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(54) Title: HUB-MOUNTED ACTIVE VIBRATION CONTROL (HAVC) DEVICES, SYSTEMS, AND METHODS

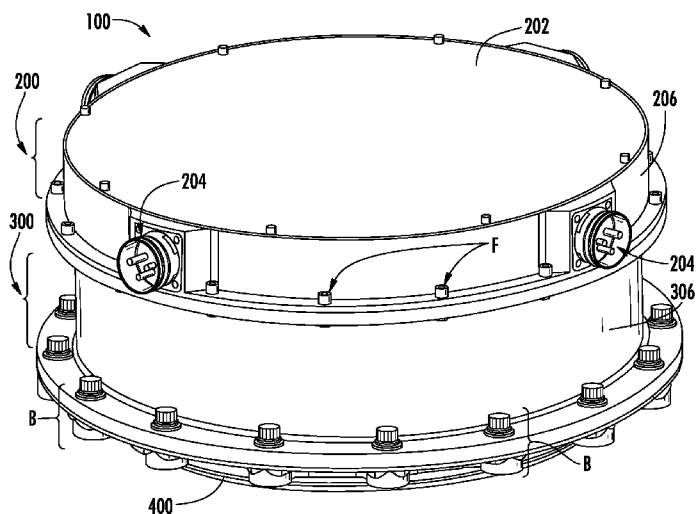


FIG. 1

(57) Abstract: Hub-mounted active vibration control (HAVC) devices, systems, and related methods are provided. An HAVC device includes a housing having a tolerance ring attached to a rotary hub. The tolerance ring can accommodate dissimilar coefficients of thermal expansion between dissimilar metals. The HAVC device can also include a plurality of coaxial ring motors configured to rotate a plurality of imbalance masses for controlling vibration. An HAVC system can further include a de-icing distributor for communicating instructions to one or more heating sources provided at one or more rotary blades of a vehicle or aircraft. A method of controlling vibratory loads occurring at a moving platform can include providing a moving platform, mounting a vibration control device to a portion of the moving platform, and rotating at least one pair of imbalance masses such that the combined forces of the masses substantially cancel unwanted vibration of the platform.



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## HUB-MOUNTED ACTIVE VIBRATION CONTROL (HAVC) DEVICES, SYSTEMS, AND METHODS

### CROSS REFERENCE TO RELATED APPLICATION

**[0001]** This application relates to and claims priority to U.S. Provisional Patent Application Serial No. 61/718,962, filed October 26, 2012, the disclosure of which is incorporated by reference herein in the entirety.

### TECHNICAL FIELD

**[0002]** The present subject matter relates generally to active vibration control (AVC) devices, systems, and methods. More particularly, the present subject matter relates to hub-mounted active vibration control (HAVC) devices, systems, and methods for reducing rotor vibration levels within an aircraft.

### BACKGROUND

**[0003]** Vibration of moving platforms can cause fatigue and wear on equipment, structural elements, occupants thereof, and/or contents associated therewith. Moving platforms can include vehicular and/or non-vehicular systems having moving elements, such as for example, aircraft, helicopters, ships, hovercraft, and/or other modes of transportation.

**[0004]** In rotating assembly aircraft vehicles such as helicopters for example, vibrations are particularly problematic as the vibrations can damage the helicopter structure, which can significantly limit the helicopter's operational life and/or components thereof. Conventional vibration control devices and systems utilize hub-mounted bifilar absorbers for mitigating vibrations. However, such devices and systems operate as a function of force input from the rotor and achieve maximum efficiency at only one force frequency level. In addition, conventional devices and systems incorporate multiple different materials without compensating for mismatches in thermal coefficients of expansion, and are therefore susceptible to thermal degradation, fretting, wear, and damage from heat generated by the devices and/or systems.

**[0005]** Accordingly, there is a need for improved vibration control devices, systems, and methods for controlling vibrations of a moving platform. In particular, there is a need to control rotary vibrations induced by a helicopter hub so that the vibrations are more

efficiently minimized. There is also a need to for lightweight, compact, and robust vibration control devices, systems, and methods.

### SUMMARY

**[0006]** In accordance with the disclosure provided herein, novel and improved active vibration control (AVC) devices, systems, and related methods are provided. In many aspects, devices, systems, and methods disclosed herein have improved heat dissipation, thermal management properties, de-icing capabilities, reduced wear, reduced fretting, reduced weight, extended life expectancy, extended operating temperatures, and more compact dimensions. AVC devices, systems, and related methods can be mounted to a moving platform, such as a rotor hub, and can rotate or move therewith. Imbalance masses rotating at different frequencies can substantially cancel unwanted vibration of the moving platform.

**[0007]** In one aspect, the subject matter herein discloses a hub-mounted active vibration control (HAVC) device comprising a housing configured to attach to a rotary hub and capable of rotating therewith. The housing comprises a tolerance ring configured to accommodate dissimilar coefficients of thermal expansion between components of dissimilar metals. The HAVC device has a plurality of coaxial ring motors configured to rotate a plurality of imbalance masses. The HAVC device also includes an electrical unit for independently controlling a rotational position, phase, and/or speed of the plurality of imbalance masses such that the combined forces of the imbalance masses substantially cancel unwanted vibration.

**[0008]** In another aspect, the subject matter herein discloses an HAVC system. The system comprises a mechanical unit attached to a rotary hub, which is capable of rotating therewith. The mechanical unit includes at least one pair of imbalance masses co-rotating at nominally a same frequency. The mechanical unit may also have at least two pairs of imbalance masses, each pair of masses rotating at two (e.g., different or dual) frequencies and in two different directions. The system includes a de-icing distributor provided over at least a portion of the mechanical unit. The de-icing distributor is configured to communicate instructions to one or more heating sources provided at one or more rotary blades of a vehicle or aircraft.

**[0009]** In another aspect, the subject matter herein discloses a method of actively suppressing and/or controlling in-plane vibratory loads occurring at a moving platform. The method includes providing a moving platform and mounting a vibration control device

to a portion of the moving platform, the device being capable of moving therewith. The device includes a mechanical unit with at least one pair of imbalance co-rotating at substantially the same frequency or at least two pairs of masses rotating at different frequencies and in different directions. A tolerance ring is attached to the mechanical unit. The tolerance ring is configured to accommodate dissimilar coefficients of thermal expansion between components of dissimilar metals contained within the mechanical unit. The method includes rotating at least one pair of imbalance masses at substantially a same frequency such that the combined forces of the imbalance masses substantially cancel unwanted vibration of the moving platform. The method may further include rotating at least two pairs of imbalance masses at different frequencies and/or in different directions, such that the combined forces of the imbalance masses substantially cancel unwanted vibration of the moving platform.

**[0010]** These and other objects of the present disclosure as can become apparent from the disclosure herein are achieved, at least in whole or in part, by the subject matter disclosed herein.

#### **BRIEF DESCRIPTION OF THE DRAWINGS**

**[0011]** Figures 1 and 2 are perspective and sectional views, respectively, illustrating a hub-mounted active vibration control (HAVC) device according to aspects of the subject matter described herein.

**[0012]** Figures 3A to 3C are views illustrating one or more HAVC device components according to aspects of the subject matter described herein.

**[0013]** Figures 4A and 4B are perspective and sectional views, respectively, illustrating one or more other HAVC device components according to aspects of the subject matter described herein.

**[0014]** Figure 5 is a perspective view illustrating an additional HAVC device component according to aspects of the subject matter described herein.

**[0015]** Figures 6 and 7 are perspective and exploded views, respectively, illustrating an HAVC system according to aspects of the subject matter described herein.

**[0016]** Figure 8 is a schematic diagram illustrating a rotary winged aircraft incorporating HAVC devices and systems according to one aspect of the subject matter described herein.

## DETAILED DESCRIPTION

**[0017]** The subject matter described herein is directed to hub-mounted active vibration control (HAVC) devices, systems, and methods for use and installation within a rotary winged aircraft. In some aspects, HAVC devices, systems, and methods are configured to reduce rotor vibration levels within an aircraft. HAVC devices, systems, and methods described herein have improved thermal management properties including improved heat conduction. HAVC devices, systems, and methods herein also include a reduced weight and reduced/more compact dimensions for improved vibration control within an aircraft.

**[0018]** In some aspects, HAVC devices, systems, and methods described herein have improved reliability, decreased wear (e.g., decreased “fretting”), and more compact structural dimensions (e.g., reduced weight, height, and/or diameter) via use of an integrated bearing and housing. HAVC devices, systems, and methods described herein utilize a dual stage bearing having a single outer bearing race within a single flanged housing, where the inner race of each bearing is combined with the rotor of each brushless motor. This eliminates the requirement for several parts, reduces fretting, and/or eliminates several failure modes.

**[0019]** HAVC devices, systems, and methods described herein also reduce fretting and improve life expectancy, operating temperature, and oil purity, compensating for mismatches between materials having different thermal expansion coefficients.

**[0020]** In one aspect, the subject matter herein discloses an HAVC device comprising a housing configured to attach to a rotary hub and capable of rotating therewith. The housing comprises a tolerance ring configured to accommodate dissimilar coefficients of thermal expansion between components made of dissimilar metals. The HAVC device includes a plurality of coaxial ring motors configured to rotate a plurality of imbalance masses. The HAVC device also includes an electrical unit for independently controlling a rotational position, phase, and/or speed of the plurality of imbalance masses such that the combined forces of the imbalance masses substantially cancel unwanted vibration.

**[0021]** In another aspect, an integrated HAVC device and deicing system is provided. The combined system has a mechanical unit attached to a rotary hub, which is capable of rotating therewith. The mechanical unit has at least one pair of imbalance masses co-rotating at substantially the same frequency for cancelling unwanted vibration. The mechanical unit may include at least two pairs of imbalance masses rotating at two (e.g., different or dual) frequencies, the combined forces of which can cancel unwanted vibration. The system can further comprise a de-icing distributor provided over at least a

portion of the mechanical unit (for example, disposed within the inner diameter of the mechanical unit). The de-icing distributor is configured to communicate electrically to one or more heating sources provided at one or more rotary blades of a vehicle or aircraft.

**[0022]** A method of actively suppressing and/or controlling in-plane vibratory loads occurring at a moving platform is disclosed. The method includes providing a moving platform and mounting a vibration control device to a portion of the moving platform, the device being capable of moving therewith. The device includes a mechanical unit having at least one pair (e.g., in some aspects, two or more pairs) of imbalance masses for rotating about an axis, the combined rotation forces of which substantially cancel unwanted vibration of the moving platform, such as a rotor hub. A tolerance ring is provided and/or attached within a portion of the mechanical unit. The tolerance ring accommodates dissimilar coefficients of thermal expansion between components of dissimilar metals contained within the mechanical unit. The method includes rotating at least one pair of imbalance masses at substantially a same frequency such that the combined forces of the imbalance masses substantially cancel unwanted vibration of the moving platform. The method further includes rotating at least two pairs of imbalance masses at different (e.g., dual) frequencies and/or in different directions such that the combined forces of the imbalance masses substantially cancel unwanted vibration of the moving platform.

**[0023]** As used herein, the terms “bearings”, “bearing assembly”, and “bearing stage” refer to combinations of bearing components including at least one bearing inner race, bearing outer race, and ball bearing. In some aspects, a bearing outer race is a bearing component that can be integrated or formed as a single piece for multiple ball bearings, such as multiple stacked ball bearings. A tubular space or slug is an optional bearing component that can be contained within a portion of the bearing or bearing stage.

**[0024]** Figures 1 to 8 illustrate various views and/or features associated with HAVC devices, systems, and related methods for controlling vibration of a moving platform, namely, of a vehicular system such as an aircraft, a tandem or single rotor helicopter (e.g., **800**, Figure 8), a hovercraft, and/or any other vehicular system having at least one moving platform. Figures 1 and 2 illustrate an HAVC device, generally designated **100**. HAVC device **100** comprises an electrical unit generally designated **200**, a mechanical unit generally designated **300**, and an adaptor plate **400** by which HAVC device **100** directly mounted to a rotor hub (**702**, Figures 6 and 7) via one or more mechanical fasteners such as one or more pins, screws, clips, hinges, or bolted assemblies **B**. Rotor hub (e.g., **702**,

Figures 6 and 7) includes a main rotor hub of a helicopter, about which one or more blades of a rotary winged aircraft rotate.

**[0025]** HAVC device **100** includes a removable cover plate **202** disposed over electrical unit **200** for at least partially housing electronic devices contained therein. HAVC device **100** has one or more electrical interfaces **204** disposed at and/or extending from electrical unit **200** for sending and/or receiving electrical signals between electrical unit **200** and other portions of the aircraft via a wired link, a wireless link, a data link, or a data bus (not shown).

**[0026]** Cover plate **202** is removable for easy replacement of electrical components therein. Such components are accessible through the removable cover plate **202** while the remainder of HAVC device **100** remains attached to the moving platform (e.g., a rotary hub **702**, Figure 8).

**[0027]** Electrical unit **200** is mounted directly to mechanical unit **300** and interfaces with an electrical module, such as a slip ring (e.g., **500**, Figure 2) to receive power from at least two redundant busses. Outermost flange **312** of mechanical unit **300** is configured to mount to adaptor plate **400** via an easily accessed circular pattern of bolts or bolted assemblies **B**. Adaptor plate mounts directly to a moving platform, such as a rotor hub (e.g., **702**, Figures 6 and 7). The entire HAVC device **100** is rotatable with the rotor hub (**702**, Figures 6 and 7) at once per-rev (1P).

**[0028]** Electrical unit **200** has one or more independent processors housed within an outer housing **206** for controlling aspects of one or more pairs of imbalanced rotors. Electrical unit **200** also has one or more orthogonal in-plane accelerometers within housing **206** for enabling local vibration control.

**[0029]** Electrical unit **200** is configured to receive and condition aircraft power for providing power to HAVC devices and systems described herein, facilitate stable servo motor control based on motor sensor feedback, measure and process inputs (e.g., from one or more accelerometers, (not shown)), command the force amplitude and phase of the mechanical unit **300** for minimizing a cost function based upon process inputs, perform Built-In Test (BIT) and report status and fault information to the aircraft avionics system, and/or manage communication through the slip ring (**500**, Figure 2) with aircraft data busses and/or with an active vibration control (AVC) central controller.

**[0030]** NP (where "N" is the number of blades and "P" denotes "per-revolution" or "per-rev") denotes a primary frequency of vibration measured with respect to a fixed reference frame. Thus, HAVC devices and systems described herein output forces adapted to

mitigate and/or actively control NP vibration frequencies. To actively control vibration, imbalanced rotors of HAVC device **100** is configured to rotate one pair of imbalance masses at a frequency of  $(N-1)P$  or two pairs of imbalance masses at dual frequencies including  $(N-1)P$  and  $(N+1)P$ , each measured with respect to a rotating reference frame.

**[0031]** Electrical unit **200** also comprises parallel identical electronic architectures for the  $(N+1)P$  (upper) and the  $(N-1)P$  (lower) imbalanced rotors (e.g., **304** and **306**, respectively Figure 2) for minimizing the loss of operation of one or both imbalanced rotors and/or failures associated with separate AC power busses. By using improved electronics, the electronics used to drive HAVC device **100** have reduced height, and may be compactly packaged upon rectangular and/or arc-shaped boards within housing **206**. Notably, the structural aspects and design of electrical unit **200** eliminates discrete wires and creates flexible circuit interconnects between the motors (e.g., of mechanical unit **300**) and circuit boards (e.g., of electrical unit **200**).

**[0032]** Electrical unit **200** is configured to optionally utilize one or more multi-layer stacked ceramic capacitors (MLCC) as opposed to larger electrolytic capacitors. MLCC's can reduce the overall size (e.g., height) of the capacitors to approximately 0.6 inches (in.), thereby enabling low profile electronics. MLCC's are also advantageously able to withstand environments of about 125 °C, more or less.

**[0033]** Electrical unit **200** integrates circuitry required to power, drive, program, and/or control more than one portion of mechanical unit **300**. An outer diameter of housing **206** is approximately the same as an outer diameter of housing **302** of mechanical unit **300**. This reduces and/or eliminates drag associated with different diameters of housings. Electronics for both a lower portion (i.e., rotating at a frequency of  $(N-1)P$ ) of mechanical unit **300** is advantageously integrated with electronics for an upper portion (i.e., rotating at a frequency of  $(N+1)P$ ) of mechanical unit **300**, and electronics for both are contained within a single housing **206** of electrical unit **200**. Electrical unit **200** can, for example, comprise a height of less than about one inch (in.) and fit directly above the mechanical unit **300**, without requiring larger diameter housing, which could negatively affect drag.

**[0034]** Mechanical unit **300** has at least one pair of co-rotating eccentric masses or mass concentrations (e.g., having a rotation frequency of  $(N-1)P$ ) for cancelling unwanted vibration. Mechanical unit **300** can have at least two pairs (i.e., at least four total masses) of independently controlled and rotating eccentric masses or mass concentrations (e.g., one pair having a frequency of  $(N-1)P$  and the other pair having a frequency of  $(N+1)P$ ). Each pair of masses rotates at a different frequency and/or in a different direction for

collectively cancelling unwanted vibration. Where multiple pairs of imbalance masses are used, each pair of mass concentrations can be configured to produce vibration canceling forces in the plane of a rotor hub (e.g., **702**, Figures 6 to 8).

**[0035]** For example, and where at least two pairs of imbalance masses are used, a first mass or pair of masses rotates in a direction of the rotor and at a first frequency (i.e.,  $(N-1)P$ ) and at least one other mass or pair of masses rotates in a direction opposite of the rotor at a second frequency (i.e.,  $(N+1)P$ ). For each pair of rotating eccentric masses, the force amplitude of HAVC device **100** is adjusted by changing the relative phase between the two eccentric masses, and the force phase is adjusted by changing the absolute phase of the two eccentric masses with respect to a reference angle derived from a tachometer (not shown).

**[0036]** Figure 2 illustrates a partial sectional view of HAVC device **100**, which is also devoid of cover plate **202**. Electrical unit **200** has electrical interfaces **204'** configured to transmit electrical signals, control, power, and/or information between a data bus or centralized bus and portions housed within housing **206** of electrical unit **200**. HAVC device **100** has an integrated de-icing distributor **208** centrally disposed within electrical unit **200**. De-icing distributor **208** is disposable within portions of housing **206** and/or is mounted above mechanical unit **300** of HAVC device **100**. Electrical interfaces **204'** communicate electrical signals, controls, and/or other information between de-icing distributor **208** and other portions of the aircraft, such as the blades.

**[0037]** In some aspects, de-icing distributor **208** controls and distributes power to de-ice systems via electrical interfaces **204'**. De-icing distributor **208** also receives information regarding temperature and/or other inputs for detecting and preventing ice from forming on aircraft blades (e.g., **802**, Figure 8). Integrating de-icing distributor **208** within HAVC device **100** reduces and/or re-distributes weight within the aircraft by relocating the weight of the distributor to a centralized location with respect to helicopter blades. A centralized de-icing distributor **208** simplifies electrical circuitry, as circuitry is contained at a centralized location with respect to helicopter.

**[0038]** In some aspects, de-icing distributor **208** is configured to detect the formation of ice and/or detect temperatures associated with ice formation. In addition, de-icing distributor **208** is configured to communicate instructions and/or electrical power to one or more heating sources (e.g., **HS**, Figure 8) disposed at one or more rotary blades (e.g., **802**, Figure 8) for preventing ice from forming thereon or, for removing ice. De-icing distributor **208** comprises one or more processors and/or memory devices configured to

execute instructions for detecting ice formation and/or conditions for forming ice and for communicating instructions to heating sources to heat rotary blades as needed.

**[0039]** As Figure 2 further illustrates, portions of electrical unit **200** and mechanical unit **300** are integrally formed and/or mechanically joined. For example, respective housings of electrical and mechanical units **200** and **300**, respectively, are integrated via one or more mechanical connectors or fasteners, generally designated **F**. As noted hereinabove, housing **206** of electrical unit **200** has a diameter that is approximately the same as and/or equal to a diameter of housing **302** of mechanical unit **300**. This reduces or eliminates drag associated with HAVC device **100**.

**[0040]** Housings **206** and **302** of respective units may optionally comprise aluminum and/or an aluminum alloy. Aluminum and alloys thereof, have a high thermal conductivity and weigh less than traditional housing materials, such as stainless steels or titanium. Thus, housings **206** and **302** of respective units readily conduct heat away from electrical and mechanical components housed within HAVC device **100**. This improves thermal management within device **100** as well as heat dissipation therefrom. Aluminum housings also allow components to run cooler for longer periods of time, increasing operating temperatures, extending the life of HAVC devices and/or components thereof. Aluminum housings decrease weight of HAVC devices and systems. Housings **206** and **302** of respective units can comprise materials other than aluminum and/or alloys thereof, if desired.

**[0041]** In some aspects, housings **206** and **302** of electrical and mechanical units **200** and **300**, respectively, collectively define and/or include a single housing having an inner diameter for housing one or more electrical and mechanical components. For example, housings **206** and **302** have a single housing for one or more components including, a slip ring **500**, a de-icing distributor **208**, and a motor with motor winding assemblies **308/310**, imbalance masses, and/or rotors.

**[0042]** As Figure 2 further illustrates, mechanical unit **300** of HAVC device **100** has one or more stacked motors comprised of one or more stacked imbalanced rotors and/or stacked motor winding assemblies. HAVC device **100** has a device having at least one pair of co-rotating eccentric masses, or at least two pairs of independently controlled eccentric masses for rotating to produce vibration canceling forces in the plane of the rotor. Where at least two pairs are used, each pair rotates at two specific frequencies (e.g.,  $(N-1)P$  and  $(N+1)P$ ) and in opposing directions. As the imbalanced rotors and imbalances

masses rotate, the resultant forces is perceived as vibrations for counteracting, mitigating, and/or cancelling vibrations of rotor hub (e.g., 702, Figures 6 and 7).

**[0043]** HAVC device **100** contains one pair of imbalance masses configured to co-rotate in a direction of the rotor at  $(N-1)P$ , as measured with respect to a rotating reference frame. Additionally, HAVC device **100** has at least one other pair of masses configured to rotate in a direction opposite of the rotor at  $(N+1)P$ , as measured with respect to a rotating reference frame.

**[0044]** Where two pairs of masses are present, the masses with respective rotors and bearings, rotating at  $(N+1)P$  are disposed above the masses with respective rotors and bearings, rotating at  $(N-1)P$ . That is, the  $(N+1)P$  masses/rotors/bearings are disposed in an upper portion of housing **302** (e.g., located above a divider **350**) and the  $(N-1)P$  masses/rotors/bearings are disposed in a bottom portion of housing **302** below divider **350**. As described hereinbelow, the masses/rotors/bearings rotating at  $(N+1)P$  rotate in a direction opposite from the masses/rotors/bearings rotating at  $(N-1)P$ . The entire HAVC device **100** is configured to rotate with the rotor at once per-rev (1P), thus, the resultant rotational speed of both pairs of eccentric masses in the fixed reference frame is NP.

**[0045]** Still referring to Figure 2, HAVC device **100** has a first set or a first pair of imbalanced rotors generally designated **304** provided in an upper portion of mechanical unit **300**, and a second set or a second pair of imbalanced rotors generally designated **306** provided in a lower portion of mechanical unit **300**. HAVC device **100** having only one pair of imbalanced rotors **306** and one pair of respective imbalance masses is also contemplated.

**[0046]** Mechanical unit **300** is physically separated internally within housing **302** into upper and lower portions via a substantially horizontal divider **350** of housing **302**. Each pair of imbalanced rotors **304** and **306** has annular rotors configured to rotate about a center axis **Z**. Imbalanced rotors **304** rotate in a first direction (e.g., clockwise) that is opposite from imbalanced rotors **306**, which rotate in a second opposing direction (e.g., counter-clockwise).

**[0047]** First and second sets of imbalanced rotors **304** and **306**, respectively, each comprise a first upper imbalanced rotor **304A** and **306A**, respectively, and a second lower imbalanced rotor **304B** and **306B**, respectively. Each pair of imbalanced rotors **304A/304B** and **306A/306B**, respectively, is vertically stacked with respect to each other. Portions of each individual imbalanced rotors **304A**, **304B**, **306A**, and **306B** are configured to support a respective imbalance mass. That is, each of first and second sets of

imbalanced rotors **304** and **306**, respectively, has two independently controlled eccentric masses provided between and/or over respective first and second imbalanced rotors **304A**, **304B**, **306A**, and **306B** for a total of at least four imbalanced rotors supporting at least four independently controlled masses per HAVC device **100**.

**[0048]** The first set of imbalanced rotors **304** rotates at  $(N+1)P$  and is provided within an upper portion of housing **302**. The first set of imbalanced rotors **304** is configured to actively cancel in-plane  $(N+1)P$  vibratory loads occurring at a moving platform, such as a rotor hub (e.g., **702**, Figures 6 and 7) and as measured in a reference frame rotating with the rotor hub. A second set of imbalanced rotors **306** rotates at  $(N-1)P$  and is provided within a lower portion of housing **302**. That is, second set of imbalanced rotors **306** are configured to actively cancel in-plane  $(N-1)P$  loads occurring at the rotor hub as measured in a reference frame rotating with the rotor hub. Only the lower (i.e., second) set of imbalanced rotors **306** is provided in device **100** for actively cancelling in-plane  $(N-1)P$  loads occurring at the rotor hub as measured in a reference frame rotating with the rotor hub. Where multiple sets of rotors and masses are used, each set of imbalanced rotors (e.g., first and second sets of imbalanced rotors **304** and **306**) has a common design, which improves ease of assembly and manufacture.

**[0049]** Divider **350** physically separates first set of imbalanced rotors **304** from second set of imbalanced rotors **306**. Each set of imbalanced rotors is stackable, and has a dual stage bearing assembly disposed along an outer edge, at a furthest point of each rotor away from central axis **Z**. Together, the first and second sets of imbalanced rotors **304** and **306**, respectively, rotate sets of imbalanced masses for actively canceling NP vibrations in a fixed reference frame. HAVC device **100** has one pair of masses configured to co-rotate via second set of imbalanced rotors **306** in a direction of the rotor at  $(N-1)P$ , and at least one other pair of masses configured to co-rotate in a direction opposite of the rotor at  $(N+1)P$  via first set of imbalanced rotors **304**, each measured with respect to a rotating reference frame.

**[0050]** In one embodiment, HAVC device **100** has one or more brushless motors, including first and second motor winding assemblies **308** and **310**, respectively. First motor winding assembly **308** is vertically stacked with respect to and/or vertically disposed over second motor winding assembly **310**. First and second sets of imbalanced rotors **304** and **306**, respectively, rotate about first and second motor winding assemblies **308** and **310**, respectively. First and second sets of imbalanced rotors **304** and **306** rotate imbalance mass concentrations about first and second motor winding assemblies **308** and

**310**, respective. In some aspects, HAVC device **100** has only one motor assembly **310** (e.g., for rotating second set of imbalanced rotors **306**).

**[0051]** Each of first and second motor winding assemblies **308** and **310** have a pair of motor winding assemblies including a first coaxial ring motor **308A** and **310A**, respectively, and a second coaxial ring motor **308B** and **310B**, respectively. At least four imbalance masses are controlled via signals provided to at least four coaxial ring motors **308A**, **308B**, **310A**, and **310B**. Each motor winding assembly **308** and **310** rotates at least two imbalanced rotors and at least two respective imbalance masses for actively suppressing and/or controlling vibratory loads. A portion of each coaxial ring motor **308A**, **308B**, **310A**, and **310B** is integrated with a portion of each annular imbalanced rotor **306A**, **306B**, **308A**, and **308B**, respectively.

**[0052]** Still referring to Figure 2, HAVC device **100** has slip ring **500**. Slip ring **500** has a device and/or interface configured to transfer power from a main power source (not shown) of a vehicular system to HAVC device **100** and/or to de-icing distributor **208**. Slip ring **500** is configured to communicate control signals between a controller and HAVC device **100**, between a controller and de-icing distributor **208** and/or a combination thereof. Slip ring **500** communicates control signals via one or more wired data links, data busses, or wireless links to and/or from one or more controllers of vehicular system.

**[0053]** De-icing distributor **208** is integrated directly into the HAVC device **100**. Slip ring **500** and de-icing distributor **208** encompass a portion or space within an inner diameter of housing **206** of HAVC device **100**. When cover plate **202** is removed, the electrical interconnects between slip ring **500** and de-icing distributor **208**, and de-icing distributor **208** and de-ice bundles (e.g., which communicate to each blade) are visible. Electrical interconnects are removed and/or replaced easily via removal of cover plate **202**. HAVC device **100** includes electronics modules that can be individually removed and/or replaced without removing portions of HAVC device **100**.

**[0054]** In some aspects, slip ring **500** includes a wireless, non-contact slip-ring, meaning that there is no physical contact between the rotating and fixed parts of the vehicular system for which slip ring **500** facilitates communication. Non-contact slip rings provide rotor head electronic systems with more reliable power in the rotating frame for active rotor and de-icing solutions. In some embodiments, slip ring **500** includes a wireless, non-contact slip ring available from, for example, PowerbyProxi, Ltd., of Auckland, New Zealand.

[0055] Slip ring **500** can be at least partially disposed within an inner diameter of mechanical unit **300** and at least partially within an inner diameter of electrical unit **200**. In other aspects, slip ring **500** attaches directly to the bottom of de-icing distributor **208**, and hangs partly or completely below a portion of the HAVC device **100**. A helicopter mast is hollow for accommodating placement of slip ring **500**.

[0056] Figures 3A to 3C are views of one or more HAVC device components according to aspects of the subject matter described herein. Figures 3A to 3C illustrate perspective and sectional views of one set of imbalanced rotors (e.g., either the upper or lower imbalanced rotors) designated **304/306**. As Figures 3A and 3B illustrate, each set of imbalanced rotors has a first imbalanced rotor **304A/306A** vertically stacked over a portion of second imbalanced rotor **306A/306B**. Each of first and second imbalanced rotors **304A/306A** and **304B/306B**, respectively, have annular rings having one or more support members or support portions **314** configured to support one or more imbalance masses or imbalance mass concentrations (e.g., **324**, Figure 3C).

[0057] Figure 3B illustrates a dual stage integrated bearing. Imbalanced rotor **304/306** has an integrated bearing component comprised of stacked inner bearing races **316** and a single outer bearing race **318**. That is, dual stage bearing is integrated in a single housing comprised of a single outer bearing race **318** with optional flanged housing. The inner bearing races **316** and outer bearing race **318** are collectively referred to "bearing stages", in which ball bearings **325** can be provided. Tubular slug spacers **320** can be provided and/or vertically stacked between inner races of bearing stages within imbalanced rotor **304/306** to maintain spacing between the ball bearings. Tubular slug spacers **320** require lower power and a lower height than a dual riveted bearing cage, and improve bearing efficiency.

[0058] A plurality of ball bearings **325** is vertically stacked within imbalanced rotor **304/306**. Ball bearings **325** are configured to independently move between portions of each respective inner bearing race **316** and a portion of outer bearing race **318** thereby allowing imbalanced rotors **304/306** to rotate about a central axis (e.g., **Z**, Figure 2). Bearing stages (e.g., comprised of races **316**, **318**) and tubular slug spacers **320** each include a stainless steel material or alloy. Tubular slug spacers **320** have a plastic material, which contributes to weight reduction in device **100**. Different sizes and/or diameters of ball bearings **325** are provided and used within tubular slug spacers **320**.

[0059] Integrating outer race **318** of two bearings decreases the number of parts required for the bearing assembly and improves efficiency. The combination of the two

bearings into the single outer stage or outer housing is enabled by using the tubular slug spacers **320** between balls **325** in the bearing.

**[0060]** Imbalanced rotors **304/306** and respective bearings include at least one outermost flange **322** provided about an outer diameter of imbalanced rotor **304/306**. Outermost flange **322** is integrated with outer bearing race **318**. Flange **322** has a plurality of attachment holes **326** by which outer bearing race **318** and respective imbalanced rotor **304/306** are fixedly attached within housing **302** of mechanical unit **300**. For example, attachment holes **326** are configured to interface with portions of a tolerance ring (e.g., **600**, Figures 4A and 4B) and be bolted or affixed thereto. Imbalanced rotors **304/306** can be bolted within housing **306** of mechanical unit **300** via a bolt or other connector or fastener threading extending through attachment holes **326** and a threaded opening (e.g., **608**, Figures 4A and 4B) of a tolerance ring (e.g., **600**, Figures 4A and 4B) of housing **302**.

**[0061]** The integrated dual bearing stage and tubular slug spacer **320** design of HAVC device **100** improves/reduces drag and/or weight associated with HAVC device **100** by eliminating a riveted cage for housing ball bearings. In one embodiment, HAVC device **100** weighs less than approximately 100 lbs., and in another embodiment, even less than approximately 80 lbs. This is partly achieved by using lighter weight materials (such as aluminum housings **206**, **302**), stacking electrical components above mechanical components, consolidating electrical components via incorporation of a de-icing distributor **208** (Figure 2), and by eliminating steel housings and/or other steel components from bearings. By reducing the amount of steel used, significant weight savings are achieved. Using the dual stage bearing with tubular slugs between the ball bearings **325**, instead of a riveted cage, significantly reduces weight. Tubular slug spacer **320** can allow larger ball bearings **325** to fit within the same cross-section, which increases the bearing load capacity. Tubular slug spacer **320** can comprise hollow steel or hollow plastic tubes, which advantageously reduces weight compared to a metallic cage. Furthermore, by using a tubular slug bearing the load of one stage can be managed with a smaller diameter bearing; thus, an outer diameter of the HAVC device **100** housing **302** can be advantageously reduced.

**[0062]** Figure 3B further illustrates bearing integrated with brushless rotor component(s), as inner race **316** of each bearing is combined with the rotor and permanent magnet **M** of each brushless motor. One or more permanent magnets **M** is disposed proximate an end of each respective support members **314** that is away from and/or opposing an end having ball bearings **325**. Permanent magnets **M** can comprise a

portion of the brushless motor winding assemblies **308/310** (Figure 2), and can be provided on a portion of a motor rotor for interfacing with electromagnets provided on the motor winding assembly. Permanent magnets **M** interface with electromagnets for at least controlling a direction, a rotational speed, a rotational position, and/or a rotational phase of the plurality of imbalanced rotors **304/306** and respective masses, according to commands from electrical unit **200**. HAVC device **100** integrates the motor and/or portions thereof (e.g., motor rotors, permanent magnets **M**) as part of the bearing assembly. This dramatically lowers the number of discrete components, reduces weight, eliminates failure modes, and increase reliability of the device.

**[0063]** Figure 3C illustrates placement of an imbalanced mass **324** over a portion of imbalanced rotor **304/306**. Another imbalance mass (not shown) is provided on support portion **314** below mass **324**, thus forming at least one pair of masses (e.g., two masses total) per imbalanced rotor **304/306**. In this embodiment, mechanical unit **310** has two pairs of imbalanced rotors **304/306** in upper and lower portions thereof, thus, a total of four imbalance masses **324** or imbalance mass concentrations can be provided per HAVC device **100**.

**[0064]** Thermal management and heat dissipation of HAVC device **100** is improved via the integrated dual bearing stage design provided herein. For example, electrical components within electrical unit (**200**, Figures 1 and 2) generate heat and are also in close proximity to heat generating components housed within mechanical unit **300** (Figures 1 and 2). Improved cooling of components within electrical unit **200** (Figures 1 and 2) provide for lower operating temperatures and increased operating life. HAVC device **100** provides a dual stage bearing assembly comprised of inner bearing races **316** and a single outer bearing race **318**. Bearing assembly is bolted within an aluminum housing **302**. As aluminum and/or alloys thereof can readily conduct heat, the provision of bearings within housing **302** increases the amount of aluminum surrounding the outer bearing race **318**, and improves thermal management within HAVC device **100**. The amount of heat conducted away from an aluminum electronics cavity, such as electrical unit **200** (Figures 1, 2) is also improved. Heat is easily conducted outside of HAVC device **100** via respective aluminum housings **206** and **302**.

**[0065]** Reducing mechanical wear or “fretting” is also improved with a dual bearing stage within HAVC device **100**. Using a bearing assembly having an integrated outer race **318** reduces and/or eliminates almost all fretting due to discrete components wearing against each other. This change allows a two-stage bearing to be assembled as a single

piece. Any wear due to the fretting components happens outside of an O-Ring seal (not shown), keeping the lubricating oil inside HAVC device **100** clean and/or more pure.

**[0066]** Figures 3A to 3C illustrate bearing stages associated with either the (N-1)P (i.e., lower) and/or (N+1)P (i.e., upper) imbalanced rotors **304/306**. Thus, imbalanced rotors **304/306** have a common design, and do not require different, specific parts. This improves cost and commonality, as imbalanced rotors **304/306** can be efficiently produced and manufactured.

**[0067]** As Figure 3C illustrates, portions of the bearing assembly including bearing inner races **316** are combined into a single piece with the brushless motor rotor with permanent magnets **M**. The single piece eliminates numerous parts, thereby increasing reliability and ease of assembly. A single piece reduces an envelope for installing the HAVC device **100**. In this configuration, flanges **322** or flanged portions imbalanced rotors **304/306** bolt through the motor rotor and into each other. When used, outer flange **322** contributes to providing a solid and non-fretting connection.

**[0068]** Figures 4A and 4B illustrate perspective and sectional views of mechanical unit **300** and respective housing **302**. First and second tolerance rings **600** and **602** are provided between portions of housing **302** and bearing assemblies of upper and lower imbalanced rotors **304/306** (e.g., which are provided on either side of divider **350**). Tolerance rings **600** and **602** compensate for mismatches in thermal expansion between components of dissimilar metals, for example, a stainless steel outer race **318** (Figure 3B) and an aluminum housing **302**. Compensation for mismatches in thermal expansion via tolerance rings **600** and **602** increases bearing life by reducing wear and fretting, as well as preventing binding of the bearing.

**[0069]** For example, tolerance rings **600** and **602** mitigate the effects of thermal expansion differences between dissimilar metals, which, if not addressed, result in large power increases (e.g., due to potential binding of the bearing) and extreme size differentials between steel and aluminum parts. Furthermore, extreme wear causes extensive operations requirements by having to change the oil in the system at greatly increased intervals.

**[0070]** As described hereinabove, housing **302** of mechanical unit **300** is aluminum, thereby improving heat dissipation and reducing weight of device **100**. However, other materials can be provided and are contemplated herein. To accommodate the differential thermal expansion between a steel bearing assembly (e.g., comprised of inner races **316** and outer race **318**) and the aluminum housing **302**, upper and lower tolerance rings **600**

and **602** are used therebetween. Tolerance rings **600** and **602** allow expansion and/or contraction between bearing assemblies and housing **302** in response to changes in temperature without affecting vibration control. In some aspects, tolerance rings **600** and **602** comprise a high strength steel material.

**[0071]** As Figures 4A and 4B illustrate, tolerance rings **600** and **602** have a plurality of threaded openings **604** configured to align with a plurality of attachment holes **326** (Figure 3B) provided in flange **322** (Figure 3B) of bearing assembly. Imbalanced rotors **304/306** are bolted into housing **302** via interfacing between attachment holes **326** of flange **322** and openings **604** of tolerance ring **600**.

**[0072]** Tolerance rings **600** and **602** have a lower attachment point **606** and a track **608**. Track **608** extends directly against and/or along an inner diameter of housing **302**. In some aspects, track **608** of tolerance ring extends about an entire inner circumference of housing **302**. Tolerance rings **600** and **602** can be press fit with housing **302** and retained via bolted flange **322** of outer race **318** of the bearing assembly. The bearing assembly of imbalanced rotors **304/306** is free to expand and contract when subjected to different temperatures without binding. The bolted rotor/bearing/tolerance ring/housing assembly also continues to stay tight over the entire operating temperature range to avoid fretting. The steel imbalanced rotors **304/306** and respective bearing assemblies expand at a different rate than the aluminum housing **302** due to differences in thermal expansion coefficients. Tolerance rings **600** and **602** make up for the differences, and allow bearings room to expand and contract freely within housing **302** while maintaining a tight fit.

**[0073]** Figure 5 is a perspective view of one set of heat sunk inside out brushless motor assemblies (e.g., either the upper or lower motor assemblies shown and described in Figure 2) designated **308/310**. Motor assemblies **308/310** comprise first and second vertically stacked motor windings (e.g., **308A** stacked over **308B** and **310A** stacked over **310B**) for rotating imbalanced rotors **304/306**. First and second motor winding assemblies **308/310** comprise steel and copper windings comprising two inside out stators. The stators are bonded to aluminum rings using a thermally conductive potting compound for optimal heat sinking.

**[0074]** Figures 6 and 7 illustrate HAVC systems **700** having an HAVC device **100** mounted to a rotor hub **702**. Rotor hub **702** has one or more openings **704** configured to receive and fixedly engage one or more respective rotary blades of a vehicular system, such as of a helicopter or hovercraft.

[0075] As Figure 7 illustrates, HAVC system **700** having an HAVC device **100** with an integrated de-icing distributor **208** within electrical unit **200**. De-icing distributor **208** is centrally disposed directly into the HAVC device **100**. Slip ring **500** and de-icing distributor **208** encompass a portion of an inner diameter of HAVC device **100**. The cover plate **202** of HAVC device **100** is removable for easy access to electrical components. When cover plate **202** is removed, electrical interconnects between the slip ring **500** and de-icing distributor **208**, and the de-icing distributor **208** and the HAVC mechanical unit **300**, and de-icing distributor **208** and de-ice bundles, which go out to each blade, are visible.

[0076] Drag within an aircraft is reduced via HAVC device **100**. For example, refining the HAVC device **100** to have the electronics to fit in an electrical unit **200** above the motor windings assemblies and other mechanical components eliminates the need for a separate housing. Reduction of the space and volume required for the electronics includes reducing the power draw, moving three-phase rectification into the fixed frame of the aircraft, and increasing the density of the electronics design.

[0077] Figure 8 illustrates a rotary winged aircraft **800** including HAVC device **100** and HAVC system **700**. Helicopter **800** comprises one or more rotary blades **802** configured to be received in openings **704** of rotor hub **702**. Helicopter **800** further comprises a non-rotating or fixed body **804** frame. HAVC system **700** comprises HAVC device **100** mounted to rotor hub **702**. In some aspects, HAVC device **100** has a dual frequency device configured to actively control (N-1)P and (N+1)P in-plane vibratory loads caused by rotation of rotor hub **702**. HAVC devices, systems, and related methods described herein can be configured for use in single rotor and/or a tandem rotor aircraft.

[0078] HAVC device **100** rotates with the rotor hub **702** at once per revolution (1 per-rev or 1P) in a counter-clockwise direction as viewed from above rotor **702**. Cancellation of the (N-1)P and (N+1)P in-plane vibrations as measured in the rotating reference frame is equivalent to canceling the NP in-plane vibrations as measured in the non-rotating reference (e.g., the helicopter airframe **804**).

[0079] HAVC system **700** has one or more heating sources **HS** provided at one or more rotary blades **802**. De-icing distributor **208** (Figure 7) disposed within a portion of HAVC device **100** communicates instructions and/or electrical power to the one or more heating sources **HS** for preventing ice from forming on and/or for removing ice from the rotary blades **802**.

[0080] In some aspects, hub-mounted active vibration control (HAVC) methods and/or methods of controlling in-plane vibratory loads occurring at a moving platform are

provided. The method includes providing a moving platform, such as a rotor hub. The method includes mounting an HAVC device **100** to a portion of the moving platform. The device includes improved wear resistance, thermal properties, and compact dimensions as described hereinabove. The device has at least one pair of co-rotating imbalance masses for cancelling unwanted vibration. The device also has at least pairs of imbalance masses, each pair rotating at different frequencies and in different, opposing directions for cancelling unwanted vibration. The device has a tolerance ring (e.g., **600**, Figure 4A) attached to the mechanical unit. The tolerance ring accommodates expansion and contraction of dissimilar metals contained within the mechanical unit (such as the aluminum housing and stainless steel bearing assemblies). The method include rotating at least one pair of imbalance masses at a same frequency and/or two pairs of imbalance masses at different (e.g., dual) frequencies such that the combined forces of the imbalance masses substantially cancel unwanted vibration of the moving platform.

**[0081]** Other embodiments of the current invention will be apparent to those skilled in the art from a consideration of this specification or practice of the invention disclosed herein. Thus, the foregoing specification is considered merely exemplary of the current invention with the true scope thereof being defined by the following claims.

## CLAIMS

What is claimed is:

1. A hub-mounted active vibration control (HAVC) device, comprising:
  - a housing configured to attach to a rotary hub and rotate therewith, wherein the housing includes a tolerance ring configured to accommodate dissimilar coefficients of thermal expansion between components of dissimilar metals;
  - a plurality of coaxial ring motors configured to rotate a plurality of imbalance masses; and
  - an electrical module for independently controlling a rotational position, phase, and/or speed of the plurality of imbalance masses such that the combined forces of the imbalance masses substantially cancel unwanted vibration.
2. The HAVC device of claim 1, wherein the housing is aluminum.
3. The HAVC device of claim 2, wherein a stainless steel bearing component is provided in the aluminum housing.
4. The HAVC device of claim 3, wherein the tolerance ring is provided between the housing and the stainless steel bearing component.
5. The HAVC device of claim 1, further comprising a de-icing distributor integrated within the housing.
6. The HAVC device of claim 1, wherein the plurality of coaxial ring motors has four coaxial ring motors.
7. The HAVC device of claim 6, wherein the four coaxial ring motors are configured to rotate four imbalance masses.
8. The HAVC device of claim 7, wherein two of the imbalance masses are configured to rotate at a first frequency and two other of the imbalance masses are configured rotate at a second frequency for cancelling unwanted vibration.

9. The HAVC device of claim 1, wherein the tolerance ring is press fit directly against an inner diameter of the housing.
10. The HAVC device of claim 9, wherein the tolerance ring extends about an entire inner circumference of the housing.
11. The HAVC device of claim 1, further comprising a removable lid.
12. The HAVC device of claim 11, wherein the electrical module further comprises a slip ring that is accessible through the removable lid while the housing remains attached to the rotary hub.
13. The HAVC device of claim 1, further comprising a plurality of imbalanced rotors integrated with a portion of the plurality of coaxial ring motors.
14. The HAVC device of claim 13, wherein each imbalanced rotor further comprises a dual stage bearing assembly with a single outer race.
15. A hub-mounted active vibration control (HAVC) system, comprising:
  - a mechanical unit attached to a rotary hub and configured to rotate therewith, wherein the mechanical unit including at least one pair of imbalance masses co-rotating at substantially a same frequency; and
  - a de-icing distributor provided over at least a portion of the mechanical unit, wherein the de-icing distributor is configured to communicate instructions to one or more heating sources provided at one or more rotary blades.
16. The HAVC system of claim 15, wherein the de-icing distributor is centrally disposed over the mechanical unit.
17. The HAVC system of claim 15, wherein the de-icing distributor and components within the mechanical unit electrically interface with a slip ring.
18. The HAVC system of claim 15, wherein an electrical unit is provided directly above the mechanical unit.

19. The HAVC system of claim 15, wherein the mechanical unit further comprises a bearing assembly disposed within a housing.
20. The HAVC system of claim 19, wherein a tolerance ring provided between portions of the bearing assembly and the housing.
21. The HAVC system of claim 19, wherein the bearing assembly further comprises a dual stage bearing assembly with a single outer race.
22. A method of controlling in-plane vibratory loads occurring at a moving platform, the method comprising:  
providing a moving platform;  
mounting a vibration control device to a portion of the moving platform, the device configured to move therewith, wherein the device includes:  
a mechanical unit with at least one pair of imbalance masses for rotating at different frequencies; and  
a tolerance ring attached to the mechanical unit, wherein the tolerance ring is configured to accommodate dissimilar coefficients of thermal expansion between components of dissimilar metals contained within the mechanical unit; and  
rotating at least a first pair of imbalance masses at a first frequency such that the combined forces of the imbalance masses substantially cancel unwanted vibration of the moving platform.
23. The method of claim 22, wherein providing a moving platform, the moving platform being a rotor hub of a helicopter.
24. The method of claim 22, wherein the vibration control device is integrated with a de-icing distributor.
25. The method of claim 22, further comprising independently controlling a rotational position, phase, and/or speed of the first pair of imbalance masses.

26. The method of claim 22, further comprising rotating at least a second pair of imbalance masses at a second frequency that is different than the first frequency.

27. The method of claim 26, further comprising rotating the second pair of imbalance masses in a different direction than the first pair of imbalance masses.

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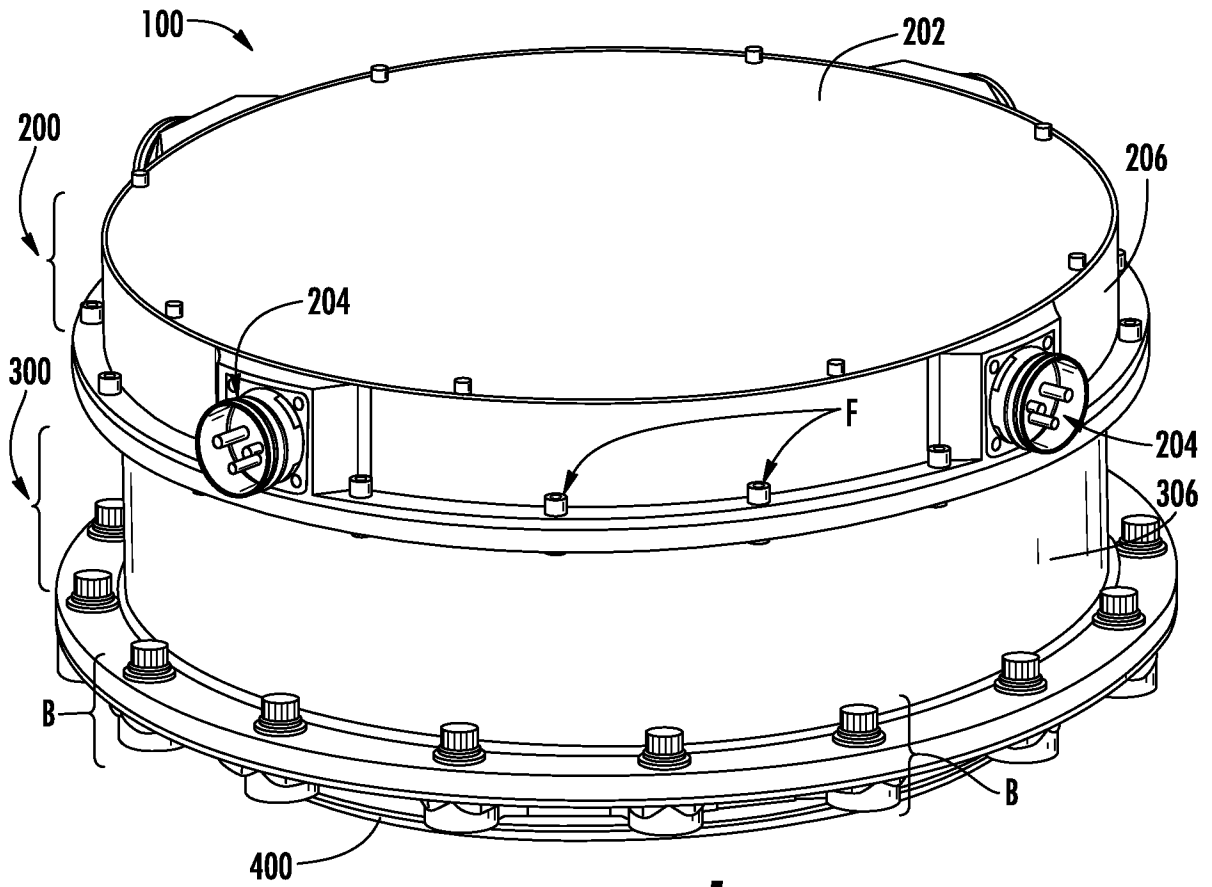


FIG. 1

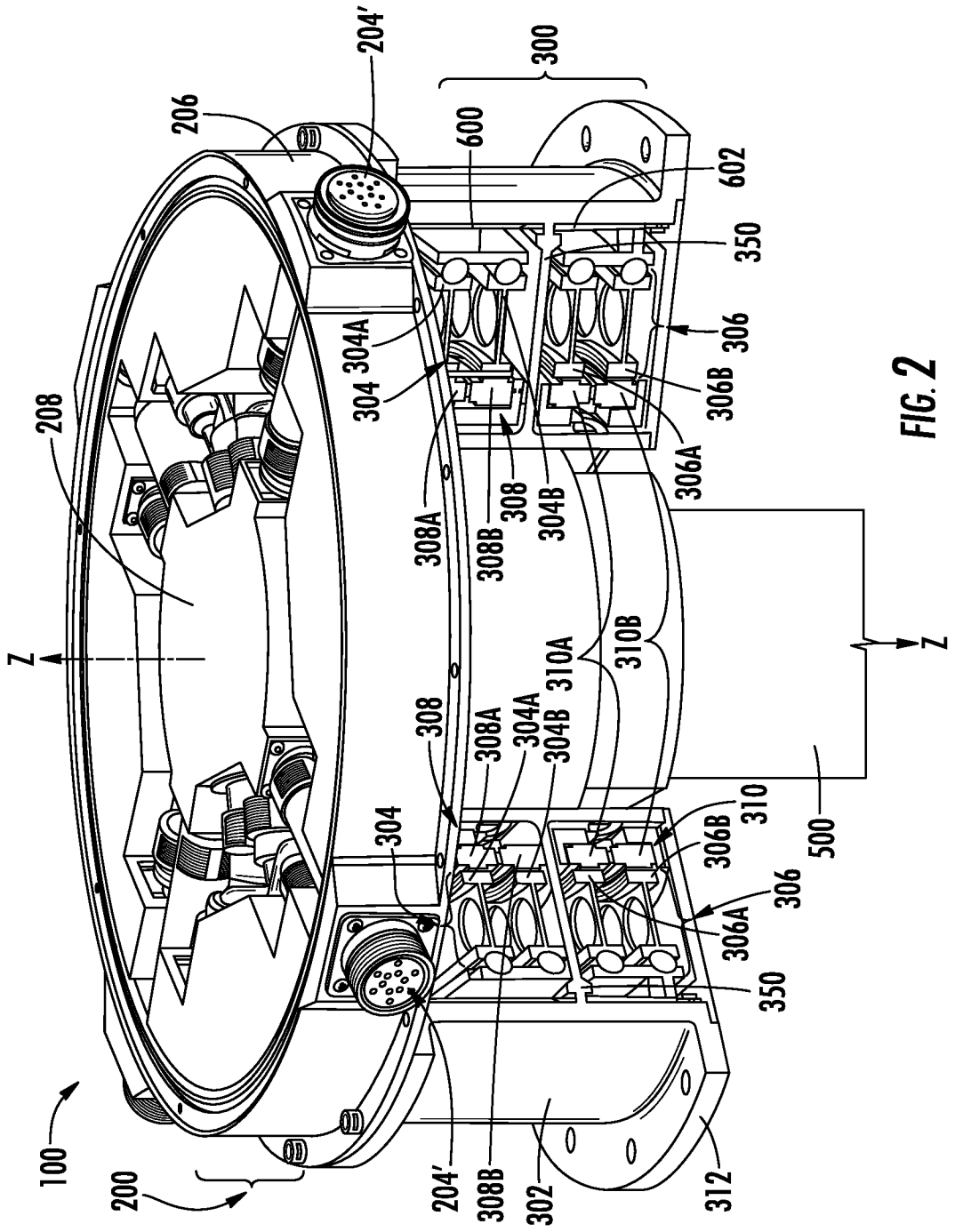


FIG. 2

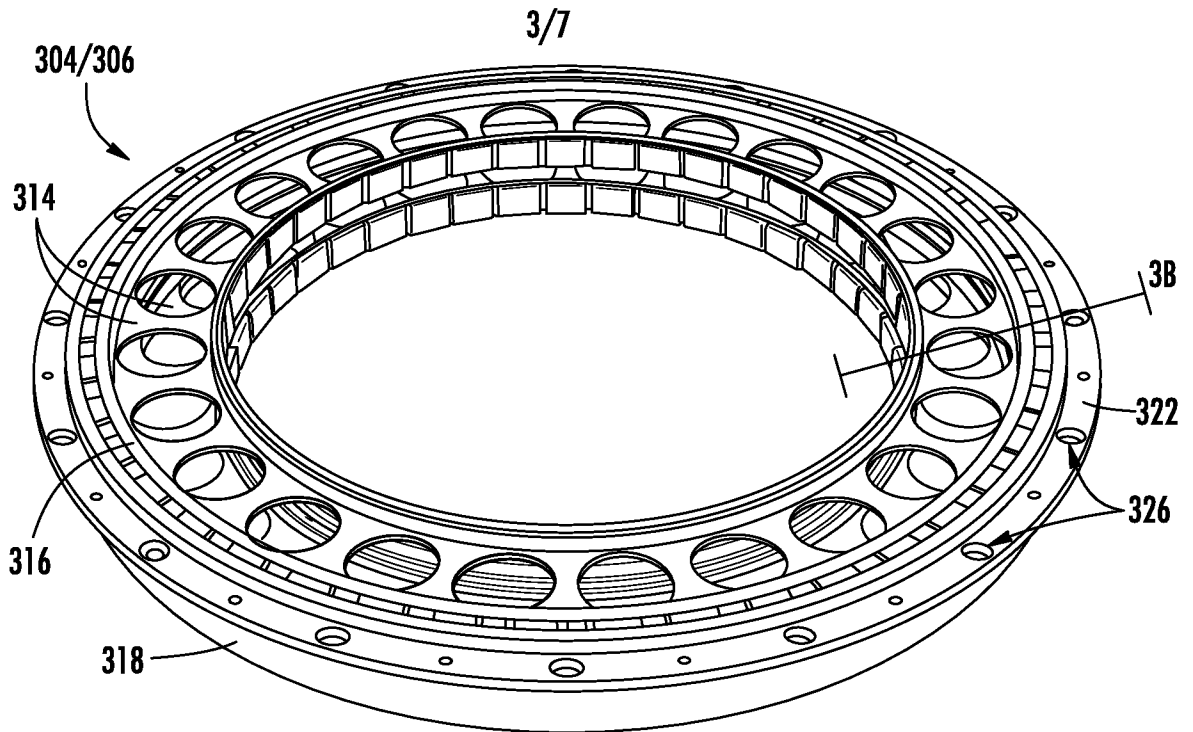


FIG. 3A

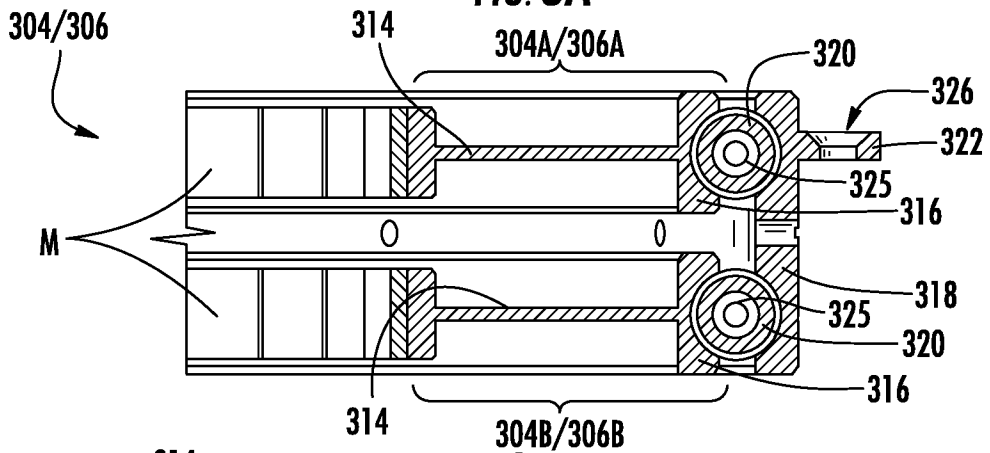


FIG. 3B

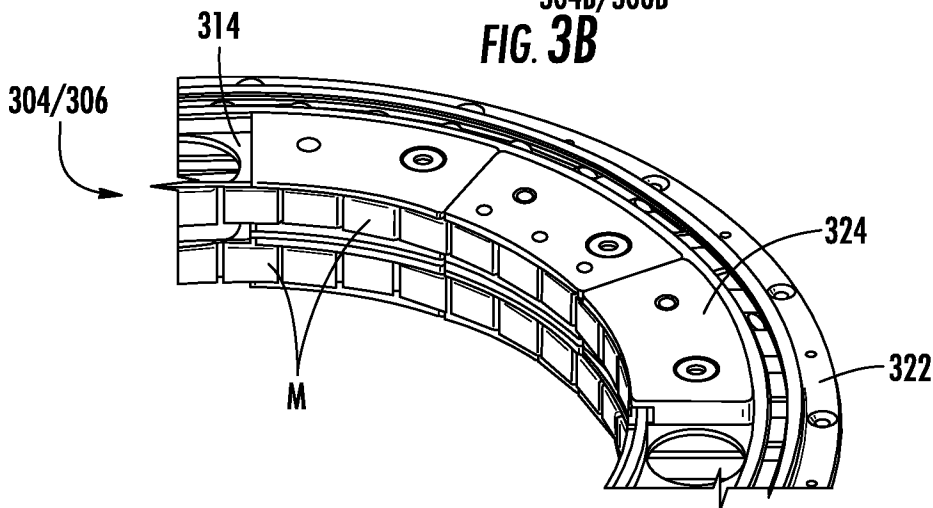


FIG. 3C

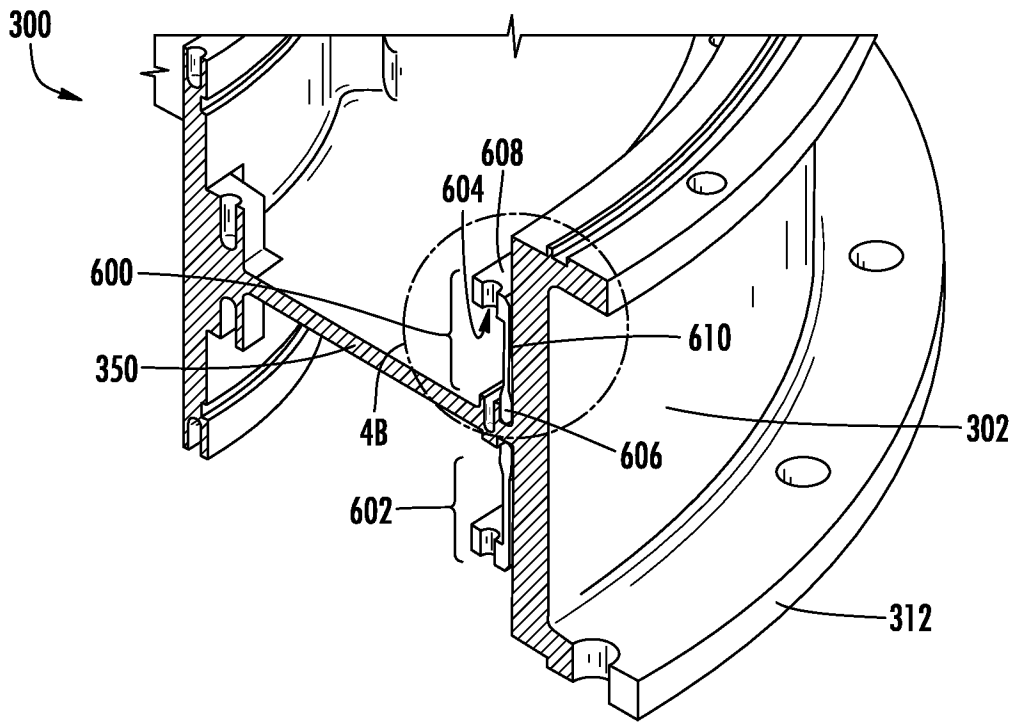


FIG. 4A

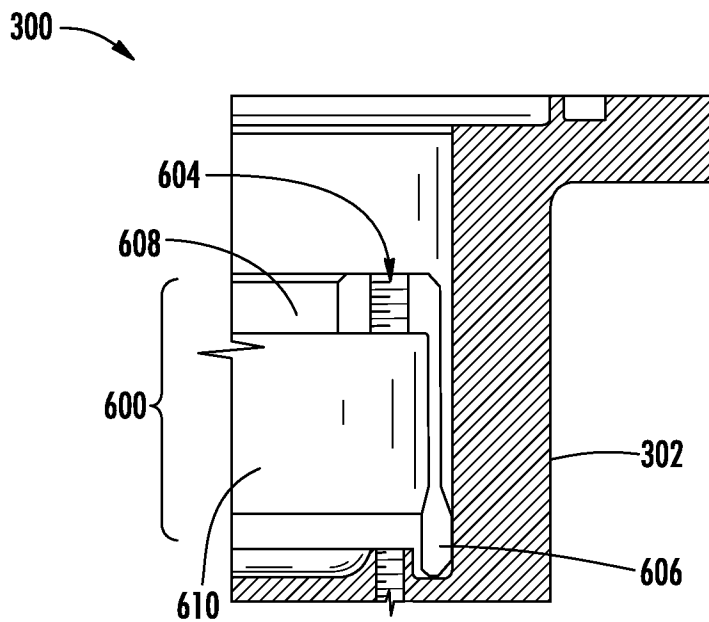


FIG. 4B

