitable characteristics), any other suitable action, or any combination thereof.

[0098] To illustrate, the bearing structures of the present disclosure may exhibit or achieve any or all of the following: [0099] (i) elimination of thermal-pinch-related bearing failures, where a disc hinge or other designs (e.g., not using the L-bracket hub sections), may have issues with thermal over-constraint; [0100] (ii) reduced-amplitude axial vibrations on the encoder signal, at a high enough frequency that they can be safely discarded from control algorithms; [0101] (iii) long-term robustness and reliability over thousands of hours of operation and hundreds of startups and shutdowns; [0102] (iv) an ability to enable in-situ bearing sleeve replacements; and [0103] (v) large axial stiffness that provides an ability to achieve “air-off startups” where the bearings are permitted to rub very briefly while the system (e.g., linear generator) pumps itself up to an operating pressure. Designs with lower axial stiffness and/or “stiction” in a self-aligning joint could have more trouble operating in this mode (e.g., during startup).

[0104] FIG. **17** shows a side cross-sectional side view of a portion of illustrative generator **1700** assembly having a bearing structure, in accordance with some embodiments of the present disclosure. As illustrated, the bearing structure includes front plate **1702**, support block **1704** (e.g., shown as dash-dotted for purposes of illustration), flexures **1711**, **1712**, and **1713** (e.g., each including a hinge and mounting features), hubs **1721** and **1723**, and sleeves **1730** and **1731** (e.g., inner and outer sleeves having a surface for providing a gas bearing in gap **1780**). Enlargement AA, showing sleeves **1730** and **1731** (e.g., an recess **1735**) is included for purposes of clarity. Generator assembly **1700** includes at least one bearing structure, as illustrated, at least one stator (e.g., stator **1750** configured to interact with translator **1760**). In generator assembly **1700**, there may be a set of load paths between the bearing housing (e.g., sleeves **1730** and **1731**, forming recess **1735** for containing bearing gas) and stator **1750**. Rigid connections **1795**, where components are affixed (e.g., using fasteners, clamps, clips, welds, pins, or any other suitable affixment) and load is transferred among components, are illustrated by small, hashed circles. Illustrative load path **1790** includes paths from: [0105] stator **1750** to stator mount **1756**; [0106] stator mount **1756** to flexure **1712**; [0107] flexure **1712** to support block **1704** (e.g. an axially forward portion thereof); [0108] support block **1704** to rear of respective flexures **1711** and **1713**; [0109] respective flexures **1711** and **1713** to front plate **1702**; [0110] front plate **1702** to the front of respective hubs **1721** and **1723**; [0111] the front of respective hubs **1721** and **1723** to respective axially rear portions; and [0112] the

rear portions of respective hubs **1721** and **1723** to the bearing housing.
[0113] It will be understood that the present disclosure is not limited to the embodiments described herein and can be implemented in the context of any suitable system. In some suitable embodiments, the present disclosure is applicable to reciprocating engines and compressors. In some embodiments, the present disclosure is applicable to free-piston linear generators, engines, and compressors. In some embodiments, the present disclosure is applicable to combustion and reaction devices such as a reciprocating engine, free-piston engine, and linear generator. In some embodiments, the present disclosure is applicable to non-combustion and non-reaction devices such as reciprocating compressors and free-piston compressors. In some embodiments, the present disclosure is applicable to linear reciprocating devices with driver sections (e.g., gas springs). In some embodiments, the present disclosure is applicable to oil-free reciprocating and free-piston engines and compressors. In some embodiments, the present disclosure is applicable to oil-free free-piston engines with internal or external combustion or reactions. In some embodiments, the present disclosure is applicable to oil-free free-piston engines that operate with compression ignition (e.g., homogeneous charge compression ignition (HCCI), stratified charge compression ignition (SCCI), or other compression ignition), spark ignition, or both. In some embodiments, the present disclosure is applicable to oil-free free-piston engines that operate with gaseous fuels, liquid fuels, or both. In some embodiments, the present disclosure is applicable to linear free-piston engines. In some embodiments, the present disclosure is applicable to engines that can be combustion engines with internal combustion/reaction or any type of heat engine with external heat addition (e.g., from a heat source or external reaction such as combustion).
[0114] The foregoing is merely illustrative of the principles of this disclosure, and various modifications may be made by those skilled in the art without departing from the scope of this disclosure. The above-described embodiments are presented for purposes of illustration and not of limitation. The present disclosure also can take many forms other than those explicitly described herein. Accordingly, it is emphasized that this disclosure is not limited to the explicitly disclosed methods, systems, and apparatuses, but is intended to include variations to and modifications thereof, which are within the spirit of the following claims.

Claims

1. (canceled)
2. A bearing assembly comprising: a sleeve defining a bearing gap; a front plate; and a feature comprising a pair of flanges connected by a hinge, wherein: a first flange of the pair of flanges is coupled to the front plate; a second flange of the pair of flanges is coupled to the sleeve; and the feature is configured to deform at the hinge based on displacement of the sleeve relative to the front plate.
3. The bearing assembly of claim 2, wherein the feature comprises a flexure.
4. The bearing assembly of claim 2, wherein the feature is configured to elastically deform.
5. The bearing assembly of claim 2, wherein the feature is of an I shape.
6. The bearing assembly of claim 2, further comprising a support block coupled to the front plate.
7. The bearing assembly of claim 6, wherein the feature is one of a plurality of flexures, wherein the support block is configured to be coupled to a stator using the plurality of flexures.
8. The bearing assembly of claim 7, wherein the plurality of flexures is arranged around the bearing assembly.
9. The bearing assembly of claim 2, further comprising at least one hub affixing the sleeve to the front plate.
10. The bearing assembly of claim 2, wherein the bearing gap is configured to be filled with pressurized gas during operation.
11. The bearing assembly of claim 2, wherein the sleeve comprises a plurality of passages

configured for providing pressurized gas to the bearing gap during operation.

12. A bearing assembly feature comprising: a hinge; and a pair of flanges connected by the hinge, wherein: a first flange of the pair of flanges is coupled to a front plate; a second flange of the pair of flanges is coupled to a sleeve; and the bearing assembly feature is configured to deform at the hinge based on displacement of the sleeve relative to the front plate.

13. The bearing assembly feature of claim 12, wherein the bearing assembly feature comprises a flexure.

14. The bearing assembly feature of claim 12, wherein the bearing assembly feature is configured to elastically deform.

15. The bearing assembly feature of claim 12, wherein the bearing assembly feature is of an I shape.

16. The bearing assembly feature of claim 12, further comprising a support block coupled to the front plate.

17. The bearing assembly feature of claim 16, wherein the bearing assembly feature is one of a plurality of flexures, wherein the support block is configured to be coupled to a stator using the plurality of flexures.

18. The bearing assembly feature of claim 17, wherein the plurality of flexures is arranged around a bearing assembly comprising the bearing assembly feature.

19. The bearing assembly feature of claim 12, further comprising at least one hub affixing the sleeve to the front plate.

20. The bearing assembly feature of claim 12, wherein: the sleeve comprises a plurality of passages for providing pressurized gas to a bearing gap during operation; and the bearing gap is between an inner surface of the sleeve and an outer surface of a translator.

21. A device comprising: a translator to move relative to a stator; and a bearing assembly supporting the translator as the translator moves along the stator, the bearing assembly comprising: a feature comprising a pair of flanges connected by a hinge, wherein: a first flange of the pair of flanges is coupled to a front plate; a second flange of the pair of flanges is coupled to a sleeve; and the feature is configured to deform at the hinge based on displacement of the sleeve relative to the front plate.