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Gyroscopic boat roll stabilizer with bearing cooling

Abstract

A gyroscopic roll stabilizer includes an enclosure, a flywheel assembly, a bearing, a motor, and a bearing cooling circuit. The enclosure is mounted to a gimbal for rotation about a gimbal axis and configured to maintain a below-ambient pressure. The flywheel assembly includes a flywheel and flywheel shaft. The bearing rotatably mounts the flywheel assembly inside the enclosure for rotation about a flywheel axis. The bearing has an inner race and an outer race. The inner race is rotationally fixed relative to the flywheel shaft, and the outer race is held rotationally fixed relative to the enclosure. The motor is operative to rotate the flywheel assembly. The bearing cooling circuit is configured to transfer heat away from the bearing by recirculating coolant along a closed fluid pathway. The gyroscopic roll stabilizer is configured to transfer heat away from the inner and/or outer race of the bearing to the coolant.

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Background/Summary

RELATED APPLICATIONS (1) This application is a continuation of U.S. application Ser. No. 18/406,574, filed Jan. 8, 2024, which is a continuation of U.S. application Ser. No. 18/102,456, filed Jan. 27, 2023, now U.S. Pat. No. 11,873,064, which is a continuation of U.S. application Ser. No. 17/184,988, filed Feb. 25, 2021, now U.S. Pat. No. 11,591,052, which claims benefit of U.S. Provisional Application No. 63/070,530, filed Aug. 26, 2020, and U.S. Provisional Application No. 62/984,013, filed Mar. 2, 2020, the disclosures of each of which are incorporated herein by reference in their entirety.

TECHNICAL FIELD

(1) The present disclosure relates generally to boat roll stabilizers for reducing the sideways rolling motion of a boat and, more particularly, to controlled moment gyroscopes for reducing the roll of a boat based on the gyroscopic effect.

BACKGROUND

(2) The sideways rolling motion of a boat can create safety problems for passengers and crew on boats, as well as cause discomfort to passengers not accustomed to the rolling motion of the boat. A number of technologies currently exist to reduce the sideways rolling motion of a boat. One technology currently in use is active fin stabilization. Stabilizer fins are attached to the hull of the boat beneath the waterline and generate lift to reduce the roll of the boat due to wind or waves. In the case of active fin stabilization, the motion of the boat is sensed and the angle of the fin is controlled based on the motion of the boat to generate a force to counteract the roll. Fin stabilization is most commonly used on large boats and is effective when the boat is underway. Fin stabilization technology is not used frequently in smaller boats and is generally not effective when the boat is at rest. Stabilizer fins also add to the drag of the hull and are susceptible to damage.

(3) Gyroscopic boat stabilization is another technology for roll suppression that is based on the gyroscopic effect. A control moment gyroscope (CMG) is mounted in the boat and generates a torque that can be used to counteract the rolling motion of the boat. The CMG includes a flywheel that spins at a high speed. A controller senses the attitude of the boat and uses the energy stored in the flywheel to “correct” the attitude of the boat by applying a torque to the hull counteracting the rolling motion of the boat. CMGs work not only when a boat is underway, but also when the boat is at rest. CMGs are also typically less expensive than stabilizer fins, do not add to the drag of the hull, and are not exposed to risk of damage from external impacts.

(4) Although, CMGs are gaining in popularity, particularly for smaller fishing boats and yachts, this technology has some limitations. The energy used to counteract the rolling motion of the boat comes from the angular momentum of the rotation of the flywheel at a high rate of speed. Consequently, heat builds up in the bearings supporting the flywheel and bearing failure can result if the operational temperature of the bearings is exceeded. The flywheel is typically mounted inside an enclosure for safety reasons. In order to obtain the high spin rate, the flywheel is typically contained in a vacuum enclosure, which makes heat dissipation problematic.

(5) Another problem with existing CMGs is that it takes a significant amount of time for the flywheel to “spin up,” i.e., to obtain its desired operating speed. In some CMGs currently on the market, it can take as long as seventy minutes before the CMG is ready for use. The long “spin up”

period means that the CMG cannot be used for trips of short duration, which comprises a majority of boating occasions.

(6) Thus, there remains a need for alternative approaches to gyroscopic boat stabilization, advantageously approaches that allow for better cooling of the bearings, so that performance can be improved.

SUMMARY

(7) The present disclosure relates to a gyroscopic roll stabilizer for a boat. In an aspect, the gyroscopic roll stabilizer includes an enclosure mounted to a gimbal and configured to maintain a below-ambient pressure, a flywheel assembly including a flywheel and flywheel shaft, one or more bearings for rotatably mounting the flywheel assembly inside the enclosure, a motor for rotating the flywheel, and a bearing cooling system for cooling the bearings supporting the flywheel. In one embodiment, the bearing cooling system comprises a heat sink that is disposed within a cavity formed within the end of the flywheel shaft. Heat is transferred from the flywheel shaft to the heat sink and then by solid and/or liquid conduction to the heat exchanger. In another embodiment, cooling is achieved by delivering a liquid coolant into a tapered cavity in the end of the flywheel shaft. The cavity is shaped so that the centrifugal force causes the liquid coolant to flow towards the open end of the shaft, where the liquid coolant is collected by a fluid collection system.

(8) In another aspect, a gyroscopic roll stabilizer for a boat is disclosed. The gyroscopic stabilizer includes an enclosure, a flywheel assembly, a first bearing, a bearing block, a motor, and a bearing cooling circuit. The enclosure is mounted to a gimbal for rotation about a gimbal axis and configured to maintain a below-ambient pressure. The flywheel assembly includes a flywheel and flywheel shaft. The first bearing rotatably mounts the flywheel assembly inside the enclosure for rotation about a flywheel axis. The first bearing has an inner race and an outer race, the inner race affixed to the flywheel shaft. The bearing block is disposed between the outer race of the first bearing and the enclosure and configured to hold the outer race rotationally fixed relative to the enclosure. The motor is operative to rotate the flywheel assembly. The bearing cooling circuit is configured to transfer heat away from the outer race of the first bearing. The bearing cooling circuit has a closed fluid pathway for recirculating cooling fluid therein. The fluid pathway includes a fluid channel disposed between the bearing block and the enclosure and having the cooling fluid therein. The gyroscopic roll stabilizer is configured to transfer heat away from the outer race of the first bearing to the bearing block, and from the bearing block to the cooling fluid.

(9) In another aspect, a method of operating a gyroscopic roll stabilizer for a boat is disclosed. The method includes 1) maintaining a below ambient pressure within an enclosure surrounding a flywheel assembly, the flywheel assembly including a flywheel shaft and a spinning flywheel; 2) supporting the spinning flywheel for rotation about a flywheel axis via a bearing, the bearing comprising an inner race and an outer race, the inner race affixed to the flywheel shaft; 3) supporting the outer race via a bearing block disposed between the outer race and the enclosure and configured to hold the outer race rotationally fixed relative to the enclosure; 4) dissipating heat from the outer race by transferring the heat by conduction and convection to a cooling fluid flowing through a fluid channel disposed between the bearing block and the enclosure; 5) cooling the cooling fluid by removing heat from the cooling fluid external to the portion of the enclosure maintained at the below-ambient pressure; and 6) recirculating the cooling fluid through a closed fluid pathway that includes the fluid channel.

(10) In another aspect, another gyroscopic roll stabilizer for a boat is disclosed. The gyroscopic stabilizer includes an enclosure, a flywheel assembly, a first bearing, a motor, and a bearing cooling circuit. The enclosure is mounted to a gimbal for rotation about a gimbal axis and configured to maintain a below-ambient pressure. The flywheel assembly includes a flywheel and flywheel shaft, with an open-ended cavity formed in an end of the flywheel shaft. The first bearing rotatably mounts the flywheel assembly inside the enclosure for rotation about a flywheel axis. The first bearing has an inner race affixed to the flywheel shaft proximate the cavity and an outer race

rotationally fixed relative to the enclosure. The motor is operative to rotate the flywheel assembly. A liquid heat transfer medium is disposed in the cavity. The bearing cooling circuit is configured to transfer heat away from the inner race of the first bearing by recirculating a cooling fluid. The bearing cooling circuit includes a heat transfer shaft assembly and a closed fluid pathway. The heat transfer shaft assembly is rotationally fixed relative to the flywheel axis and extends from the enclosure into the cavity so as to contact the liquid heat transfer medium. The closed fluid pathway for the cooling fluid extends through the heat transfer shaft assembly to internally cool the heat transfer shaft assembly. The gyroscopic roll stabilizer is configured to transfer heat away from the inner race of the first bearing to the flywheel shaft, and from the flywheel shaft to the liquid heat transfer medium, and from the liquid heat transfer medium to the heat transfer shaft assembly, and from the heat transfer shaft assembly to the cooling fluid.
(11) In another aspect, a method of operating a gyroscopic roll stabilizer for a boat is disclosed. The method includes 1) maintaining a below ambient pressure within an enclosure surrounding a flywheel assembly, the flywheel assembly including a flywheel shaft and a spinning flywheel; wherein the flywheel shaft has an open-ended cavity formed in an end of the flywheel shaft; wherein a liquid heat transfer medium is disposed in the cavity; 2) supporting the spinning flywheel for rotation about a flywheel axis via a bearing, the bearing comprising an inner race and an outer race, the inner race affixed to the flywheel shaft; 3) dissipating heat from the inner race by transferring the heat by conduction and convection to a bearing cooling circuit configured to transfer heat by recirculating a cooling fluid along a closed fluid pathway; 4) cooling the cooling fluid by removing heat from the cooling fluid external to the portion of the enclosure maintained at the below-ambient pressure; and 5) recirculating the cooling fluid through the closed fluid pathway. The dissipating heat comprises internally cooling, by the cooling fluid, a heat transfer shaft assembly rotationally fixed relative to the flywheel axis and extending from the enclosure into the cavity so as to contact the liquid heat transfer medium. In the method, heat is transferred away from the inner race of the bearing to the flywheel shaft, and from the flywheel shaft to the liquid heat transfer medium, and from the liquid heat transfer medium to the heat transfer shaft assembly, and from the heat transfer shaft assembly to the cooling fluid.
(12) The features, functions and advantages that have been discussed above, and/or are discussed below, can be achieved independently in various aspects or may be combined in yet other aspects, further details of which can be seen with reference to the following description and the drawings.

Description

BRIEF DESCRIPTION OF THE DRAWINGS
(1) FIGS. **1**A and **1**B illustrate a boat equipped with a CMG as herein described.
(2) FIG. **2** show an elevation view of a CMG configured as a boat roll stabilizer according to an embodiment.
(3) FIG. **3** shows a section view through the enclosure of a CMG according to an embodiment.
(4) FIG. **4** shows a partial section view of FIG. **3**.
(5) FIG. **5** shows a cooling circuit for a CMG.
(6) FIG. **6** shows a torque control system for the CMG.
(7) FIG. **7** shows a partial section view illustrating the bearing cooling system according to another embodiment.
(8) FIG. **8** shows a partial section view illustrating a CMG with both an inner race bearing cooling circuit and an outer race bearing cooling circuit.
(9) FIG. **9** shows a simplified schematic of a bearing cooling circuit for cooling the outer race.
(10) FIG. **10** shows a simplified flowchart of an exemplary method for cooling the outer race.
(11) FIG. **11** shows a simplified schematic of a bearing cooling circuit for cooling the inner race.

(12) FIG. **12** shows a simplified flowchart of an exemplary method for cooling the inner race.

DETAILED DESCRIPTION

(13) Referring now to the drawings, FIGS. **1**A and **1**B illustrate a control moment gyroscope (CMG) **10** mounted in a boat **5** for roll stabilization. Multiple embodiments of the CMG **10** are described. For convenience, similar reference numbers are used in the following description of the embodiments to indicate similar elements in each of the embodiments.

(14) Referring now to FIGS. **2** and **3**, the main functional elements of the CMG **10** comprise a single-axis gimbal **20**, an enclosure **30** mounted to the gimbal **20** for rotation about a gimbal axis G, a flywheel assembly **40** mounted by bearings **50** inside the enclosure, a motor **60** (FIG. **5**) to rotate the flywheel assembly **40**, and a torque control system **70** (FIG. **5**) to control precession of the flywheel assembly **40**, with the energy of the flywheel assembly **40** transferred to the hull of the boat **5** to counteract rolling motions. Each of the embodiments further comprises a bearing cooling system **100** to cool the flywheel bearings **50**. Various designs of the bearing cooling system **100** are disclosed.

(15) The gimbal **20** comprises a support frame **22** that is configured to be securely mounted in the boat **5**. Preferably, the gimbal **20** is mounted along a longitudinal axis L of the boat **5** with the gimbal axis G extending transverse to the longitudinal axis L. Conventionally, the gimbal **20** is mounted in the hull of the boat **5**, but could be mounted at any location. The support frame **22** of the gimbal **20** comprises a base **24** and two spaced-apart supports **26**. A bearing **28** is mounted on each support **26** for rotatably mounting the enclosure **30** to the supports **26**. For this purpose, the enclosure **30** includes two gimbal shafts **32** projecting from diametrically opposed sides of the enclosure **30**. The gimbal shafts **32** are rotatably journaled in the gimbal bearings **28** to allow the enclosure **30** (and flywheel assembly **40** disposed therein) to rotate or precess about the gimbal axis G in the fore and aft directions.

(16) The basic elements of enclosure **30** are the same in the various embodiments described herein but vary in some details depending on the design of the bearing cooling system **100**. The enclosure **30** is advantageously generally spherical in form and comprises two main housing sections **34** and two cover plates **36**. The two main housing sections **34** join along a plane that typically bisects the spherical enclosure **30**. The cover plates **36** join the main housing sections **34** along respective planes closer to the “poles” of the spherical enclosure **30**. All joints in the enclosure **30** are sealed to maintain a below-ambient pressure within the enclosure **30** to reduce aerodynamic drag on the flywheel assembly **40**. Typical below-ambient pressures should be in the range of 1-40 torr (133-5333 Pa, 0.02-0.77 psi). Although the construction of the enclosure **30** is generally the same in the embodiments herein described, the details of the housing sections **34** and cover plates **36** vary as described more fully below depending on the design of the bearing cooling system **100** used.

(17) Referring to FIG. **3**, the flywheel assembly **40** conceptually comprises a flywheel **42** and flywheel shaft **44** that is mounted for rotation inside the enclosure **30** of the gimbal **20** so that the axis of rotation F of the flywheel assembly **40** is perpendicular to the gimbal axis G. Thus, when the boat **5** is level such that gimbal axis G is horizontal, the axis of rotation F of the flywheel shaft **44** will be in the vertical direction, typically perpendicular to the deck of the boat. The flywheel **42** and shaft **44** may be formed as a unitary piece, or may comprise two separate components. In one exemplary embodiment, the diameter and the flywheel **42** is approximately 20.5 inches; the flywheel assembly **40** has a total weight of about 614 pounds; and the flywheel assembly **40** has a moment of inertia of about 32,273 lbm in.sup.2. When rotated at a rate of 9000 rpm, the angular momentum of the flywheel assembly **40** is about 211,225 lbm ft.sup.2/s.

(18) The flywheel assembly **40** is supported by upper and lower bearing assemblies inside the enclosure **30**. Each bearing assembly comprises a bearing **50** mounted within a bearing block **58**. Each bearing **50** comprises an inner race **52** that is affixed to and rotates with the flywheel shaft **44**, an outer race **54** that is mounted inside the bearing block **58**, and one or more ball bearings **56** disposed between the inner and outer races **52**, **54**. The bearing blocks **58** are secured to the interior

of the enclosure **30**. Seals (not shown) may advantageously be disposed on the top and bottom of the bearings **50** to contain lubricant in the bearings **50**.
(19) The motor **60** rotates the flywheel assembly **40** at a high rate of speed (e.g., 9000 rpm). The motor **60** includes a rotor **62** that connects to the flywheel shaft **44** and a stator **64** that this secured to the enclosure **30** by any suitable mounting system. Although the motor **60** is advantageously mounted inside the enclosure **30**, it is also possible to mount the motor **60** on the exterior of the enclosure **30**. In one embodiment, the motor **60** operates on 230 Volt single phase AC power (or could be three-phase AC power, or AC or DC battery power, such as from a lithium ion battery pack) and is able to accelerate a flywheel assembly with a moment of inertia of about 32,273 lbm in.sup.2 from rest to a rotational speed of 9000 rpm preferably in about 30 minutes or less for an average acceleration of about 5 rpm/s, and more preferably in about 20 minutes or less for an average acceleration of about 7.75 rpm/s, and even more preferably in about 10 minutes or less for an average acceleration of about 15 rpm/s (or 1.57 radians/s.sup.2).
(20) The torque control system **70**, shown in FIG. **5**, controls the rate of precession of the flywheel assembly **40** about the gimbal axis G. The rolling motion of a boat **5** caused by wave action can be characterized by a roll angle and roll rate. The rolling motion causes the flywheel **42** to precess about the gimbal axis G. Sensors **74**, **76** measure the roll angle and roll rate respectively, which are fed to a controller **72**. The controller **72** generates control signals to control an active braking system or other torque applying device **78** that controls the rate of precession of the flywheel assembly **40**. By controlling the rate of precession, the flywheel assembly **40** generates a torque in opposition to the rolling motion. This torque is transferred through the gimbal **20** to the boat **5** to dampen the roll of the boat **5**. An example of the active braking system **78** is described in U.S. Patent Application Publication No. US20200317308.
(21) When the flywheel assembly **40** rotates at high speed, the bearings **50** and motor **60** will generate a substantial amount of heat, which could lead to bearing and/or motor failure. Conventional air and liquid cooling techniques are not suitable for bearings **50** or other heat generating components contained within a vacuum or significantly below ambient pressure environment. Various embodiments of the bearing cooling system **100** are disclosed herein allow cooling of bearings **50** and optionally other heat generating components contained within the enclosure **30** without direct contact of the recirculated liquid coolant with the bearings **50** or other moving heat generating components, which would result in high frictional losses. In general, heat is transferred by solid and/or liquid conduction to a heat sink that is cooled by oil, glycol, or other liquid coolant. Liquid cooling enables more heat to be dissipated compared to air cooling or gaseous convection and conduction. Reliance on gaseous convection and conduction in existing CMGs imposes limitations on the amount of heat that can be dissipated because the interior of the enclosure **30** is typically maintained at a below ambient pressure. The limited heat transfer capacity in conventional CMGs imposes limitations on the size of the electric motor that is used, which in turn extends the time required to engage and use the conventional CMG. Because the electric motor in conventional CMGs is undersized to avoid heat generation, conventional CMGs require significant time to accelerate the flywheel assembly **40** to a speed that provides the desired counter-torque and roll stabilization. Providing more efficient cooling of the bearings **50** as herein described enables use of a larger and more powerful motor **60** and faster acceleration of the flywheel assembly **40** so that the benefits of using the CMG **10** can be obtained in significantly shorter time periods.
(22) FIG. **6** is a schematic diagram of a cooling circuit **80** for circulating the liquid coolant. A fluid reservoir **82** contains the liquid coolant which is circulated in a “closed” circuit by a fluid pump **84**. The fluid reservoir **82** may include a heat exchanger **83** to cool the liquid coolant in the fluid reservoir **82**. After leaving the fluid reservoir **82**, the liquid coolant passes through the heat exchanger **86** where it adsorbs and carries away heat generated by the bearings **50**, as described more fully below. In some embodiments, heat is transferred from the flywheel shaft **44** to a heat

sink and then by solid and liquid conduction to the heat exchanger **86**. In other embodiments, heat is transferred from the flywheel shaft **44** to the liquid coolant which is circulated through a cavity **46** in the flywheel shaft **44**. Accordingly, the heat transfer to the liquid coolant occurs within the cavity **46** of the flywheel shaft **44** so the heat exchanger **86** is not required. In some embodiments, a scavenging circuit **88** is provided to collect liquid coolant that may seep into the interior of the enclosure **30** and return the liquid coolant to the fluid reservoir **82**.

(23) FIG. **4** illustrates one embodiment of a bearing cooling system **100** using a heat sink to dissipate heat generated by the bearings **50** and/or motor **60**. While the present discussion of the bearing cooling system **100** is generally in the context of cooling the upper bearing **50**, it should be noted that the upper and lower bearings **50** may be cooled in similar ways, if desired. For the upper bearing **50**, the upper portion of the flywheel shaft **44** is secured within bearing **50** that is, in turn, secured within the enclosure **30**. Each bearing **50** includes an outer race **54**, one or more ball bearings **56**, and an inner race **52** that engages the flywheel shaft **44** and rotates therewith. The flywheel shaft **44** includes a cavity **46** at each end thereof. The cavity **46** in each end of the flywheel shaft **44** is open at one end and includes a side wall and a bottom wall (opposite the opening of the cavity **46**).

(24) A heat transfer member **102** that functions as a heat sink is suspended in the cavity **46**. The heat transfer member **102** does not directly engage the side or bottom walls of the cavity **46**. Rather, the outer surface of the heat transfer member **102** is spaced from the side and bottom walls of the cavity **46**. In one embodiment, the spacing between the heat transfer member **102** and the walls of the cavity **46** is approximately 0.035-0.095 inches. Various materials can be used for the heat transfer member **102** discussed herein. Preferably, copper, aluminum, or alloys thereof are used because of their relatively high thermal conductivity.

(25) A heat transfer medium is contained in the gap between the heat transfer member **102** and the walls of the cavity **46**. As one example, the heat transfer medium comprises a low vapor pressure fluid that is suitable for the low pressure environment in the enclosure **30**. A low vapor pressure fluid is a liquid, such as oil, that has a relatively low boiling point compared to water and is suitable for employment in a vacuum environment. For example, aerospace lubricants, such as perfluoropolyether (PFPE) lubricants, designed for vacuum environments can be used as the heat transfer medium. The low vapor pressure fluid enables transfer of heat from the flywheel shaft **44** to the heat transfer member **102** by liquid conduction and liquid convection. A labyrinth seal **110** extends around the heat transfer member **102** and effectively seals the cavity **46** such that the heat transfer medium is maintained within the cavity **46**. The labyrinth seal **110** is preferably fixed to the heat transfer member **102**, which means that the flywheel shaft **44** rotates around the labyrinth seal **110**.

(26) As seen in FIG. **4**, heat transfer member **102** extends from cavity **46**, through an opening in a cover plate **36** forming a part of the enclosure **30**, and into a heat exchanger **86**. Seals **108** located in corresponding grooves in the cover plate **36** maintain vacuum within the enclosure **30**. The heat exchanger **86** is mounted to the exterior surface of the cover plate **36**. The heat exchanger **86** comprises a housing **106** and a heat exchange plate **104** confined within the housing **106**. The heat transfer member **102** is secured by a fastener **103** to the heat exchange plate **104** so that the heat transfer member **102** is effectively suspended in the cavity **46** formed in the flywheel shaft **44**. More particularly, the heat exchange plate **104** includes a recess in the bottom surface thereof that receives the end of the of the heat transfer member **102**. The surface contact between the end of the heat transfer member **102** and the heat exchange plate **104** facilitates the efficient transfer of heat by solid conduction from the heat transfer member **102** to the heat exchange plate **104**.

(27) A liquid coolant, such as a glycol coolant, is circulated through the heat exchanger **86** to absorb and carry heat away from the heat exchange plate **104**. The upper surface of the heat exchange plate **104** can be provided with fluid channels and/or cooling fins to increase the surface area of the heat exchange plate **104** and to facilitate heat transfer from the heat exchange plate **104**

to the liquid coolant.
(28) Heat is generated in the inner and outer races of the bearing assemblies **50** due to the high side loads generated from the CMG's torque as the enclosure **30** rotates about the gimbal axis G. The outer race **54** has a continuous heat conductive path through the enclosure **30** which permits the heat associated with the outer race **54** to be conveyed into the atmosphere. The inner race **52** requires a heat sink path through parts of the enclosure **30**. In this embodiment, heat from the inner race **52** of the bearing assembly **50** is transferred by solid conduction to the flywheel shaft **44**. The heat is then transferred by liquid conduction from the flywheel shaft **44** to the heat transfer member **102**, and by solid conduction through the heat transfer member **102** to the heat exchange plate **104** that continuously conveys the heat into surrounding liquid coolant. In some embodiments, the heat exchanger **86** could employ air or gas cooling rather than liquid cooling.
(29) FIG. **7** illustrates an alternate bearing cooling system **100** that also uses a heat sink. This bearing cooling system **100** in FIG. **7** is similar to the design shown in FIG. **4**. The main differences lie in the shapes of the heat transfer member **102**, labyrinth seal **110**, and the heat exchange plate **104**. In this embodiment, the heat transfer member **102** includes a channel that increases the surface area exposed to the heat transfer medium. The heat exchange plate **104**, in contrast to the previous embodiment, has a smooth top surface without grooves or vanes. The heat transfer path, however, is conceptually similar. That is, heat associated with the inner race **52** is transferred to the flywheel shaft **44** by solid conduction. The cavity **46** formed in the flywheel shaft **44**, like the above design (FIG. **4**), is configured to hold the heat transfer medium (typically a low vapor pressure fluid) so that heat is transferred by liquid conduction from the flywheel shaft **44** through the heat transfer medium to the lower portion of a heat transfer member **102**. Thereafter, heat in the heat transfer member **102** is transferred by solid conduction to the heat exchange plate **104**. A liquid coolant is circulated through the heat exchanger **86**. In doing so, the liquid coolant contacts the heat exchange plate **104** and heat associated with the heat exchange plate **104** is transferred to the circulating liquid coolant.
(30) FIG. **8** is another alternative design for a bearing cooling system **100** for a gyroscopic boat stabilizer (e.g., CMG **10**). This design is similar in concept to the preceding designs but differs in a number of respects. For example, the bearing cooling system **100** of FIG. **8** has an optional bearing cooling circuit **100′** (see FIG. **9**) for the outer race **54** of the bearing. As another example, the bearing cooling system **100** of FIG. **8** has a heat transfer shaft assembly **130** that extends into the cavity **46** of the flywheel shaft **44**, and that is internally cooled. Except where noted below, the basic design of the gimbal **20**, enclosure **30**, flywheel assembly **40**, bearing assemblies **50** and motor **60** (FIG. **5**) of the CMG **10** shown in FIG. **8** are essentially the same as previously described. Therefore, the following description will not reiterate the details of these elements.
(31) Referring to FIG. **8**, the CMG **10** includes an enclosure **30**, a flywheel assembly **40**, a bearing **50**, a bearing block **58**, a motor **60**, and a bearing cooling circuit. The portions of the enclosure **30**, flywheel assembly **40**, and motor **60** (not shown in FIG. **8**) are similar to that discussed above, and only briefly discussed herein for clarity. As discussed above, the enclosure **30** is mounted to the gimbal **20** for rotation about the gimbal axis G, and is configured to maintain a below-ambient pressure inside the enclosure **30**. The flywheel assembly **40** is rotatably mounted in the enclosure **30**, and includes flywheel **42** and flywheel shaft **44**. The flywheel assembly **40** is rotatably mounted inside the enclosure **30** for rotation about flywheel axis F. While the flywheel assembly **40** is advantageously rotatably mounted in the enclosure **30** by at least two bearings **50** disposed towards opposing “poles” of the flywheel assembly **40**, in some versions the flywheel assembly **40** is rotatably mounted by one bearing **50**. The cooling of the upper bearing **50** (typically located generally opposite the motor **60**) will be discussed, it being understood that other bearings **50**, if present, are advantageously cooled by similar corresponding bearing cooling circuits, or sub-portions of a bearing cooling circuit.
(32) As is conventional, the bearing includes inner race **52** and outer race **54**. The inner race **52** is

affixed to the flywheel shaft **44** so that the inner race **52** rotates with the flywheel shaft **44**. The outer race **54** is mounted to a bearing block **58**, and the bearing block **58** is mounted to the enclosure **30**, so that the outer race **54** is rotationally fixed relative to the enclosure **30**. The mounting of the bearing block **58** to the enclosure **30** may be via any suitable means, such as by suitable lip(s) in the bearing block **58** and one or more bearing cap plates **59***a* held by screws. Likewise, the affixing of the inner race **52** to the flywheel shaft **44** may be by any suitable means, such as press fitting, and/or suitable lip(s) in the flywheel shaft **44** and one or more bearing cap plates **59***b* held by screws. The bearing block **58** may be generally round in cross-section (perpendicular to flywheel axis F), but this is not required and any suitable shape may be employed, including faceted shapes.

(33) A bearing cooling circuit **100′** is used to transfer heat away from the outer race **54**. See FIG. **9**. The bearing cooling circuit **100′** includes a fluid pathway **210** that is closed, and is sometimes referred to as the closed fluid pathway **210**. The fluid pathway **210** is used for recirculating cooling fluid **90**, with the cooling fluid **90** being used as part of the heat dissipation mechanism for removing heat from the outer race **54**. The cooling fluid **90** may be any suitable fluid, with a liquid such as glycol and/or glycol mixtures being particular examples. The fluid pathway **210** includes a fluid channel **220** disposed near the outer race **54** and between the bearing block **58** and the enclosure **30**. The fluid channel **220** has cooling fluid **90** therein. The fluid channel **220** is advantageously jointly defined by the bearing block **58** and the enclosure **30**. For example, the bearing block **58** may include one or more grooves **222** on its outer surface. Such groove(s) **222** are conceptually closed off, to form the fluid channel **220**, by the inner wall of enclosure **30** facing the bearing block **58**. Alternatively and/or additionally, the enclosure **30** may include one or more grooves **222** on an inner surface that faces the bearing block **58**. Such groove(s) **222** are conceptually closed off, to form the fluid channel **220**, by the outer surface of the bearing block **58** facing the enclosure **30**. Note that the groove(s) **222** may be oriented perpendicular to the flywheel axis F, or may advantageously spiral around the flywheel axis F, such as by being helical or other spiral shape. Alternatively, the groove(s) **222** may wind around the interface of the bearing block **58** and the enclosure **30** in any suitable fashion, such as in a sinusoidal shape, or a zig-zag shape, whether regular or irregular. Optionally, the fluid pathway **210** peripherally surrounds the flywheel axis F, such as by circumnavigating the bearing block **58**. The flow direction in the fluid pathway **210** may be in any suitable direction, such as clockwise or counter-clockwise, or both as appropriate. When the fluid channel **220** is spiral (e.g., helical), the cooling fluid **90** advantageously flows through the fluid channel **220** spirally (e.g., helically) either outward away from the flywheel **42**, or inward toward flywheel **42**.

(34) The bearing cooling circuit **100′** optionally also includes a reservoir **82** for the cooling fluid **90** flowing through the cooling circuit **100′**, and a fluid pump **84** operative to recirculate the cooling fluid **90** through bearing cooling circuit **100′**. Thus, the fluid pathway **210** for the cooling fluid **90** optionally extends through the fluid reservoir **82**, the fluid channel **220**, and the fluid pump **84**. Thus, the pump **84** is operatively connected to the fluid channel **220** and configured to recirculate the cooling fluid **90** through the fluid channel **220** to remove heat from the outer race **54** via the bearing block **58**. The presence of the bearing cooling circuit **100′** in the gyroscopic roll stabilizer allows the gyroscopic roll stabilizer to be configured to transfer heat away from the outer race **54** to the bearing block **58**, and from the bearing block **58** to the cooling fluid **90**. Note that a heat exchanger, such as heat exchanger **83**, is operatively connected to closed fluid pathway **210** and configured to remove heat from the cooling fluid **90** to ambient after the cooling fluid **90** has passed through the fluid channel **220**.

(35) In some aspects, the fluid pathway **210** also includes an inlet port **206** and an outlet port **208**. The inlet port **206** is operatively disposed between the pump **84** and the fluid channel **220**, and operative to allow passage of the cooling fluid **90** into the enclosure **30** toward the fluid channel **220**. The outlet port **208** is operatively disposed between the fluid channel **220** and the heat

exchanger **83**, and operative to allow passage of the cooling fluid **90** out of the enclosure **30** toward the heat exchanger **83**.

(36) For the FIG. **8** arrangement, the heat flow for dissipating heat from the outer race **54** is from the outer race **54**, to the bearing block **58**, then to the cooling fluid **90** in the fluid channel **220**, then to external to the CMG **10** via the heat exchanger **83**. Note that the heat is transferred by solid conduction from the outer race **54** to the bearing block **58**, then by solid conduction through the bearing block **58**, then by conduction and convection to the cooling fluid **90**.

(37) A method (**300**) of operating a gyroscopic roll stabilizer **10** that includes a bearing cooling circuit **100′** for the outer race **54** of the bearing discussed above is shown in FIG. **10**. The method (**300**) includes maintaining (**310**) a below ambient pressure within enclosure **30**, with enclosure **30** surrounding flywheel assembly **40**. The flywheel assembly **40** includes flywheel shaft **44** and spinning flywheel **42**. The method also includes supporting (**320**) the spinning flywheel for rotation about flywheel axis F via bearing **50**, the bearing **50** comprising inner race **52** and outer race **54**, with the inner race **52** affixed to the flywheel shaft **44**. The method further includes supporting (**330**) the outer race **54** via bearing block **58** disposed between the outer race **54** and the enclosure **30** and configured to hold the outer race **54** rotationally fixed relative to the enclosure **30**. The method also includes dissipating (**340**) heat from the outer race **54** by transferring the heat by conduction and convection to a cooling fluid **90** flowing through fluid channel **220** disposed between bearing block **58** and enclosure **30**. Further, the method includes cooling (**360**) the cooling fluid **90** by removing heat from the cooling fluid **90** external to the portion of the enclosure **30** maintained at the below-ambient pressure. In addition, the method includes recirculating (**370**) the cooling fluid **90** through closed fluid pathway **210** that includes the fluid channel **220**. Note that the recirculating (**370**) optionally includes routing (**372**) the cooling fluid **90** from the fluid channel **220** to reservoir **82**, and pumping (**374**) the cooling fluid **90** from the reservoir **82** to the fluid channel **220**, and the cooling (**360**) the cooling fluid **90** comprises cooling the cooling fluid **90** via a heat exchanger **83** disposed external to the enclosure **30**. Optionally, the operating method includes driving (**350**) the flywheel **42** to spin about flywheel axis F via motor **60** disposed internal to the enclosure **30**. Note that the various steps of method (**300**) may be carried out in any suitable order, including in whole or in part in parallel. For example, at least the maintaining (**310**), the supporting (**320**) the flywheel, the supporting (**330**) the outer race, and the dissipating (**340**) are advantageously carried out simultaneously.

(38) Referring again to FIG. **8**, the CMG **10** alternatively and/or additionally includes an arrangement for dissipating heat from the inner race **52**. In this regard, the flywheel shaft **44** includes open-ended cavity **46** formed in an end of the flywheel shaft **44**. A liquid heat transfer medium **122** is disposed in cavity **46**. The liquid heat transfer medium **122** may be any suitable material for operating in the low-pressure environment of the enclosure **30**. For example, the liquid heat transfer medium **122** may be hydrocarbon oils (alkylated aromatics as well as alkanes, paraffinic mineral oils, and other synthetic hydrocarbons), fluorocarbon oils (such as PFPE), silicone fluids of various chain lengths (e.g., polydimethylsiloxane (PDMS)), glycol mixtures, and combinations thereof. The liquid heat transfer medium **122** is held in cavity **46** by one or more suitable seals **125**. Note that the inner race **52** is affixed to the flywheel shaft **44** proximate cavity **46**.

(39) A bearing cooling circuit **100″** is configured to transfer heat away from the inner race **52** of the by recirculating cooling fluid **90**. See FIG. **11**. As with bearing cooling circuit **100′**, the cooling fluid **90** in bearing cooling circuit **100″** may be any suitable fluid, with a liquid such as glycol and/or glycol mixtures being particular examples. Bearing cooling circuit **100″** includes a heat transfer shaft assembly **130** rotationally fixed relative to the flywheel axis F and extending from the enclosure **30** into cavity **46** so as to contact liquid heat transfer medium **122**. The bearing cooling circuit **100″** also includes a closed fluid pathway **210** for the cooling fluid **90** that extends through the heat transfer shaft assembly **130** to internally cool the heat transfer shaft assembly **130**. The

CMG **10** is configured to transfer heat away from the inner race **52** to the flywheel shaft **44**, and from the flywheel shaft **44** to the liquid heat transfer medium **122**, and from the liquid heat transfer medium **122** to the heat transfer shaft assembly **130**, and from the heat transfer shaft assembly **130** to the cooling fluid **90**. Note that the cavity **46** is wider (in the horizontal direction of FIG. **8**) than the corresponding section of the heat transfer shaft assembly **130**. Thus, the heat transfer assembly **130** and the inner wall of the cavity **46**, assuming both are round in cross-section, are annularly spaced from one another by a gap, and the liquid heat transfer medium **122** is disposed in this gap. Optimal sizing of this gap may depend on the viscosity, heat transfer, and other characteristics of the heat transfer medium **122**, which impact the viscous drag and/or corresponding heat generation of the heat transfer medium **122**. In some aspects, this gap is advantageously in the range of about one half to one and a half inches.

(40) In some aspects, the heat transfer shaft assembly **130** is a simple unified shaft that includes an internal chamber for the cooling fluid to be circulated through. In other aspects, the heat transfer shaft assembly **130** includes a shaft **131**, a sleeve **136**, and fluid channel **120**. The shaft **131** extends from the enclosure **30** and into cavity **46**. The shaft **131** advantageously has outer groove(s) **132** and an inner passage **134**. As with groove(s) **222**, groove(s) **132** may be oriented perpendicular to the flywheel axis F, or may advantageously spiral around the flywheel axis F, such as by being helical or other spiral shape. Alternatively, groove(s) **132** may wind around the shaft **131** in any suitable fashion, such as in a sinusoidal shape, or a zig-zag shape, whether regular or irregular. Advantageously, the groove(s) **132** peripherally surround the flywheel axis F, such as by circumnavigating the shaft **131**. The sleeve **136** is disposed about the shaft **131** in spaced relation to the “floor” of the groove(s) **132** and in spaced relation to an inner wall on flywheel shaft **44** defining the cavity **46**. For example, as shown in FIG. **8**, the sleeve **136** disposed about the shaft **131** so as to overlap the groove(s) **132** and is disposed in spaced relation to an inner wall defining the cavity **46**. A fluid channel **120** is jointly defined by the sleeve **136** and the groove(s) **132**, with the fluid channel **120** having the cooling fluid **90** therein. The closed fluid pathway **210** extends through fluid channel **120**.

(41) Note that in alternative embodiments, the groove(s) **132** are alternatively and/or additionally formed on the sleeve **136**. Thus, it should be considered that the fluid channel **120** is jointly formed by the shaft **131** and sleeve **136**, regardless of whether the groove(s) **132** are in the shaft **131**, or the sleeve **136**, or both.

(42) In some aspects, the bearing cooling circuit **100″** further includes a pump **84** and a heat exchanger **83**. The pump **84** is operatively connected to the fluid channel **120** and configured to recirculate the cooling fluid **90** through the fluid channel **120** to remove heat from the inner race **52** via the flywheel shaft **44**, the liquid heat transfer medium **122**, and heat transfer shaft assembly **130**. The heat exchanger **83** is operatively connected to the closed fluid pathway **210** and configured to remove heat from the cooling fluid **90** to ambient after the cooling fluid **90** has passed through fluid channel **120**.

(43) Cooling fluid **90** flows through the bearing cooling circuit **100″**, including the fluid channel **120**. When shaft **131** with inner passage **134** is present, the inner passage **134** may be downstream relative to the fluid channel **120** along the fluid pathway **210**, so that cooling fluid **90** flows through the fluid channel **120**, and then out of the heat transfer shaft assembly **130** via the inner passage **134**. In other aspects, the flow is reversed so that cooling fluid **90** flows through the inner passage **134**, and then out of the heat transfer shaft assembly **130** via the fluid channel **120**.

(44) For the FIG. **8** arrangement, the heat flow for dissipating heat from the inner race **52** is from the inner race **52**, to the flywheel shaft **44**, then to the liquid heat transfer medium **122**, then to the heat transfer shaft assembly **130**, then to the cooling fluid **90**, typically then to external to the CMG **10** via the heat exchanger **83**. Note that the heat is transferred by solid conduction from the inner race **52** to the flywheel shaft **44**, then by conduction and convection to the liquid heat transfer medium **122**, then by conduction and convection to the heat transfer shaft assembly **130**, then by

conduction and convection to the cooling fluid **90**.

(45) A method (**400**) of operating a gyroscopic roll stabilizer that includes a bearing cooling circuit **100**″ for the outer race **54** of the bearing discussed above is shown in FIG. **12**. The method (**400**) includes maintaining (**410**) a below ambient pressure within enclosure **30**, with the enclosure **30** surrounding flywheel assembly **40**. The flywheel assembly **40** includes a flywheel shaft **44** and a spinning flywheel **42**. The flywheel shaft **44** has an open-ended cavity **46** formed in an end of the flywheel shaft **44**. A liquid heat transfer medium **122** is disposed in the cavity **46**. The method also includes supporting (**420**) the spinning flywheel for rotation about flywheel axis F via bearing **50**, the bearing **50** having inner race **52** and outer race **54**, with the inner race **52** affixed to the flywheel shaft **44**. The method further includes dissipating (**440**) heat from the inner race **52** by transferring the heat by conduction and convection to bearing cooling circuit **100**″ configured to transfer heat by recirculating cooling fluid **90** along closed fluid pathway **210**. The dissipating heat comprises internally cooling, by the cooling fluid **90**, heat transfer shaft assembly **130** rotationally fixed relative to the flywheel axis and extending from the enclosure **30** into the cavity **46** so as to contact the liquid heat transfer medium **122**. In some aspects, the heat transfer shaft assembly **130** includes a shaft **131** and a sleeve **136**, as described above, with the fluid channel **120**, and the closed fluid pathway **210** extends through the fluid channel **120**. Further, the method includes cooling (**460**) the cooling fluid **90** by removing heat from the cooling fluid **90** external to the portion of the enclosure **30** maintained at the below-ambient pressure. In addition, the method includes recirculating (**470**) the cooling fluid **90** through closed fluid pathway **210**. Note that the recirculating (**470**) optionally includes routing (**472**) the cooling fluid **90** from the heat transfer shaft assembly **130** to reservoir **82**, and pumping (**474**) the cooling fluid **90** from the reservoir **82** to the heat transfer shaft assembly **130**, and the cooling (**460**) the cooling fluid **90** comprises cooling the cooling fluid **90** via a heat exchanger **83** disposed external to the enclosure **30**. Optionally, the operating method includes driving (**450**) the flywheel **42** to spin about flywheel axis F via motor **60** disposed internal to the enclosure **30**. In the method, heat is transferred away from the inner race **52** of bearing to the flywheel shaft **44**, and from the flywheel shaft **44** to the liquid heat transfer medium **122**, and from the liquid heat transfer medium **122** to the heat transfer shaft assembly **130**, and from the heat transfer shaft assembly **130** to the cooling fluid **90**. Note that the various steps of method (**400**) may be carried out in any suitable order, including in whole or in part in parallel. For example, at least the maintaining (**410**), the supporting (**420**) the flywheel, and the dissipating (**440**) are advantageously carried out simultaneously.

(46) Note that the discussion above has generally been in the context of a given end of the flywheel assembly **40** being rotationally supported in the enclosure **30** by a single bearing **50**. However, it should be noted that one or both ends (e.g., just north end, just south end, or both north and south ends) of the flywheel shaft **42** may alternatively be supported by a corresponding plurality of bearings **50**, such as two or more stacked bearings **50** at one or both ends.

(47) Further note that while not required, the CMG **10** advantageously includes both bearing cooling circuit **100**′ and bearing cooling circuit **100**″ (instead of just one or the other) so that heat is efficiently transferred away from both the inner race **52** and the outer race **54**. In some embodiments, bearing cooling circuit **100**′ and bearing cooling circuit **100**″ share a common reservoir **82** and heat exchanger **84** (and optionally inlet port **206**, and outlet port **208**), so as to form a meta-circuit that shares cooling fluid **90** between fluid channel **220** and the heat transfer shaft assembly **130**. For example, the fluid channel **220** and the heat transfer shaft assembly **130** may be disposed along a common bearing cooling circuit **100**, such that the fluid channel **220** is disposed in series with and downstream/upstream of the heat transfer shaft assembly **130** (and fluid channel **120**), before/after the common reservoir **82**, in a bearing cooling circuit **100** that cools both the inner race **52** and the outer race **54**.

(48) The bearing cooling systems **100** (which may be alternatively denoted **100**′ or **100**″) as herein described allow much greater heat dissipation compared to current technology, which enables use

of a larger motor **60**, and advantageously lower operating temperature even with the larger motor **60**. The larger motor and lower operating temperature enable rapid spin up and spin down of the flywheel assembly **40**, and a significantly lower time to engage as discussed further below.

(49) In use, the gimbal **20** is normally locked during spin up, i.e., while the flywheel assembly **40** is being accelerated, to prevent precession of the flywheel **42** until a predetermined rotational speed is achieved. The CMG **10** can be locked to prevent rotation of the enclosure **30** by the active braking system **78**. When the CMG **10** is unlocked, precession of the flywheel **42** will place side loads on the bearings **50**. The bearing friction from the side loading of the bearings **50** generates heat. In addition, the bearing friction from the side loading also adds drag, which must be overcome by the motor **60** in order to continue acceleration of the flywheel's rotation. Thus, the frictional losses of side loading the bearings **50** have two impacts: generating heat and increasing the load on the motor **60**.

(50) Conceptually, there are two main sources of heat in a CMG: heat generated by the motor inside the enclosure **30** and heat generated by bearing friction. A large percentage of the heat budget is needed to dissipate heat from the bearings in order to prevent bearing failure. The remaining portion of the heat budget, after accounting for bearing cooling, determines the size of the motor that can be used inside the enclosure.

(51) The bearing cooling systems **100** as described herein enable more efficient heat transfer, which enables a far greater heat transfer capacity and an increased heat budget. The increased heat budget means that larger and more powerful motors **60** that generate more heat can be used without causing bearing failure. With a larger and more powerful motor **60**, the improved CMG **10** of the present disclosure is able to achieve greater acceleration of the flywheel assembly **40** and lower time to engage than a conventional CMG. In addition to the higher rates of acceleration, which naturally lead to lower times to engage assuming the same minimum operating speed, a larger motor **60** enables the flywheel assembly **40** to be engaged at a lower operating speed (e.g., a lower percentage of nominal operating speed), which further reduces the time to engage, because the larger motor **60** is able to overcome the additional friction from the loading of the bearings **50**. In some embodiments, the motor **60** is configured to enable the CMG **10** to be unlocked in under twenty minutes, and preferably in under ten minutes and more preferably in under five minutes. By combining higher acceleration with lower operating speeds at the time of engagement, a time to engage can be reduced to a few minutes. The rapid spin up and shorter time to engage enables beneficial use of the CMG **10** even for short trip times, which makes up a majority of boating trips. Thus, the rapid spin-up enables the CMG **10** to be used on a greater number of boating occasions.

(52) The disclosure of U.S. Patent Application Publication No. US20200317308 is incorporated herein by reference in its entirety.

(53) The present disclosure may, of course, be carried out in other ways than those specifically set forth herein without departing from essential characteristics of the disclosure. The present embodiments are to be considered in all respects as illustrative and not restrictive, and all changes coming within the meaning and equivalency range of the appended claims are intended to be embraced therein.

Claims

1. A gyroscopic roll stabilizer for a boat, the gyroscopic roll stabilizer comprising: an enclosure mounted to a gimbal for rotation about a gimbal axis and configured to maintain a below-ambient pressure; a flywheel assembly including a flywheel and a flywheel shaft with an open-ended bore bounded by an inner wall; a bearing for rotatably mounting the flywheel assembly inside the enclosure for rotation about a flywheel axis; a motor operative to rotate the flywheel assembly; a heat transfer shaft rotationally fixed relative to the flywheel axis and extending from the enclosure into the open-ended bore, wherein the heat transfer shaft functions as a heat sink to absorb heat

generated by the bearing; and a cooling circuit extending into the heat transfer shaft for recirculating liquid coolant through the heat transfer shaft to remove heat absorbed by the heat transfer shaft.

2. The gyroscopic roll stabilizer of claim 1, wherein the heat transfer shaft includes an internal chamber through which the liquid coolant circulates.

3. The gyroscopic roll stabilizer of claim 1, further comprising a gap between the heat transfer shaft and the inner wall of the open-ended bore.

4. The gyroscopic roll stabilizer of claim 2, wherein the cooling circuit further comprises: a fluid pump to recirculate the liquid coolant through the heat transfer shaft; and a heat exchanger external to the enclosure to remove heat from the liquid coolant.

5. A method of dissipating heat from a gyroscopic roll stabilizer for a boat, the method comprising: maintaining a below ambient pressure within an enclosure surrounding a flywheel assembly, the flywheel assembly including a flywheel shaft and a spinning flywheel and mounted for rotation inside the enclosure by a bearing, wherein the flywheel shaft has an open-ended bore; transferring heat generated by the bearing to a heat transfer shaft extending from the enclosure into the open-ended bore in the flywheel shaft; and removing the heat generated by the bearing from the enclosure by circulating a liquid coolant through an internal chamber in the heat transfer shaft assembly.

6. A gyroscopic roll stabilizer for a boat, comprising: an enclosure mounted to a gimbal for rotation about a gimbal axis and configured to maintain a below-ambient pressure; a flywheel assembly including a flywheel and a flywheel shaft with an opening formed in an end of the flywheel shaft; a bearing rotatably mounting the flywheel assembly inside the enclosure for rotation about a flywheel axis; a motor operative to rotate the flywheel assembly; a heat transfer shaft assembly rotationally fixed relative to the flywheel axis and the enclosure and extending into the opening in the flywheel shaft to enable transfer of heat generated by the bearing to the heat transfer shaft assembly; and a cooling circuit extending into the heat transfer shaft assembly at least as far as the bearing and configured to circulate a coolant through the heat transfer shaft assembly to remove the heat generated by the bearing from the enclosure.

7. The gyroscopic roll stabilizer of claim 6: wherein the heat transfer shaft includes a first central longitudinal bore that forms a portion of the cooling circuit; wherein the coolant is routed through the first central longitudinal bore.

8. The gyroscopic roll stabilizer of claim 7, wherein the first central longitudinal bore, the bearing, and the flywheel shaft longitudinally overlap each other.

9. The gyroscopic roll stabilizer of claim 7: wherein the bearing is a first bearing; wherein the first bearing is disposed proximate a first end of the flywheel shaft; wherein the gyroscopic roll stabilizer further comprises: a second bearing disposed proximate a second end of the flywheel shaft is spaced relation to the first bearing; a second central longitudinal bore extending at least as far as the second bearing; wherein the cooling circuit extends into the second end of the flywheel shaft and is configured to circulate a coolant through the second longitudinal bore to remove heat generated by the second bearing from the enclosure.

10. The gyroscopic roll stabilizer of claim 6, wherein the heat transfer shaft assembly is spaced from the flywheel shaft by a gap with the flywheel assembly configured to rotate relative to the heat transfer shaft assembly.

11. The gyroscopic roll stabilizer of claim 6, wherein the heat transfer shaft assembly comprises: a shaft having an outer groove and an inner passage; a sleeve disposed about the shaft so as to overlap the groove; a fluid channel jointly formed by the sleeve and the groove, the fluid channel having the coolant therein.

12. A method of dissipating heat from a gyroscopic roll stabilizer for a boat, the method comprising: maintaining a below ambient pressure within an enclosure surrounding a flywheel assembly; the flywheel assembly including a flywheel shaft and a spinning flywheel and mounted

for rotation inside the enclosure about a flywheel axis by a bearing; wherein the flywheel shaft has an opening formed in an end of the flywheel shaft; transferring heat generated by the bearing to a heat transfer shaft assembly; the heat transfer shaft assembly rotationally fixed relative to the flywheel axis and the enclosure and extending into the opening in the flywheel shaft to enable transfer of heat generated by the bearing to the heat transfer shaft assembly; and removing the heat generated by the bearing from the enclosure by circulating a coolant through a cooling circuit extending into the heat transfer shaft assembly at least as far as the bearing.

13. The method of claim 12: wherein the heat transfer shaft assembly includes a first central longitudinal bore that forms a portion of the cooling circuit; wherein the removing heat comprises circulating the coolant through the first central longitudinal bore.

14. The method of claim 13, wherein the first central longitudinal bore, the bearing, and the flywheel shaft longitudinally overlap each other.

15. The method of claim 12: wherein the bearing is a first bearing disposed proximate a first end of the flywheel shaft; wherein the gyroscopic roll stabilizer further comprises: a second bearing disposed proximate a second end of the flywheel shaft is spaced relation to the first bearing; a second central longitudinal bore extending at least as far as the second bearing; wherein the cooling circuit extends into the second end of the flywheel shaft; wherein the removing heat further comprises removing heat generated by the second bearing from the enclosure by circulating the coolant through the second central longitudinal bore.

16. The method of claim 12, wherein the heat transfer shaft assembly is spaced from the flywheel shaft by a gap; wherein the method further comprises rotating the flywheel assembly relative to the heat transfer shaft assembly via a motor.

17. The method of claim 12: wherein the heat transfer shaft assembly comprises: a shaft extending through the opening in the flywheel shaft and having an outer groove and an inner passage; a sleeve disposed about the shaft so as to overlap the groove; and a fluid channel jointly formed by the sleeve and the groove; wherein the fluid channel forms a portion of the cooling circuit; wherein the removing the heat comprises circulating the coolant through the fluid channel.