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Active Centering Control of a Gyroscope

Abstract

A controller controls precession of a gyroscope that oscillates about a precession axis perpendicular to a spin axis and a roll axis of the gyroscope. To do so, the controller detects a deviation of a center of the oscillation away from a nominal center. The precession is caused by roll of the gyroscope about the roll axis and imposes decreasing amounts of damping upon the roll as the precession moves away from the nominal center. The controller reduces the deviation of the center of the oscillation by applying an asymmetric amount of braking to the precession when the precession and the deviation are in a same direction relative to when the precession and the deviation are in opposing directions.

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Background/Summary

RELATED APPLICATIONS [0001] The present application is a divisional of U.S. patent application Ser. No. 17/591,222, which was filed on Feb. 2, 2022, the disclosure of which is incorporated herein by reference in its entirety.

TECHNICAL FIELD

[0002] The present disclosure generally relates to the use of computing systems to actively control the motion of a spinning gyroscope and, more particularly, to control the precession of a gyroscope to improve the efficiency of its anti-roll effects.

BACKGROUND

[0003] Gyroscopes demonstrate certain physical properties that have historically made them quite useful in a wide variety of technical settings. A traditional gyroscope as is known in the prior art is illustrated in FIG. **1**.

[0004] Traditionally, a gyroscope **10** comprises a spinning body (e.g., a flywheel **40**) that rotates around a spin axis **50**. The example flywheel **40** of FIG. **1** is mounted into three gimbals **20***a*, **20***b*, **20***c*, each of which allows the flywheel **40** to pivot about an axis that is perpendicular to the others. When three gimbals **20** are used (as in FIG. **1**), the flywheel **40** is provided with three degrees of axial freedom such that the orientation of the flywheel **40** and its spin axis **50** are independent of its mount **30**.

[0005] The spinning flywheel **40** has an angular momentum that is perpendicular to the plane in which it spins. If the flywheel **40** spins clockwise as viewed from the top, the angular momentum is downward. If the flywheel **40** spins counter-clockwise as viewed from the top, the angular momentum is upward. In either case, if the angular momentum is in alignment with the sum of the external forces acting on the gyroscope **10** (e.g., gravity), the spin axis **50** will remain vertical and stationary.

[0006] When the gyroscope **10** is mounted such that movement of the spin axis **50** is not restricted, the orientation of the spin axis **50** is generally not impacted when the mount **30** is tilted. In general, the larger the mass and/or spin rate of the flywheel **40**, the greater the stability of the spin axis **50**.

[0007] The difference between the orientation of the mount **30** as compared to the spin axis **50** may be used for a variety of technical purposes. For example, the orientation of the spin axis **50** as compared to the orientation of the mount **30** may be used in an instrument to indicate the orientation of a platform or vehicle to which the gyroscope **10** is mounted. In one particular example, a gyroscope **10** may be useful to indicate the amount of roll occurring to an aircraft. This may be particularly useful to a pilot who is unable to observe this roll through their natural senses, e.g., because visibility of the horizon is obscured by weather.

[0008] When an external torque is applied to the gyroscope **10**, a phenomenon known as precession occurs. Precession is a movement of the spin axis **50** resulting from the application of external torque that moves the spin axis **50**. This external torque may be, for example, due to gravity acting on the center of mass of the gyroscope after the gyroscope has been tipped over, as shown in FIG. **2**A.

[0009] FIG. **2**A illustrates an example of a gyroscope **10** that has been tipped such that the flywheel **40** is spinning around a horizontal spin axis **50** in a spin direction **60**. In this example, the gyroscope **10** is experiencing a gravitational force **90** that produces a torque on the gyroscope **10** in a direction that is orthogonal to its angular momentum **55**, resulting in precession of the spin axis **50** around a precession axis **80** in a precession direction **70**.

[0010] FIG. **2**B is a simplified schematic view of the tipped gyroscope **10** of FIG. **2**A as seen from above. From FIG. **2**B, the torque **75** caused by the spinning of the flywheel **40** causes the angular momentum **55** of the gyroscope **10** to change direction in a sweeping pattern around the precession axis **80**, which in this example passes through the center of the mount **30**.

[0011] When the gyroscope is mounted such that precession is limited, this precession imposes a force onto the mount **30** that can used to stabilize a surface against rolling. FIGS. **3**A and **3**B illustrate an example of a gyroscope **10** mounted in a boat **5** for roll stabilization about a roll axis **95**. The roll axis **95** in this example is a longitudinal axis of the boat **5**.

[0012] FIG. **4** illustrates a cutaway view of the boat **5** revealing the gyroscope **10** mounted therein. As can be seen in FIG. **4**, the gyroscope **10** is mounted such that the spin axis **50** is prevented from moving about the roll axis **95**. When a rolling force **85** acts upon the boat **5**, precession of the gyroscope **10** in a precession direction **70** about the precession axis **80** causes a stabilizing torque **75** that pulls up on one side of the mount (**30***a*) and down on the other (**30***b*), essentially twisting against the mount **30** in opposition to the rolling force **85**. As the boat **5** rolls side-to-side, the precession of gyroscope **10** oscillates fore and aft, countering roll in respective directions along the way.

[0013] Stabilizing gyroscopes such as those described above can enhance safety and comfort for passengers of a boat, aircraft, or other vessel or platform to which the gyroscope **10** is mounted. Although such **10** gyroscopes are gaining in popularity, the technology has some significant limitations. For example, as the precession of the gyroscope **10** moves the spin axis **50** away from the vertical and towards the horizontal, the stabilizing torque **75** is directed in an increasingly horizontal plane rather than a vertical plane. When this happens, the stabilizing torque **75** increasingly induces yaw and the desired roll stabilizing properties of the gyroscope **10** increasingly diminish.

SUMMARY

[0014] Embodiments of the present disclosure are generally directed to techniques that actively control the precession of a gyroscope in order to make efficient use of the forces that gyroscope produces.

[0015] Particular embodiments include a method of controlling precession of a gyroscope that oscillates about a precession axis perpendicular to a spin axis and a roll axis of the gyroscope. The method comprises detecting a deviation of a center of the oscillation away from a nominal center. The precession is caused by roll of the gyroscope about the roll axis and imposes decreasing amounts of damping upon the roll as the precession moves away from the nominal center. The method further comprises reducing the deviation of the center of the oscillation by applying an asymmetric amount of braking to the precession when the precession and the deviation are in a same direction relative to when the precession and the deviation are in opposing directions.

[0016] In some embodiments, applying the asymmetric amount of braking comprises generating a control signal based on a target amount of damping upon the braking system and sending the control signal to a braking system controlling the braking. In some such embodiments, generating the control signal based on the target amount of damping upon the braking system comprises correcting the target amount of damping upon the braking system based on the deviation. Generating the control signal further comprises combining the corrected target amount of damping upon the braking system with damping feedback from the braking system to determine a damping error. Generating the control signal further comprises generating the control signal such that an amount of damping applied to the braking system is adjusted to correct for the damping error.

[0017] In some embodiments, applying the asymmetric amount of braking comprises generating the control signal based on a target amount of precession acceleration and sending the control signal to a braking system controlling the braking. In some such embodiments, generating the control signal based on the target amount of precession acceleration comprises correcting a target precession rate based on the deviation and determining the target amount of precession acceleration based on the corrected target precession rate. Generating the control signal further comprises combining the target amount of precession acceleration with precession feedback from a precession sensor to determine a precession acceleration error and generating the control signal such that an amount of precession acceleration permitted by the braking system is adjusted to correct for the precession acceleration error. In some such embodiments, generating the control signal based on the target amount of precession acceleration further comprises combining the corrected target precession rate with further precession feedback to determine a precession rate error. Generating the control signal further comprises determining the target amount of precession acceleration based on the corrected target precession rate comprises calculating the target amount of precession acceleration based on the precession rate error.

[0018] In some embodiments, the method further comprises calculating an amount of current that, when sent to a hydraulic damping valve of a braking system controlling the braking, reduces the deviation. The method further comprises generating a pulse width modulated (PWM) control signal having a duty cycle that provides the amount of current. Reducing the deviation by applying the asymmetric amount of braking comprises sending the PWM control signal to the hydraulic damping valve.

[0019] Other embodiments include a gyroscopic precession controller comprising processing circuitry and interface circuitry communicatively coupled to the processing circuitry. The processing circuitry is configured to detect a deviation of a center of the oscillation away from a nominal center. The precession is caused by roll of the gyroscope about the roll axis and imposes decreasing amounts of damping upon the roll as the precession moves away from the nominal center. The processing circuitry is further configured to reduce the deviation of the center of the oscillation by applying an asymmetric amount of braking to the precession when the precession and the deviation are in a same direction relative to when the precession and the deviation are in opposing directions.

[0020] In some embodiments, to apply the asymmetric amount of braking, the processing circuitry is configured to generate a control signal based on a target amount of damping upon the braking system and send the control signal to a braking system controlling the braking. In some such embodiments, to generate the control signal based on the target amount of damping upon the braking system, the processing circuitry is configured to correct the target amount of damping upon the braking system based on the deviation and combine the corrected target amount of damping upon the braking system with damping feedback from the braking system to determine a damping error. The processing circuitry is further configured to generate the control signal such that an amount of damping applied to the braking system is adjusted to correct for the damping error.

[0021] In some embodiments, to apply the asymmetric amount of braking, the processing circuitry is configured to generate a control signal based on a target amount of precession acceleration and send the control signal to a braking system controlling the braking. In some such embodiments, to generate the control signal based on the target amount of precession acceleration, the processing circuitry is configured to correct a target precession rate based on the deviation and determine the target amount of precession acceleration based on the corrected target precession rate. The processing circuitry is further configured to combine the target amount of precession acceleration with precession feedback from a precession sensor to determine a precession acceleration error and generate the control signal such that an amount of precession acceleration permitted by the braking system is adjusted to correct for the precession acceleration error. In some such embodiments, to generate the control signal based on the target amount of precession acceleration, the processing circuitry is further configured to combine the corrected target precession rate with further precession feedback to determine a precession rate error. To determine the target amount of precession acceleration based on the corrected target precession rate, the processing circuitry is configured to calculate the target amount of precession acceleration based on the precession rate error.

[0022] In some embodiments, the processing circuitry is further configured to calculate an amount of current that, when sent to a hydraulic damping valve of a braking system controlling the braking, reduces the deviation. The processing circuitry is further configured to generate a pulse width modulated (PWM) control signal having a duty cycle that provides the amount of current. To reduce the deviation by applying the asymmetric amount of braking, the processing circuitry is configured to send the PWM control signal to the hydraulic damping valve.

[0023] Yet other embodiments include an anti-roll system. The anti-roll system comprises a gyroscope and a motor configured to spin the gyroscope about a spin axis. The anti-roll system further comprises a mount configured to restrict precession of the gyroscope to oscillation about a precession axis perpendicular to the spin axis and a braking system configured to apply a braking force that controls an extent of the oscillation. The anti-roll system further comprises a gyroscopic precession controller configured to detect a deviation of a center of the oscillation away from a nominal center. The precession is caused by roll of the gyroscope about a roll axis perpendicular to the spin axis and precession axis. The precession imposes decreasing amounts of damping upon the roll as the precession moves away from the nominal center. The gyroscopic precession controller is further configured to reduce the deviation of the center of the oscillation by controlling the braking system to apply an asymmetric amount of braking to the precession when the precession and the deviation are in a same direction relative to when the precession and the deviation are in opposing directions.

[0024] In some embodiments, to apply the asymmetric amount of braking, the gyroscopic precession controller is configured to generate a control signal based on a target amount of damping upon the braking system and send the control signal to the braking system. In some such embodiments, to generate the control signal based on the target amount of damping upon the braking system, the gyroscopic precession controller is configured to correct the target amount of damping upon the braking system based on the deviation and combine the corrected target amount of damping upon the braking system with damping feedback from the braking system to determine a damping error. The gyroscopic precession controller is further configured to generate the control signal such that an amount of damping applied to the braking system is adjusted to correct for the damping error.

[0025] In some embodiments, to apply the asymmetric amount of braking, the gyroscopic precession controller is configured to generate a control signal based on a target amount of precession acceleration and send the control signal to the braking system. In some such embodiments, to generate the control signal based on the target amount of precession acceleration, the gyroscopic precession controller is configured to correct a target precession rate based on the deviation and determine the target amount of precession acceleration based on the corrected target precession rate. The gyroscopic precession controller is further configured to combine the target amount of precession acceleration with precession feedback from a precession sensor to determine a precession acceleration error and generate the control signal such that an amount of precession acceleration permitted by the braking system is adjusted to correct for the precession acceleration error. In some such embodiments, to generate the control signal based on the target amount of precession acceleration, the gyroscopic precession controller is further configured to combine the corrected target precession rate with further precession feedback to determine a precession rate error. To determine the target amount of precession acceleration based on the corrected target precession rate, the gyroscopic precession controller is configured to calculate the target amount of precession acceleration based on the precession rate error.

[0026] In some embodiments, the braking system comprises a hydraulic damping valve. The gyroscopic precession controller is further configured to calculate an amount of current that, when sent to a hydraulic damping valve of a braking system controlling the braking, reduces the deviation and generate a pulse width modulated (PWM) control signal having a duty cycle that provides the amount of current. To reduce the deviation by applying the asymmetric amount of braking, the gyroscopic precession controller is configured to send the PWM control signal to the hydraulic damping valve.

Description

BRIEF DESCRIPTION OF THE DRAWINGS

[0027] Aspects of the present disclosure are illustrated by way of example and are not limited by the accompanying figures with like references indicating like elements. In general, the use of a reference numeral should be regarded as referring to the depicted subject matter according to one or more embodiments, whereas discussion of a specific instance of an illustrated element will append a letter designation thereto (e.g., discussion of a combiner **210**, generally, as opposed to discussion of particular instances of combiners **210***a-u*).

[0028] FIG. **1** is an illustration of a gyroscope spinning about a vertical spin axis according to the prior art.

[0029] FIG. **2**A is an illustration of a gyroscope spinning about a horizontal spin axis according to the prior art.

[0030] FIG. **2**B is a schematic view of a gyroscope spinning about a horizontal spin axis as viewed from above according to the prior art.

[0031] FIGS. **3**A and **3**B are schematic views of a gyroscope mounted to a boat according to the prior art, as viewed from the side and from above, respectively.

[0032] FIG. **4** is a schematic cutaway view of an example boat in which a gyroscope has been mounted according to the prior art.

[0033] FIG. **5** is a schematic block diagram of an example anti-roll system according to one or more embodiments of the present disclosure.

[0034] FIG. **6** is an isometric view of an example mountable gyroscope and a braking system for controlling the precession thereof according to one or more embodiments of the present disclosure.

[0035] FIG. **7** is a cutaway view of an example gyroscope from the side according to one or more embodiments of the present disclosure.

[0036] FIG. **8** is an isometric view of an example braking system according to one or more embodiments of the present disclosure.

[0037] FIG. **9** is a schematic block diagram of an example gyroscopic precession controller according to one or more embodiments of the present disclosure.

[0038] FIG. **10** is a schematic block diagram of a gyroscopic precession controller controlling a braking system according to one or more embodiments of the present disclosure.

[0039] FIGS. **11**A-**11**B are schematic block diagrams of another example gyroscopic precession controller controlling a braking system according to one or more embodiments of the present disclosure.

[0040] FIG. **12** is a schematic block diagram illustrating example sensors used by a braking system controller according to one or more embodiments of the present disclosure.

[0041] FIG. **13** is a block diagram illustrating example calibration data used by a braking system controller according to one or more embodiments of the present disclosure.

[0042] FIGS. **14**A and **14**B is a schematic block diagram illustrating a further example of a gyroscopic precession controller controlling a braking system according to one or more embodiments of the present disclosure.

[0043] FIG. **15** is a schematic block diagram illustrating a yet further example of a gyroscopic precession controller controlling a braking system according to one or more embodiments of the present disclosure.

[0044] FIG. **16** is a flow diagram illustrating an example method of controlling gyroscopic precession according to one or more embodiments of the present disclosure.

DETAILED DESCRIPTION

[0045] Embodiments of the present disclosure relate to controlling the precession of a gyroscope **10**, e.g., to effectively combat undesired motion of a platform to which the gyroscope is mounted.

Although embodiments of the present disclosure may be used in a variety of settings (e.g., aircraft, watercraft, buildings, oil platforms, spacecraft), installed in a variety of positions therein or thereon, and used to apply force in a variety of directions, for simplicity and clarity of explanation the embodiments below will be discussed in terms of a gyroscope **10** installed in the hull of a boat **5** to provide increased stabilization against roll. It should be appreciated that, in other embodiments of the present disclosure, similar principles may be applied in other settings to efficiently transfer the torque produced by the spin of a flywheel **40** within a gyroscope **10** to a platform of interest in a useful direction.

[0046] FIG. **5** illustrates an example anti-roll system **100** according to one or more embodiments of the present disclosure. The anti-roll system **100** comprises a gyroscope **10**, a braking system **110**, a motor **65**, and a controller **102**. In some embodiments, the anti-roll system **100** further comprises one or more sensors **104** and/or calibration data **108** stored in non-transitory computer readable medium.

[0047] The gyroscope **10** is configured to spin about a spin axis and precess in an oscillating manner about a precession axis perpendicular to the spin axis. The motor **65** is configured to spin the gyroscope **10**. The braking system **110** is configured to apply a braking force that controls an extent of the precession oscillation. The controller **102** is configured to control the amount of braking applied by the braking system **110**. The sensor(s) **104** and calibration data each provide one or more inputs used by the controller **102** to determine an appropriate amount of braking to be applied by the braking system **110**.

[0048] FIGS. **6** and **7** illustrate a gyroscope **10** according to one or more embodiments of the present disclosure. The gyroscope **10** comprises a single-axis gimbal **20**, an enclosure **130** mounted to the gimbal **20** for rotation about a precession axis **80**, a flywheel **40** that is mounted inside the enclosure **30**, and a motor **65** configured to rotate the flywheel **40** about a spin axis **50**. As will be shown in greater detail below, precession of the gyroscope **10** is controlled by a gyroscopic precession controller so that torque from the flywheel **40** is effectively transferred to the hull of the boat **5** to counteract rolling motions.

[0049] 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 such that the roll axis **95** stabilized by the gyroscope **10** is aligned with a longitudinal axis of the boat **5** (i.e., fore to aft) and such that the precession axis **80** extends transversely (i.e., port to starboard). Although the gimbal **20** is conventionally mounted in the hull of the boat **5**, the gimbal **20** may be mounted anywhere on the boat **5** depending on the embodiment.

[0050] The enclosure **30**, in this example, is rotatably mounted to the support frame **22** by spherical roller bearings housed in pillow blocks (not shown in FIG. **7**) so as to rotate about the precession axis **80** extending transversely across the boat **5**. 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 received in the spherical bearings to allow the enclosure **30** and flywheel **40** to rotate or precess about the precession axis **80** in the fore and aft directions.

[0051] The enclosure **30** is generally spherical in form and comprises joints that are sealed to maintain a below-ambient pressure within the enclosure **30** to reduce aerodynamic drag on the flywheel **40**. The flywheel **40** is connected to a shaft **44** that is mounted for rotation inside the enclosure **30** so that the spin axis **50** of the flywheel **40** is perpendicular to the precession axis **80**. Thus, when the boat **5** is level, the spin axis **50** of the flywheel shaft **44** will be in the vertical direction, i.e., generally perpendicular to the deck of the boat.

[0052] The flywheel **40** and shaft **44** may be formed as a unitary piece or may comprise separate components. In one example, the diameter of the flywheel **40** is approximately 20 inches, has a weight of approximately 600 lbs., and a moment of inertia of approximately 32,000 lb in.sup.2. Further, when rotated at a rate of 9000 rpm, the angular momentum of the flywheel **40** is approximately 210,000 lbm ft.sup.2/s.

[0053] The motor **65** rotates the flywheel **40** at a high rate of speed (e.g., 9000 rpm) and may be mounted inside the enclosure **30** or on the exterior of the enclosure **30**. In one embodiment, the motor **65** comprises operates on 230 volt single phase AC power and is able to accelerate the flywheel **40** with a moment of inertia of about 32,273 lb in2 (including the shaft **44**) 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).

[0054] A braking system **110** (e.g., as shown in FIG. **6** and in further detail in FIG. **8**) is provided to control precession of the gyroscope **10** as needed. One reason to control precession may be to constrain the precession to within a maximum operational range. Another purpose may be to guide the center of precession toward a nominal center, e.g., in order to combat drift of the gyroscope **10** over time in a particular direction and/or to improve the overall efficiency of the gyroscope in combating roll.

[0055] By imposing limitations on precession (e.g., the amount and/or rate of precession), the roll stabilizing characteristics of the gyroscope **10** may be tuned. That said, although the braking system **110** provides at least a measure of control over precession, the braking system **110** may or may not be sufficient to effectively counter the rolling motion of the boat in various circumstances, depending on one or more factors including the particular implementation of the gyroscope **10**, braking system **110**, the amount of roll being experienced, the physical properties of the boat **5**, and so on.

[0056] In one example, the precession of the flywheel **40** is limited by the braking system **110** to within +/−22 degrees. In another example, the braking system **110** is designed to enable the flywheel **40** to precess up to about +/−45 degrees.

[0057] As seen in FIG. **8**, the braking system **110** comprises a pair of actuator assemblies **120** that control the precession of the flywheel **40** about the precession axis **80**, and a manifold assembly **150** for transferring fluid between the opposing cylinders **120** as the flywheel **40** precesses. Hydraulic lines **160** connect the fluid cylinders **120** with the manifold assembly **150** to form a closed fluid flow path between the cylinders **120**.

[0058] The actuator assemblies **120** each comprise a fluid cylinder **122** having a housing, piston, and piston rod. The fluid cylinders **122** each include a piston side port and a rod side port. A lockout valve **130** is mounted on the housing of the fluid cylinder **122** and is in fluid communication with the piston side port of each fluid cylinder **122**. The lockout valve **130** is normally open and is closed by actuation of a solenoid **132**. In one embodiment, the housing of the lockout valve **130** is secured to or integrally formed with the housing of the fluid cylinder **122** to form a unitary assembly. Each fluid cylinder **122** is pivotally connected at one end to the support frame **22** and at the other end to the enclosure **30**. The housing of the fluid cylinder **122** pivotally connects to the support frame **22** and the piston rod pivotally connects to the enclosure **30** via a connecting plate **140**.

[0059] The connecting plate **140** bolts to the exterior of the enclosure **30** and includes two pivot pins **142** that are rotatably journaled in bushings or bearings (not shown) disposed at the end of respective piston rods. The connecting plate **140** is symmetrical about a frontal plane and the pivot pins are offset from the frontal plane. As used herein, the term “frontal plane” refers to a vertical plane (when the enclosure **30** is in a neutral position) that includes the precession axis **80** and divides the enclosure **30** into front and back sections. The axes of the pivot pins **142** are parallel to the frontal plane. Bolts pass through corresponding openings in the connecting plate **140** and thread into threaded holes (not shown) in the enclosure **30** to secure the connecting pale **140** to the enclosure. Due to the mechanical arrangement of the braking system **110**, the enclosure **30** is able to precess up to a mechanical limit (e.g., up to +/−45 degrees).

[0060] The manifold assembly **150** comprises a main valve **152** mounted to a manifold block **151** and controlled by a solenoid **134**. Ports connect the fluid lines **160** to the normally closed lockout valves **130** in the actuator assemblies **120**. Other ports connect the main valve **152** to respective accumulators **158**. Fluid flowing into the main valve **152** via one of the fluid lines **160** exits into a corresponding one of the accumulators **158**. Check valves control the direction of the fluid flow through the main valve **152** and prevent back flow. Additionally, pressure relief valves prevent over-pressurization of the fluid in the fluid components of the braking assembly **10** due to thermal expansion of fluid when the enclosure **30** is locked. The main valve **152** and lockout valves **130** are controlled by solenoids **132** and **134** respectively, which are actuated by a controller discussed in greater detail below.

[0061] When the enclosure **30** precesses such that the piston of one of the fluid cylinders **122** retracts, fluid flows from the piston side of the fluid cylinder **122** through the corresponding lockout valve **130**. A portion of the fluid exiting the fluid cylinder **122** flows through a corresponding bypass line **162** to the rod side of the fluid cylinder **122**. The rod side of the cylinder is unable to accommodate all of the fluid exiting the piston side of the cylinder due to the volume of the rod. Therefore, a portion of the fluid flows into the main valve **152**. From the main valve **152**, the fluid exits through a check valve that prevents backflow into the manifold **150** and through the other fluid line **160** to the other lockout valve **130** on the piston side of the other fluid cylinder **122**. When the enclosure **30** precesses in the opposite direction, the fluid flow reverses.

[0062] The accumulators **158** provide additional capacity in case the fluid expands due to heat, or due to imbalance of the fluid flow. The heating or imbalance of the fluid flow will create a higher pressure in the main valve **152**, which in turn will cause any excess fluid to flow into the accumulators **158**.

[0063] The braking system **110** is controlled by a controller **102**, as shown in the example of FIG. **9**. The controller **102** comprises interface circuitry **105** and processing circuitry **107** that are communicatively connected to each other. The interface circuitry **105** comprises one or more signaling pathways (e.g., electrical buses, wires, lines, cables) for accepting input to be used by the processing circuitry **107** and for providing output to the braking system **110** from the processing circuitry **107**. As will be shown in further detail below, the processing circuitry **107** may comprise one or more sub-controllers that receives one or more inputs and produces a control signal in response.

[0064] More specifically, the processing circuitry **107** receives an input via the interface circuitry **105** indicating a deviation in the center of oscillation of the gyroscope **10** away from a nominal center and sends a control signal to via the interface circuitry **105** to the braking system **110** to reduce the deviation. To reduce the deviation, the control signal produced by the controller **102** causes the braking system **110** to apply an asymmetric amount of braking to the precession when the precession and the deviation are in a same direction relative to when the precession and the deviation are in opposing directions.

[0065] The processing circuitry **107** may be implemented in a variety of ways, e.g., through programmable sub-controllers capable of executing control software stored in memory circuitry **106** and/or through dedicated sub-controllers. In some embodiments, the control signal generated by the controller **102** is based on input provided by one or more sensor(s) **104**. In some embodiments, the controller **102** additionally or alternatively generates a further control signal for controlling the gyroscope motor **65**. The control signal(s) produced by the controller **102** control precession of the flywheel **40** to counteract a rolling force imposed upon the boat **5**.

[0066] In some embodiments, the controller **102** additionally or alternatively generates the control signals based on calibration data **108**. This calibration data **108** may be adjusted, e.g., by providing and/or editing a configuration file stored in memory circuitry **106** of the controller **102**. By adjusting this calibration data **108**, the controller **102** may be tuned to accommodate a wide variety of braking systems, operating conditions, gyroscopes **10**, vehicles, and/or other factors. In some embodiments, this calibration data **108** is received by the processing circuitry **107** via the interface circuitry **105**. In other embodiments, the calibration data **108** is stored in the memory circuitry **106**.

[0067] FIG. **10** is a schematic block diagram illustrating an example controller **102** in accordance with particular embodiments of the present disclosure. As will be explained in greater detail below, the controller **102** accepts a target value representing a desired outcome with respect to the gyroscope **10**. This target value is processed over a plurality of control stages in order to convert the target value into the aforesaid control signal for controlling the braking system **110**. At each control stage, feedback is used to determine a respective error in the control system **100**, and this error is used as an input into a sub-controller to calculate a solution that corrects the error. The feedback may be provided by one or more sensors **104** comprised in, and/or external to, the braking system **110**. In the figures, subscripts are used to denote whether a given value is a target value (T), an error value (E), a corrected target value (CT), a correction factor (CF), or an actual value (A) provided, e.g., by the braking system **110** and/or from a sensor **104**.

[0068] Although the examples discussed below will describe particular sub-controllers as proportional-integral-derivative controllers (PIDs) **200**, it should be noted that one or more other forms of controllers may be used instead of, or together with, each of the PIDs **200** shown as appropriate, including (but not limited to) proportional (P), integral (**1**), derivative (D), proportional-integral (PI), and/or proportional-derivative (PD) controllers, and/or any combination thereof. In the example of FIG. **10**, each PID **200** produces a corrective control output based on an input representing a form of error in the control system **100**.

[0069] As shown in FIG. **10**, the controller **102** receives a target precession amplitude (AMP.sub.T) that represents a desired amount of gyroscopic precession for damping roll upon the boat **5**. This target precession amplitude is combined with feedback indicating the actual precession amplitude (AMP.sub.A) of the gyroscope **10** at combiner **210***a*. The difference between the target precession amplitude (AMP.sub.T) and the actual precession amplitude (AMP.sub.A) represents an amount of precession amplitude error (AMP.sub.E) in the control system **100**.

[0070] The precession amplitude error (AMP.sub.E) is provided as an input to a PID **200***a*. The PID **200***a* determines a target amount of damping (DAMP.sub.T) upon the braking system **110** based on the precession amplitude error (AMP.sub.E). This target amount of damping (DAMP.sub.T) may, for example, represent an amount of damping that a hydraulic damping valve should apply in order to accomplish the target precession amplitude (AMP.sub.T).

[0071] At combiner **210***b*, the target amount of damping (DAMP.sub.T) is combined with a damping correction factor (DAMP.sub.CF) provided by another PID **200***d* to generate a corrected target amount of damping (DAMP.sub.CT). The damping correction factor (DAMP.sub.CF) provided by PID **200***d* is a value (e.g., a coefficient, a weighting factor) based on a deviation of a center of the oscillation of the precession away from a nominal center. In this example, this deviation is provided as feedback from the braking system **110** in the form of an actual precession bias (BIAS.sub.A). This combination of PID **200***a*, **200***d* outputs into a corrected damping target (DAMP.sub.CT) enables the controller **102** to target, with significant precision, a particular amount of damping that will be effective for bringing the center of precession oscillation back to the nominal center, and thereby improve anti-roll efficiency of the gyroscope **10**.

[0072] At combiner **210***c*, the corrected target amount of damping (DAMP.sub.CT) is combined with feedback indicating an actual amount of damping (DAMP.sub.A) being applied by the braking system **110**. The difference between the corrected target amount of damping (DAMP.sub.CT) and the actual amount of damping (DAMP.sub.A) represents an amount of damping error (DAMP.sub.E) in the control system **100**.

[0073] The damping error (DAMP.sub.E) is provided as an input to PID **200***b*. The PID **200***b* determines a target amount of current (CUR.sub.T) to provide to the braking system **110** (e.g., to a damping valve of the braking system **110**) based on the damping error (DAMP.sub.E). This target amount of current (CUR.sub.T) may, for example, be an amount of current required by a hydraulic damping valve of the braking system **110** in order for the hydraulic damping valve to apply the corrected target amount of damping (DAMP.sub.CT).

[0074] At combiner **210***d*, the target amount of current (CUR.sub.T) is combined with feedback indicating an actual amount of current (CUR.sub.A) being used by the braking system **110** (e.g., to operate the hydraulic damping value that controls braking). The difference between the target amount of current (CUR.sub.T) and the actual amount of current (CUR.sub.A) represents an amount of current error (CUR.sub.E) in the control system **100**.

[0075] The current error (CUR.sub.E) is provided as an input to PID **200***c*. The PID **200***c* determines a control signal to provide to the braking system **110** (e.g., to a damping valve of the braking system **110**) based on the damping error (CUR.sub.E). This control signal may, for example, be a pulse width modulated (PWM) control signal having a duty cycle (DC) that provides an amount of current that corrects for the current error (CUR.sub.E). In this way, a control signal is adjusted to implement a target amount of precession amplitude (AMP.sub.T) by using precession deviation as a weighting factor upon the damping calculations of the controller **102**.

[0076] Other embodiments use other representations of the precession deviation to influence the internal calculations of the controller **102** in a way that improves precession centering in other ways. FIGS. **11**A and **11**B are schematic block diagrams illustrating another example controller **102** in accordance with particular embodiments of the present disclosure. In contrast to the example of FIG. **10** (which used oscillation deviation feedback to influence the controller's damping calculations), the example of FIGS. **11**A and **11**B uses oscillation deviation feedback to influence precession rate calculations. Thus, while the controller **102** of FIG. **10** yields improvements to the control system **100** by focusing on correcting the damping applied by a damping valve of the braking system **110**, the controller **102** of FIGS. **11**A and **11**B yields improvements to the control system **100** by focusing on correcting the rate in which the gyroscope **10** is precessing.

[0077] Starting with reference to FIG. **11**A, the controller **102** receives a target precession amplitude (AMP.sub.T) that represents a desired amount of gyroscopic precession for damping roll upon the boat **5**. This target precession amplitude is combined with feedback indicating the actual precession amplitude (AMP.sub.A) of the gyroscope **10** at combiner **210***e*. The difference between the target precession amplitude (AMP.sub.T) and the actual precession amplitude (AMP.sub.A) represents an amount of precession amplitude error (AMP.sub.E) in the control system **100**.

[0078] The precession amplitude error (AMP.sub.E) is provided as an input to a PID **200***e*. The PID **200***a* determines a target precession rate (PR.sub.T) of the gyroscope **10** based on the precession amplitude error (AMP.sub.E). This target precession rate (PR.sub.T) may, for example, represent a rate of precession calculated to result in the target precession amplitude (AMP.sub.T).

[0079] At combiner **210***f*, the target precession rate (PR.sub.T) is combined with a precession rate correction factor (PR.sub.CF) provided by another PID **200***h* to generate a corrected target precession rate (PR.sub.CT). The precession rate correction factor (PR.sub.CF) provided by PID **200***h* is a value (e.g., a coefficient, a weighting factor) based on a deviation of a center of the oscillation of the precession away from a nominal center. In this example, this deviation is provided as feedback from the braking system **110** in the form of an actual precession bias (BIAS.sub.A). This combination of PID **200***e*, **200***h* outputs into a corrected target precession rate (PR.sub.CT) enables the controller **102** to target, with significant precision, a particular rate of precession that will be effective for bringing the center of precession oscillation back to the nominal center, and thereby improve anti-roll efficiency of the gyroscope **10**.

[0080] At combiner **210***g*, the corrected precession rate (PR.sub.CT) is combined with feedback indicating an actual precession rate (PR.sub.A) being permitted by the braking system **110**. The difference between the corrected target precession rate (PR.sub.CT) and the actual precession rate (PR.sub.A) represents an amount of precession rate error (PR.sub.E) in the control system **100**.

[0081] The precession rate error (PR.sub.E) is provided as an input to a PID **200***f*. The PID **200***f* determines a target acceleration rate (ACC.sub.T) of the precession based on the precession rate error (PR.sub.E). This target acceleration rate (ACC.sub.T) may, for example, represent a rate of

acceleration calculated to correct for the amount of precession rate error (PR.sub.E).
[0082] At combiner **210***h*, the target acceleration rate (ACC.sub.T) is combined with feedback indicating an actual acceleration rate (ACC.sub.A) of the precession. The difference between the target acceleration rate (ACC.sub.T) and the actual acceleration rate (ACC.sub.A) represents an amount of acceleration rate error (ACC.sub.E) in the control system **100**.
[0083] The acceleration rate error (ACC.sub.E) is provided as an input to a PID **200***g*. The PID **200***g* determines a target amount of damping (DAMP.sub.T) upon the braking system **110** based on the acceleration rate error (ACC.sub.E). This target amount of damping (DAMP.sub.T) may, for example, represent an amount of damping that a hydraulic damping valve should apply in order to correct for the acceleration rate error (ACC.sub.E).
[0084] Now with reference to FIG. **11**B, at combiner **210***i*, the target amount of damping (DAMP.sub.T) is combined with feedback indicating an actual amount of damping (DAMP.sub.A) being applied by the braking system **110**. The difference between the target amount of damping (DAMP.sub.T) and the actual amount of damping (DAMP.sub.A) represents an amount of damping error (DAMP.sub.E) in the control system **100**.
[0085] The damping error (DAMP.sub.E) is provided as an input to PID **200***i*. The PID **200***i* determines a target amount of current (CUR.sub.T) to provide to the braking system **110** (e.g., to a damping valve of the braking system **110**) based on the damping error (DAMP.sub.E). This target amount of current (CUR.sub.T) may, for example, be an amount of current required by a hydraulic damping valve of the braking system **110** in order for the hydraulic damping valve to correct for the damping error (DAMP.sub.E).
[0086] At combiner **210***j*, the target amount of current (CUR.sub.T) is combined with feedback indicating an actual amount of current (CUR.sub.A) being used by the braking system **110** (e.g., to operate the hydraulic damping value that controls braking). The difference between the target amount of current (CUR.sub.T) and the actual amount of current (CUR.sub.A) represents an amount of current error (CUR.sub.E) in the control system **100**.
[0087] The current error (CUR.sub.E) is provided as an input to PID **200***j*. The PID **200***j* determines a control signal to provide to the braking system **110** (e.g., to a damping valve of the braking system **110**) based on the current error (CUR.sub.E). This control signal may, for example, be a PWM control signal having a duty cycle (DC) that provides an amount of current that corrects for the current error (CUR.sub.E). In this way, a control signal is adjusted to implement a target amount of precession amplitude (AMP.sub.T) by using precession deviation as a weighting factor upon the precession rate calculations of the controller **102**.
[0088] Although FIGS. **10** and **11**A-B provide relatively simple examples for purposes of explanation, other embodiments of the present disclosure include a controller **102** that considers one or more additional or alternative factors in its calculations. For example, while each of the examples of FIGS. **10** and **11**A-B resulted in the calculation of a PWM control signal having a particular duty cycle, the PID **200***c*, **200***j* responsible for generating that control signal may take into account the oil temperature in the braking system **110**. Given that colder oil is typically more viscous and therefore offers greater resistance in flowing through the hydraulic damping valve, the PID **200***c*, **200***j* responsible for generating the control signal may provide a control signal having a duty cycle that supplies more or less current based on the oil temperature. Thus, generally speaking, a PID **200** may be configured to adjust its calculations in response to feedback from the braking system **110** and/or readings from one or more sensors **104**.
[0089] FIG. **12** is a schematic block diagram illustrating a non-limiting example of sensors **104** that may provide inputs to the controller **102** for use in performing one or more calculations according to particular embodiments of the present disclosure. In the example of FIG. **12**, the sensors **104** comprise an oil temperature sensor **301**, an oil pressure sensor **302**, a roll sensor **303**, a flywheel angular velocity sensor **304**, a gyro precession angle sensor **305**, and/or a current sensor **306**, each of which may provide a sensor output to one or more of the subcontrollers (e.g., PIDs **200**) of the

controller **102**.

[0090] The controller **102** may additionally or alternatively make adjustments based on certain calibration data **108**. This calibration data **108** may be stored in a centralized memory or programmed into the subcontrollers themselves, for example. FIG. **13** is a schematic block diagram illustrating a non-limiting example of certain configuration data **108** according to one or more embodiments of the present disclosure. In the example of FIG. **13**, the calibration data **108** comprises a precession angle threshold (PA.sub.TH) **311**, a precession damping increment gain (GAIN.sub.D+) **312**, a precession damping decrement gain (GAIN.sub.D−) **313**, one or more hydraulic system dimensions (DIM) **314**, a damping correction PID gain (GAIN.sub.COR) **315**, precession centering gain (GAIN.sub.C) **316**, a flywheel mass moment of inertia (MOI) **317**, a precession control PID gain (GAIN.sub.PCON) **318**, one or more gyro mass properties (MASS) **319**, an anti-roll torque increment gain (GAIN.sub.AR+) **321** and/or an ant-roll torque decrement gain 322 (GAINAR−).

[0091] FIGS. **14**A and **14**B are schematic block diagrams illustrating an example controller **102** that uses sensors **104** and calibration data **108** as inputs in order to generate a control signal for controlling a hydraulic proportioning valve **115** of a braking system **110** according to one or more embodiments of the present disclosure. Similar to the example of FIG. **10**, the controller **102** in FIG. **14** combines sub-controller outputs to apply a damping correction factor (DAMP.sub.CF) to obtain a corrected target amount of damping (DAMP.sub.CT).

[0092] Beginning with reference to FIG. **14**A, the actual precession angle of the gyroscope (PA.sub.A) is provided by the sensors **104** and a precession angle threshold (PA.sub.TH) is provided by the calibration data **108**. The magnitude of the actual precession angle (PA.sub.A) is combined with the precession angle threshold (PA.sub.TH) at combiner **210***k* to provide a precession angle error (PA.sub.E). If the value of the precession angle error (PA.sub.E) is out of a given range (in this example, zero to infinity), the precession angle error is clamped to the closest value that is in range at saturation stage **340**.

[0093] At combiner **210***o*, the clamped precession angle error (PA.sub.E) is combined with a precession damping increment gain (GAIN.sub.D+) provided by the calibration data **108** which acts as a weighting factor. The result of the combiner **210***o* is used at combiner **210***l* as one of a plurality of inputs toward calculating a hydraulic damping correction factor (DAMP.sub.CF).

[0094] Another of the inputs to the combiner **210***l* is the magnitude of roll angle experienced by the vessel as weighted by a precession damping decrement gain (GAIN.sub.D−) at combiner **210***p*, with the roll angle being provided by the sensors **104** and the precession damping decrement gain (GAIN.sub.D−) being provided by the calibration data **108**. Thus, at combiner **210***l*, a factor indicating that damping upon the precession should increase competes against a factor indicating that damping upon the precession should decrease so that an appropriate hydraulic valve damping correction factor (DAMP.sub.CF) may be calculated. More specifically, the difference between these two competing factors is fed back into the combiner **210***l* as a denominator so that the ratio of future calculations at combiner **210***l* may be compared against previous ones to determine a dynamic ratio. This ratio serves as the damping correction factor (DAMP.sub.CF), which is provided to a precession centering controller **300** in order to calculate a corrected target amount of damping (DAMP.sub.CT) that should be applied by a hydraulic proportioning value **210** of the braking system **110** to control precession of the gyroscope **10**.

[0095] The precession centering controller **300** uses a variety of inputs in order to determine the corrected target damping target (DAMP.sub.CT). These inputs include the roll angle, the gyro procession angle (PA.sub.A), and the flywheel angular velocity provided by the sensors **104** as well as a precession centering gain (GAIN.sub.C) and a flywheel mass moment of inertia (MOI) provided by the calibration data **108**, in addition to the damping correction factor (DAMP.sub.CF) previously mentioned.

[0096] As will be shown in greater detail below, the corrected target amount of damping

(DAMP.sub.CT) will be used as a basis for determining an open loop current component (CUR.sub.OL) and as a basis for determining a closed loop current component (CUR.sub.CL). These two current components are combined at combiner **210**_n_ to determine a target amount of current (CUR.sub.T) for controlling the hydraulic proportioning valve **115** of the braking system **110**. For example, these the current components may be a respective number of amps that, when added together, specify a total amount of current to provide to the hydraulic proportioning valve **115** in order for the braking system **110** to provide braking that corrects precession deviation. Accordingly, the PWM control signal provided to the hydraulic proportioning valve may have a duty cycle intended to provide the target amount of current (CUR.sub.T).
[0097] Hydraulic value proportioning valve characterization **330** is performed using the corrected target amount of damping (DAMP.sub.CT) and the temperature of the oil flowing through the hydraulic proportioning valve **115** to determine the open loop current component (CUR.sub.OL). That is, the oil temperature provided by the sensors **104** is used along with the corrected target amount of damping (DAMP.sub.CT) to model the characteristics of the hydraulic proportioning valve **115** in order to calculate the open loop current component (CUR.sub.OL).
[0098] The corrected target amount of damping (DAMP.sub.CT) is also used at combiner **210**_m_ where it is compared against an actual amount of damping (DAMP.sub.A) to determine a damping error (DAMP.sub.E). This damping error (DAMP.sub.E) is used by a damping correction PID **320** along with a damping correction PID gain (GAIN.sub.COR) to determine the closed loop current component (CUR.sub.CL).
[0099] The actual amount of damping (DAMP.sub.A) is provided to the combiner **210**_m_ by an actual damping calculation **310**. The actual damping calculation **310** calculates the actual amount of damping (DAMP.sub.A) based on the oil pressure and actual precession angle (PA.sub.A) provided by the sensors **104**, one or more dimensions (DIM) of the hydraulic braking system **110** provided by the calibration data **108**, and a target precession rate (PR.sub.T) determined from observance of the actual precession angle (PA.sub.A) over time to obtain an instantaneous rate of change.
[0100] Turning to FIG. **14**B, the target amount of current (CUR.sub.T) is used to obtain a closed loop duty cycle component (DC.sub.OL) and a closed loop duty cycle component (DC.sub.CL). Each of these duty cycle components may, for example, represent a portion of a target duty cycle (DC.sub.T) of the PWM control signal that will control the hydraulic proportioning valve **115**.
[0101] To determine the open loop duty cycle component (DC.sub.OL), an hydraulic valve coil characterization **370** is performed based on the target amount of current (CUR.sub.T). For example, the controller **102** may model one or more power attributes of the braking system **110** to determine an appropriate portion of the PWM control signal duty cycle that accounts for how the braking system **110** behaves electrically.
[0102] To determine the closed loop duty cycle component (DC.sub.CL), the target amount of current is combined with an actual amount of current (CUR.sub.A) provided by the sensors **104** at combiner **210**_v_ to obtain an amount of current error (CUR.sub.E). Based on this current error (CUR.sub.E), a current control PID **380** determines the closed loop duty cycle component (DC.sub.CL). This closed loop duty cycle component (DCCL) may, for example, represent an appropriate adjustment to the PWM control signal duty cycle in view of actual current feedback from the sensors **104**.
[0103] The open loop duty cycle component (DCOL) and the closed loop duty cycle component (DCCL) are combined at combiner **210**_w_ to generate the PWM control signal having a target duty cycle (DC.sub.T). Thus, the controller **102** of FIGS. **14**A and **14**B illustrates an example in which different factors and sub-controllers are used to determine open loop and closed loop factors that form a basis for generating an appropriate PWM control signal for controlling the hydraulic proportioning valve **115** of the braking system **110**.
[0104] Another example of a controller **102** is illustrated in the schematic block diagram of FIG.

15. Similar to the example provided in FIGS. **14**A and **14**B, the controller **102** of FIG. **15** uses sensors **104** and calibration data **108** as inputs in order to generate a control signal for a hydraulic proportioning valve **115** of a braking system **110** according to particular embodiments of the present disclosure.

[0105] In the example of FIG. **15**, the actual precession angle of the gyroscope (PA.sub.A) is provided by the sensors **104** and a precession angle threshold (PA.sub.TH) is provided by the calibration data **108**. The magnitude of the actual precession angle (PA.sub.A) is combined with the precession angle threshold (PA.sub.TH) at combiner **210***k* to provide a precession angle error (PA.sub.E). If the value of the precession angle error (PA.sub.E) is out of a given range (in this example, zero to infinity), the precession angle error is clamped to the closest value that is in range at saturation stage **340**.

[0106] At combiner **210***q*, the clamped precession angle error (PA.sub.E) is combined with an anti-roll torque increment gain (GAIN.sub.D+) provided by the calibration data **108** which acts as a weighting factor. The result of the combiner **210***q* is used at combiner **210***s* as one of a plurality of inputs toward calculating a target anti-roll torque (T.sub.T).

[0107] Another of the inputs to the combiner **210***s* is the magnitude of roll angle of the vessel as weighted by an anti-roll torque decrement gain (GAIN.sub.D−) by combiner **210***r*. The roll angle is provided by the sensors **104** and the precession damping decrement gain (GAIN.sub.D−) is provided by the calibration data **108**. Thus, at combiner **210***s*, a factor indicating that damping upon the precession should increase competes against a factor indicating that damping upon the precession should decrease so that an appropriate target anti-roll torque (T.sub.T) may be calculated. More specifically, the difference between these two competing factors is fed back into the combiner **210***s* as a denominator so that the ratio of future calculations at combiner **210***s* may be compared against previous ones to determine a dynamic ratio. This ratio serves as a target anti-roll torque (T.sub.T) factor, which is provided to a precession centering controller **300** in order to calculate a corrected target anti-roll torque (T.sub.CT) desired from the braking system **110** in order to reduce roll.

[0108] The precession centering controller **300** uses a variety of inputs in order to determine the corrected target anti-roll torque (T.sub.CT). These inputs include the roll angle, the gyro procession angle (PA.sub.A), and the flywheel angular velocity provided by the sensors **104** as well as a precession centering gain (GAIN.sub.C), and a flywheel mass moment of inertia (MOI) provided by the calibration data **108**, in addition to the target anti-roll torque (T.sub.T) previously mentioned.

[0109] A transformation calculation is performed to convert the corrected target anti-roll torque (T.sub.CT) into a target precession rate (PR.sub.T) at a torque-to-precession rate transformation stage **370**. In support of this transformation, the transformation stage uses the roll angle provided by the sensors **104** and one or more gyro mass properties (MASS) provided by the calibration data **108**.

[0110] The target precession rate (PR.sub.T) is compared against an actual precession rate (PR.sub.A) at combiner **210***t* to determine a precession rate error (PR.sub.E). The actual precession rate (PR.sub.A) is obtained by observing the actual precession angle (PA.sub.A) provided by the sensors **104** over time to determine an instantaneous rate of change.

[0111] The precession rate error (PR.sub.E) is used by a precession control PID **360** along with a precession control PID gain (GAIN.sub.PCON) provided by the calibration data to determine a target angular acceleration (ACC.sub.T) of the gyroscope **10**.

[0112] The target angular acceleration (ACC.sub.T) is used along with the actual precession angle (PA.sub.A) provided by the sensors **104** and one or more dimensions (DIM) of the braking system **110** to characterize a target amount of hydraulic damping (DAMP.sub.T) to apply at damping characterization stage **350**. As will be explained more fully below, the target amount of damping (DAMP.sub.T) will be used as a basis for determining an open loop current component (CUR.sub.OL) and as a basis for determining a closed loop current component (CUR.sub.CL) of a

target current (CUR.sub.T) for controlling the braking system **110**.
[0113] Hydraulic value proportioning valve characterization **330** is performed using the target amount of damping (DAMP.sub.T) and the temperature of the oil flowing through the hydraulic proportioning valve **115** to determine the open loop current component (CUR.sub.OL). More specifically, an oil temperature provided by the sensors **104** is used along with the target amount of damping (DAMP.sub.T) to model the characteristics of the hydraulic proportioning value **210** in furtherance of subsequently generating the PWM control signal output by the controller **102** to the braking system **110**.
[0114] The target amount of damping (DAMP.sub.T) is also used at combiner **210***u* where it is compared against an actual amount of damping (DAMP.sub.A) to determine a damping error (DAMP.sub.E). This damping error (DAMP.sub.E) is used by a damping correction PID **320** along with a damping correction PID gain (GAIN.sub.COR) to determine the closed loop current component (CUR.sub.CL).
[0115] The actual amount of damping (DAMP.sub.A) is provided to the combiner **210***u* by an actual damping calculation **310**. The actual damping calculation **310** calculates the actual amount of damping (DAMP.sub.A) based on the oil pressure and actual precession angle (PA.sub.A) provided by the sensors **104**, one or more dimensions (DIM) of the hydraulic braking system **110** provided by the calibration data **108**, and the actual precession rate (PR.sub.A) previously discussed.
[0116] The open loop and closed loop current components (CUR.sub.OL, CUR.sub.CL) are combined by combiner **210***n* to produce a target amount of current (CUR.sub.T) for controlling the hydraulic proportioning valve **115** of the braking system **110**. Similar to the example illustrated in FIG. **14**B, the target amount of current (CUR.sub.T) determined in FIG. **15** may be used to determine open and closed loop duty cycle components (DC.sub.OL, DC.sub.CL) that will be combined to determine a target duty cycle (DC.sub.T) of the PWM control signal that will control the hydraulic proportioning valve **115** of the braking system **110**. Thus, the controller **102** of FIG. **15** illustrates another example in which different factors and sub-controllers are used to determine open loop and closed loop factors forming bases for generating an appropriate PWM control signal.
[0117] In view of the numerous examples described above, FIG. **16** is a flow diagram illustrating an example method **400** of controlling precession of a gyroscope **10** that oscillates about a precession axis **80** perpendicular to a spin axis **50** and a roll axis **95** of the gyroscope **10**. The method **400** comprises detecting a deviation of a center of the oscillation away from a nominal center (block **410**). The precession is caused by roll of the gyroscope about the roll axis and imposes decreasing amounts of damping upon the roll as the precession moves away from the nominal center. The method **400** further comprises reducing the deviation of the center of the oscillation by applying an asymmetric amount of braking to the precession when the precession and the deviation are in a same direction relative to when the precession and the deviation are in opposing directions (block **420**).
[0118] The present invention may, of course, be carried out in other ways than those specifically set forth herein without departing from essential characteristics of the invention. 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. An anti-roll system, comprising: a gyroscope and a motor configured to spin the gyroscope about a spin axis; a mount configured to restrict precession of the gyroscope to oscillation about a precession axis perpendicular to the spin axis; a braking system configured to apply a braking force that controls an extent of the oscillation; a gyroscopic precession controller configured to: detect a deviation of a center of the oscillation away from a nominal center, wherein the precession: is caused by roll of the gyroscope about a roll axis perpendicular to the spin axis and precession axis; and imposes decreasing amounts of damping upon the roll as the precession moves away from the nominal center; and reduce the deviation of the center of the oscillation by controlling the braking system to apply an asymmetric amount of braking to the precession when the precession and the deviation are in a same direction relative to when the precession and the deviation are in opposing directions.

2. The anti-roll system of claim 1, wherein to apply the asymmetric amount of braking, the gyroscopic precession controller is configured to: generate a control signal based on a target amount of damping upon the braking system; and send the control signal to the braking system.

3. The anti-roll system of claim 2, wherein to generate the control signal based on the target amount of damping upon the braking system, the gyroscopic precession controller is configured to: correct the target amount of damping upon the braking system based on the deviation; combine the corrected target amount of damping upon the braking system with damping feedback from the braking system to determine a damping error; and generate the control signal such that an amount of damping applied to the braking system is adjusted to correct for the damping error.

4. The anti-roll system of claim 1, wherein to apply the asymmetric amount of braking, the gyroscopic precession controller is configured to: generate the control signal based on a target amount of precession acceleration; and send the control signal to the braking system.

5. The anti-roll system of claim 4, wherein to generate the control signal based on the target amount of precession acceleration, the processing circuitry is configured to: correct a target precession rate based on the deviation; determine the target amount of precession acceleration based on the corrected target precession rate; combine the target amount of precession acceleration with precession feedback from a precession sensor to determine a precession acceleration error; and generate the control signal such that an amount of precession acceleration permitted by the braking system is adjusted to correct for the precession acceleration error.

6. The anti-roll system of claim 5, wherein: to generate the control signal based on the target amount of precession acceleration, the gyroscopic precession controller is further configured to combine the corrected target precession rate with further precession feedback to determine a precession rate error; to determine the target amount of precession acceleration based on the corrected target precession rate, the gyroscopic precession controller is configured to calculate the target amount of precession acceleration based on the precession rate error.

7. The anti-roll system of claim 1, wherein: the braking system comprises a hydraulic damping valve; the gyroscopic precession controller is further configured to: calculate an amount of current that, when sent to a hydraulic damping valve of a braking system controlling the braking, reduces the deviation; and generate a pulse width modulated (PWM) control signal having a duty cycle that provides the amount of current; to reduce the deviation by applying the asymmetric amount of braking, the gyroscopic precession controller is configured to send the PWM control signal to the hydraulic damping valve.