Feb. 13, 1968 R. I. SANN 3,368,411

MEANS FOR COMPENSATION OF MISALIGNMENT ERRORS IN A GYROSCOPE

Filed Dec. 28, 1964

3 Sheets-Sheet 1

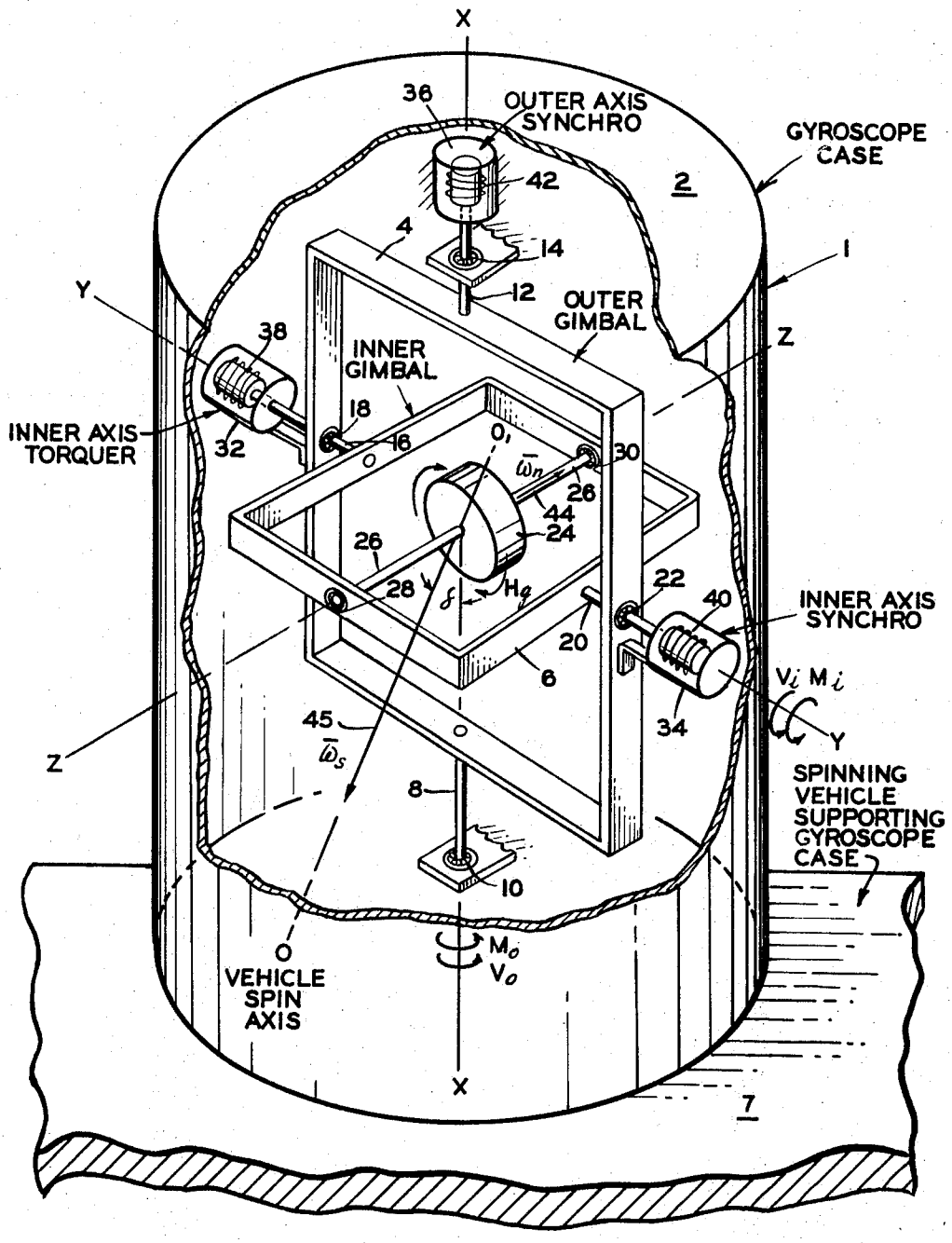


FIG. 1

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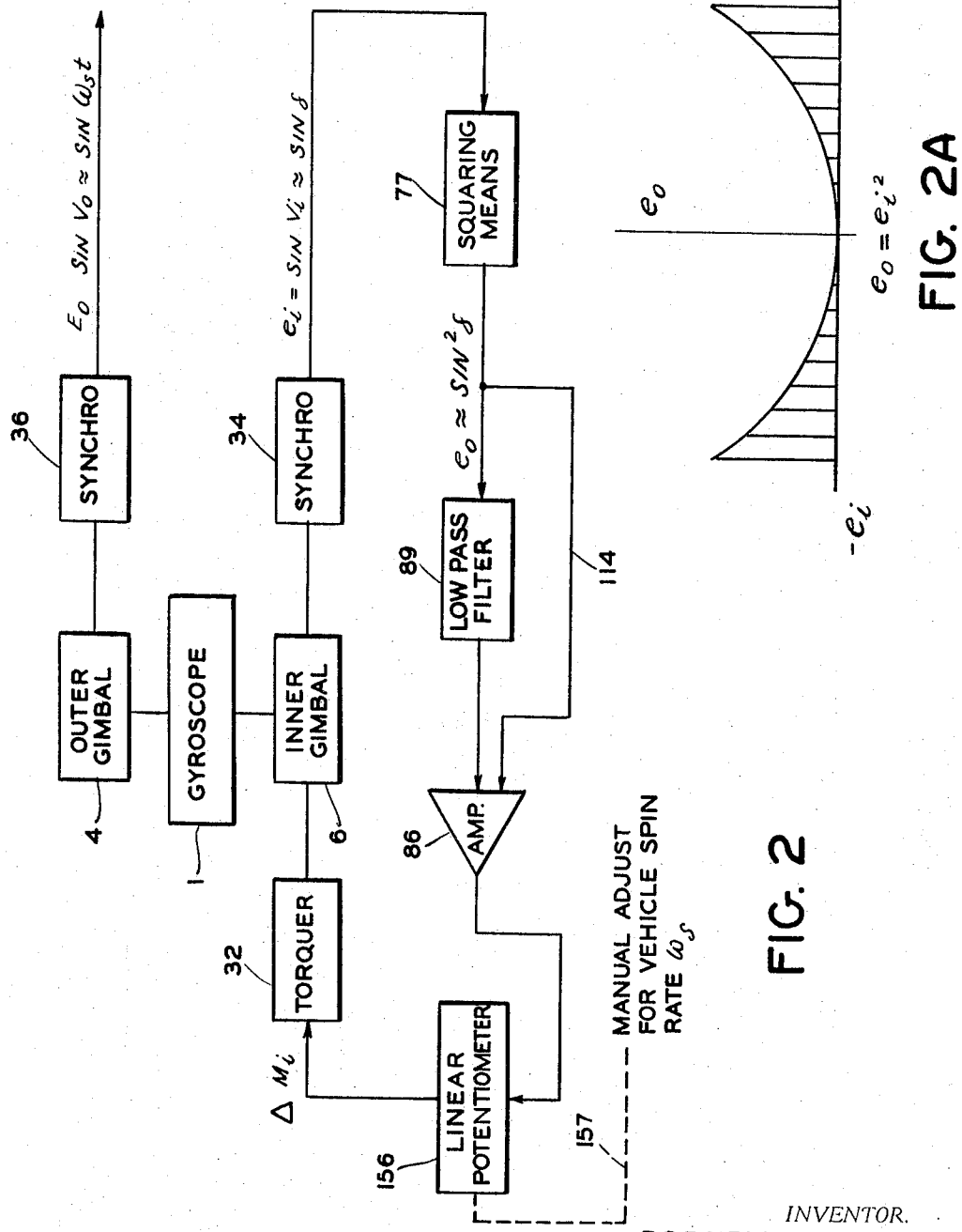


FIG. 2

FIG. 2A

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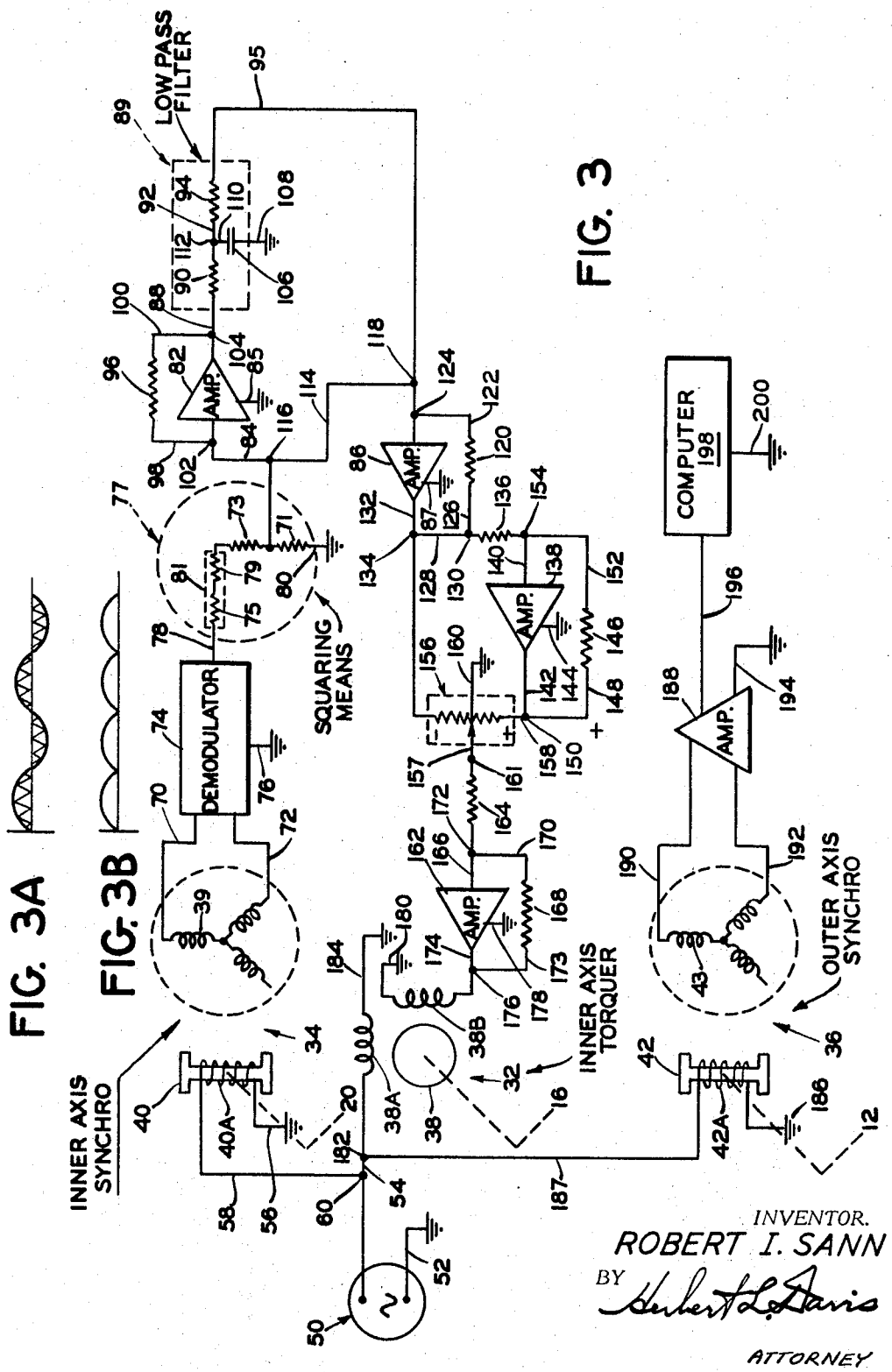


FIG. 3A

FIG. 3B

FIG. 3

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3,368,411

MEANS FOR COMPENSATION OF MISALIGNMENT ERRORS IN A GYROSCOPE

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13 Claims. (Cl. 74—5.4)

This invention relates to a novel means for eliminating the effect of an error in alignment of an outer gimbal axis of a two degree of freedom gyroscope with that of a spin axis of a spinning space vehicle, and more particularly to a novel feedback compensation means for making a two degree of freedom gyroscope more effective to measure the attitude of a spinning body by rendering the gyroscope insensitive to such misalignment between the axis of the spinning body and the gyroscope outer gimbal axis.

Certain problems are presented in the application of a two degree of freedom gyroscope to the measurement of the angular displacement of a spinning space vehicle, and in particular to a space vehicle which can be approximated as a rigid body spinning about a fixed axis at a steady rate relative to inertial space, and simultaneously rotating in a circular path about an earth centered axis. These problems essentially relate to compensation of an error resulting from an angular misalignment between the gyroscope outer gimbal axis and the vehicle spin axis due to the inherent limitations in the possible accuracy with which these axes may be physically aligned, and hence the problems relate to the provision of means to effect a control of the resultant gyroscope output error and means to compensate for the remaining misalignment between the respective gyroscope and vehicle axis that cannot be so controlled.

It is desirable to reduce the requirements on alignment accuracy of the respective axes, as long as an adequate means is available to compensate the measured attitude of the spinning vehicle for any misalignment with the output axis of the gyroscope that prevails. The present invention accomplishes this by embodying a means, based on feedback control of the inner gimbal of the gyroscope, which desensitizes the gyroscope output with regard to a misalignment of the vehicle spin axis and the outer gimbal axis.

To reduce gyro output error, the gyroscope outer gimbal axis must be as close as possible to being in complete parallelism with the vehicle spin axis. If the angular deviation (misalignment) between these two axes is δ, the steady state error e_ϕ in terms of vehicle angular displacement may be developed as follows:

ϕ=Actual vehicle angular displacement=$\omega_s t$.

ω_s=vehicle spin rate
t=time

ϕ_m=Vehicle angular displacement as measured by the gyroscope=$\omega_s t \cos \delta$.

The error, e_ϕ, is measured vehicle angular displacement, is given as

$$(1) \quad e_\phi=\phi-\phi_m=\omega_s t-\omega_s t \cos \delta=\omega_s t(1-\cos \delta)$$

An expansion of the term $(1-\cos \delta)$ in a power series provides the expression

$$(2) \quad e_\phi=\tfrac{1}{2}\delta^2\omega_s t$$

thus showing that in an uncompensated gyroscope, the error in measured vehicle angular displacement is proportional to the square of the misalignment between the vehicle axis and the gyroscope outer gimbal axis.

The compensation means embodied in the present invention reduces the error due to the misalignment angle

δ by making the error e_ϕ proportional to δ^4 rather than to δ^2.

$$(3) \quad e_\phi=\frac{\delta^4}{12}(\sin 2\omega_s t-\omega_s t)$$

The compensation means embodied herein operates by causing the gyroscope outer gimbal to precess about its axis at a constant rate. This precession rate is induced by a compensating torque supplied by the gyroscope inner gimbal torquer. The required compensating torque is computed by a feedback loop about the gyroscope inner gimbal. In order to compute this torque, the output of a gyroscope inner gimbal synchro, being proportional to the sine of the angular misalignment δ, for small δ, is coupled to a linear potentiometer through a computing circuit. The arm of the potentiometer may be manually adjusted to provide a signal proportional to the vehicle angular rate ω_s of the spinning vehicle relative to inertial space, the output of the potentiometer being thus proportional to the required compensating torque. This output may be applied to the inner gimbal torquer, with the torque evolved therefrom causing the outer gyroscope gimbal precession.

In this manner, the error e_ϕ in measured vehicle angular displacement may be reduced from that shown in Equation 2 to that shown in Equation 3.

An object of this invention is to provide novel means for eliminating the effect of alignment errors in a two degree of freedom gyroscope.

Another object of this invention is to provide novel means whereby a two degree of freedom gyroscope used to measure the attitude of a spinning space vehicle will be insensitive to a misalignment between the gyroscope outer gimbal axis and the spin axis of the vehicle.

Another object of this invention is to provide means to compensate for alignment errors in a two degree of freedom gyroscope by providing for a feedback loop around the inner gimbal of a conventional two degree of freedom gyroscope.

Another object of this invention is to provide means whereby a two degree of freedom gyroscope used to measure the attitude of a spinning space vehicle will be insensitive to a misalignment between the gyroscope outer gimbal axis and the spin axis of the vehicle, said means including a feedback loop having a means to provide an output proportional to the square of the sine of the misalignment angle, a filter means to rectify said output, an amplifier to sum the filtered and unfiltered output, and a linear potentiometer, manually adjustable to provide an output signal proportional to the angular rate of the spinning vehicle relative to inertial space.

Another object of this invention is to provide in a gyroscope having an inner and outer gimbal, a feedback loop around the inner gimbal with said feedback loop providing a signal proportional to a control torque so that when this signal is applied to an inner gimbal torquer the torque that evolves therefrom will cause a precession of the gyroscope outer gimbal about its axis, thus compensating for a misalignment between the gyroscope outer gimbal axis and the spin axis of a space vehicle.

Another object of this invention is to couple the output signal of a gyroscope inner gimbal synchro, said signal being proportional to the sine of the angular deflection of a space vehicle spin axis from the gyroscope outer gimbal axis, to a feedback loop and said feedback loop evolving a signal proportional to the torque required to precess the outer gimbal about its axis in compensation for said angular deflection, the torque being induced by applying the signal from the feedback means to a gyroscope inner gimbal torquer.

These and other objects and features of the invention

are pointed out in the following description in terms of the embodiment thereof which is shown in the accompanying drawings. It is to be understood, however, that the drawings are for the purpose of illustration only and are not a definition of the limits of the invention, reference being had to the appended claims for this purpose.

In the drawings:

FIGURE 1 is a diagrammatic view of a two degree of freedom gyroscope showing the elements pertinent to the novel means embodied in the present invention.

FIGURE 2 is a block diagram showing the feedback means embodied in the present invention.

FIGURE 2A is a diagram showing the relationship between the input and output signals of the electronic squaring means shown in FIGURE 2.

FIGURE 3 is a schematic wiring diagram showing the electrical interconnections embodied in the present invention.

FIGURE 3A is a diagram showing the signal evolved from the inner gimbal synchro in a modulated form.

FIGURE 3B is a diagram showing the absolute value of the input signal in a demodulated form.

In reference to FIGURE 1, a conventional two degree of freedom gyroscope designated by the numeral **1** is shown including a gyroscope case **2**, an outer gimbal **4** and an inner gimbal **6**. The gyroscope case **2** is securely mounted to a spinning space vehicle **7**, a fragmentary portion of which is shown in FIGURE 1. The arrangement is such that an outer gimbal axis X—X of the outer gimbal **4** is misaligned from the spin axis O—O of the space vehicle **7** due to the limitations in the possible accuracy with which the case **1**, and thereby the axis X—X thereof, can be mounted in relation to the axis O—O of the space vehicle **7**. The outer gimbal **4** having a shaft **8** and a shaft **12** is journaled in the gyroscope case **2** by the shaft **8** rotatably mounted in a bearing **10** carried by the case **2** and the shaft **12** rotatably mounted in a bearing **14** carried by the case **2**, with the outer gimbal **4** having complete fredom of rotation about the outer gimbal axis X—X.

The inner gimbal **6**, having a shaft **16** rotatably mounted in a bearing **18** carried by the outer gimbal **4** and a shaft **20** rotatably mounted in a bearing **22** carried by the outer gimbal **4**, is thus pivotally mounted relative to the outer gimbal **4** along an inner gimbal axis Y—Y, with the inner gimbal **6** having limited freedom about the inner gimbal axis Y—Y.

A rotor **24**, having a shaft **26**, is journaled along an axis Z—Z by the shaft **26** being rotatably mounted in a bearing **28** and a bearing **30** carried by the inner gimbal **6**.

An inner axis torquer **32** and an inner axis synchro **34** are fixedly mounted to the outer gimbal **4** with the rotor **38** of the inner axis torquer **32** and the rotor **40** of the inner axis synchro **34** being affixed to the shafts **16** and **20**, respectively, so as to rotate with the inner gimbal **6** about the inner gimbal axis Y—Y.

As shown in FIGURE 3, the torquer **32** may be a conventional two phase motor having a fixed phase winding **38A** and a control winding **38B** arranged in cooperative relation with the rotor **38** while the synchro **34** has a rotor **40** carrying a rotor winding **40A** energized from a main source of alternating current **50**, and a stator winding **39** inductively coupled thereto.

An outer axis synchro **36** is shown in FIGURE 1 fixedly mounted to the gyroscope case **2** with a rotor **42** of the outer axis synchro **36** affixed to the shaft **12** so as to rotate with the outer gimbal **4** about the outer gimbal axis X—X. The rotor **42** carries a rotor winding **42A** energized from a main source of alternating current **50** and a stator winding **43** inductively coupled thereto as shown in FIGURE 3.

A vector **45** representing the constant vehicle spin rate $\bar{\omega}_s$ is shown in FIGURE 1 misaligned from the outer gimbal axis X—X by the angle δ in the X–Y plane, while a vector **44** along the rotor axis Z—Z represents the spin rate $\bar{\omega}_n$ of the gyroscope provided by the rotor **24**, with

the rotor **24** also having an angular momentum H_g about the rotor axis Z—Z.

The outer gimbal **4** may have an angular displacement V_o about the outer gimbal axis X—X produced by a torque M_o. Similarly, the inner gimbal **6** may have an angular displacement V_i about the inner gimbal axis Y—Y produced by a torque M_i.

With reference to the structure as shown in FIGURE 1, the compensation means provided by the present invention provides for precessing the gyroscope outer gimbal **4** about the axis X—X at a rate which will minimize the error e_ϕ due to the misalignment δ shown in Equation 2 upon the misalignment of the vehicle spin axis O—O in relation to the outer gimbal axis X—X of FIGURE 1. This precession rate is induced by controlling the energization of the control winding **38B** of the inner gimbal torquer **32** so that the required control torque is supplied by the inner gimbal torquer **32**, as shown in FIGURE 3.

In reference to FIGURE 1, in order to determine the torque required to provide the proper precession rate, the gyroscope **1** having the outer gimbal **4** and the inner gimbal **6** is considered. The outer gimbal **4** has the synchro **36** which generates a signal proportional to the sine of the angular displacement V_o of the outer gimbal **4** about the axis X—X, this signal being also proportional to the sine of the vehicle angular displacement $\omega_s t$.

The inner gimbal **6** has the synchro **34** which generates a signal proportional to the sine of the angular deflection V_i of the inner gimbal **6** about the axis Y—Y, this signal being also proportional to the sine of the angular displacement δ. The signal generated by the synchro **34** is then coupled to a feedback loop which performs the operations necessary to compensate for the misalignment error e_ϕ.

A block diagram of the feedback loop is shown in FIGURE 2. The signal e_i from the inner axis synchro **34** which is proportional to sine V_i and to sine δ is coupled through a squaring means **77**. As shown in FIGURE 2A, the relationship between the signal supplied to the squaring means **77** (e_i) and the signal received from said squaring means **77** (e_o) is nonlinear. Because of the characteristics of the squaring means **77**, shown in detail in FIGURE 3, the output of the squaring means **77** is proportional to $\sin^2 V_i$ and $\sin^2 \delta$. This output is rectified through a filter **89**. The output of the squaring means **77** is further coupled through a conductor **114** to a summing amplifier **86** where it is joined by the output of the filter **89**. The resultant output of the summing amplifier **86** is connected to a linear potentiometer **156**, the potentiometer **156** having a control arm **157** which is manually adjusted to a position to provide an output signal proportional to the angular velocity ω_s of the spinning space vehicle **7** relative to inertial space.

The output signal of the potentiometer **156** is thus proportional to a control torque ΔM_i which is equal and opposite to M_i or the torque of the inner gimbal **6** about its axis Y—Y. This output signal from the potentiometer **156**, at such adjusted position thereof, is coupled through the inner gimbal torquer **32** which torquer **32** induces a precession rate of the outer gimbal **4** about the axis X—X so as to reduce the error e_ϕ, due to the misalignment of the outer gimbal axis X—X and the vehicle spin axis O—O from that shown in Equation 2 to that shown in the Equation 3, as heretofore noted.

With reference to FIGURE 1, a mathematical analysis of this phenomenon may be made. The kinetic energy KE of the two gimbal gyroscope system, as a function of the angular deflection V_o of the outer gimbal **4** about its axis X—X and the angular deflection V_i of the inner gimbal **6** about its axis Y—Y, may be expressed as follows:

$$KE(V_i, \dot{V}_o, \dot{V}_i, V_o) = \tfrac{1}{2} J_g (\omega_R)^2 \quad (4)$$

where:

J_g=moment of inertia of the rotor **24**

ω_R=angular speed of the rotor **24** relative to inertial space

Considering the two-gimbal arrangement to have two rectangular axis systems, one such system fixed to the gyroscope case **2** and the other fixed to the inner gimbal **6**, the two systems coinciding when $V_i=V_o=0$, the angular speed ω_R of the rotor **24** may be expressed in terms of the vehicle spin rate ω_s represented by the vector **45** or $\bar{\omega}_s$, the gyroscope spin rate ω_n represented by the vector **44** or $\bar{\omega}_n$, and the angular deflections V_o, V_i and δ, shown diagrammatically in FIGURE 1 and expressed as follows:

(5)

$$2\frac{KE}{J_g}=\dot{V}_i^2+\dot{V}_o^2+2V_o(\omega_n \sin V_i-\omega_s \cos \delta)+$$
$$2\omega_n\omega_s(\sin \delta \sin V_o \cos V_i-\cos \delta \sin V_i)+\omega_n^2+\omega_s^2$$

Applying the appropriate Lagrange dynamical equations of motion, the torque M_i about the inner axis Y—Y and the torque M_o about the outer axis X—X may be expressed as follows:

(6)
$$\frac{d}{dt}\left(\frac{\partial KE}{\partial \dot{V}_i}\right)-\frac{\partial KE}{\partial V_i}=M_i$$
$$\frac{d}{dt}\left(\frac{\partial KE}{\partial \dot{V}_o}\right)-\frac{\partial KE}{\partial V_o}=M_o$$

substituting Equation 5 in Equation 6:

(7)

$$\frac{M_i}{J_g}=\ddot{V}_i+\dot{V}_o(\omega_s \sin \delta \sin V_o-\omega_n \cos V_i)+$$
$$\omega_n\omega_s(\sin \delta \sin V_o \sin V_i+\cos \delta \cos V_i)$$

(8)

$$\frac{M_o}{J_g}=\ddot{V}_o+\dot{V}_i(\omega_n \cos V_i-\omega_s \sin \delta \sin V_o)-$$
$$\omega_n\omega_s \sin \delta \cos V_o \cos V_i$$

Considering that $M_o=0$, $V_o=\omega_s t$, V_i is a small angle. and $|\dot{V}_i|$ is much smaller than ω_n, Equation 8 can be solved for $\dot{V}_i$ and an integration performed to obtain V_i.

(9)
$$\dot{V}_i=\omega_s \sin \delta \cos \omega_s t$$
$$V_i=\sin \delta \sin \omega_s t$$

Substituting $V_o=\omega_s t$ and the expression for V_i determined in Equation 9 into Equation 7, a disturbance torque M_i about the inner gimbal axis Y—Y is represented by:

(10) $$M_i=\omega_s H_g\ (1-\cos\ \delta)+\omega_s H_g V_i \sin\ V_i$$

where: $H_g=J_g\omega_n$, the gyroscope angular momentum.

The disturbance torque given by Equation 10 introduces an error e_ϕ in the gyroscope output. This disturbance torque may be nullified by torquing the inner gimbal **6** with a compensation torque ΔM_i equal and opposite to the disturbance torque M_i. The compensation torque ΔM_i is supplied to the inner gimbal **6** by applying a voltage proportional to ΔM_i to the inner gimbal torquer **32**, with this voltage determined by using the output of the inner gimbal synchro **34** as a measure of δ and assuming the vehicle spin rate ω_s to be known.

Assuming $M_o=0$ and $V_o=\omega_s t-e_\phi$, Equation 8 may be written as follows:

(11)

$$\frac{\ddot{e}_\phi}{\omega_n}+\dot{V}_i\left[\cos V_i-\frac{\omega_s}{\omega_n}\sin \delta \sin (\omega_s t-e_\phi)\right]-$$
$$\omega_s \sin \delta \cos V_i \cos (\omega_s-e_\phi)=0$$

Assuming e_ϕ and V_i to be small and ω_n approaching infinity, an expression for $V_i(t)$ may be determined.

(12)
$$\dot{V}_i(t)=\omega_s\delta \cos \omega_s t$$
$$V_i(t)=\delta \sin \omega_s t$$

Introducing Equation 12 into Equation 8 with

$$V_o=\omega_s t-e_\phi$$

and ω_n approaching infinity, higher orders of the angular deflection δ are obtained.

(13) $$\frac{M_i}{H_g}=\dot{e}_\phi-\frac{\omega_s\delta^2}{2}\cos 2\omega_s t+\frac{\omega_s\delta^4}{12}(1-\tfrac{1}{2}\cos 2\omega_s t)$$

Using Equation 12, the steady state output of the filter **106** in FIGURE 2 is:

(14) $$\tfrac{1}{2}\delta^2-\tfrac{1}{8}\delta^4$$

The compensation torque ΔM_i can be computed using Equations 12 and 14

(15) $$\frac{\Delta M_i}{\omega_s H_g}=\frac{\delta^4}{6}(\cos 2\omega_s t-\tfrac{1}{4}\cos 4\omega_s t)$$

Considering $M_i=-\Delta M_i$, e_ϕ may be solved for by substituting equation $M_i=-\Delta M_i$ into Equation 13 using Equation 15.

(16) $$e_\phi=\frac{-\omega_s\delta^4}{6}(\tfrac{1}{2}-\cos 2\omega_s t)$$

or

(3) $$e_\phi(t)=\frac{\delta^4}{12}(\sin 2\omega_s t-\omega_s t)$$

In the foregoing derivation of Equation 3 it is apparent that the error e_ϕ, due to the angular misalignment δ, has been reduced from being proportional to δ^2 to being proportional to δ^4, by causing a precession of the outer gimbal **4** about the axis X—X to be induced by a compensating torque ΔM_i supplied by the inner gimbal torquer **32**.

In reference to FIGURE 3, there is provided the alternating current input supply **50** of conventional type having a grounded conductor **52** and an output conductor **54**. The inner gimbal synchro **34** has a stator winding **39** inductively coupled to a winding **40A** carried by a rotor **40**. The rotor winding **40A** has one terminal grounded at **56** and an opposite terminal connected by a conductor **58** joining the output conductor **54** from the alternating current supply **50** at a point **60**. The rotor **40** carrying the winding **40A** is mounted on the inner gimbal shaft **20** and angularly adjusted thereby relative to the stator winding **39** so that the output of the inner gimbal synchro **34** at output conductors **70** and **72** is proportional to the sine of the angular deviation V_i of the inner gimbal **6** about its axis Y—Y, and also proportional to the sine of the misalignment angle δ between the vehicle spin axis O—O and the outer gimbal axis X—X as shown in FIGURE 1.

This output signal from the inner gimbal synchro **34** is coupled through the conductors **70** and **72** to a demodulating device **74** of conventional type. The demodulating device **74** serves to separate the absolute value of the signal generated by the synchro **34**, as shown in FIGURE 3B, from its carrier as shown in FIGURE 3A. This demodulation is required so that the absolute value of the signal (FIGURE 3B) may be squared as will be next described.

The demodulator **74**, having a grounded output **76**, is coupled to a signal squaring means **77** by an output conductor **78**. The signal squaring means **77** may be of a conventional type in which the nonlinear properties of a varistor including resistor elements of silicon carbide, or other suitable material, may be used to effect the required signal squaring action. The current-voltage relationship in such a varistor is given by

$$I=KE^2$$

This relationship may be accomplished by putting proper linear resistances **71** and **73** in series with a varistor **81**, with said varistor **81** having a plurality of resistors shown

in FIGURE 3 as resistors 75 and 79 of a suitable silicon carbide material. A solid state, passive squaring means such as a Douglas Quadratron (type P, model D) device manufactured by the Douglas Aircraft Company, Inc., El Segundo, Calif., or a similar device, may be used as the squaring means 77 of the present invention.

The output of the squaring means 77, thus proportional to the square of the sine of the misalignment angle δ, is coupled to a grounded conductor 80 and to an amplifier means 82 by a conductor 84. The amplifier means 82 is provided to match the low impedance signal emitted from the squaring means 77 with the high impedance signal required by the remainder of the feedback loop. The output of the amplifier means 82 is coupled through a grounded conductor 85 and a conductor 88 to a summing amplifier 86. The conductor 88 leads to the summing amplifier 86 through a filter network 89 including a capacitor 106 having a grounded conductor 108 and a conductor 110 leading to a conductor 92 connecting a resistor 90 to a resistor 94 which is in turn connected to an output conductor 95 leading to the summing amplifier 86.

A resistor 96 is connected across the amplifier means 82 by a conductor 98 joining the conductor 84 at a junction 102 and a conductor 100 joining the conductor 88 at a junction 104. The resistor 96 is included so as to make the amplifier 82 a finite gain device, thus making it operational within the feedback loop.

The output signal from the amplifier means 82, coupled to the resistor 90 in the filter network 89 by the conductor 88, is filtered by the capacitor 106 in the filter network 89, said capacitor 106 having one plate connected to the grounded conductor 108 and an opposite plate connected through the conductor 110 to the conductor 92 at a junction 112 intermediate the resistors 90 and 94. The filter capacitor 106 serves to extract the direct current portion of the signal proportional to the square of the sine of the misalignment angle δ, and to provide this signal with an appropriate time delay constant so that the feedback loop may be operational in performing the computation indicated by Equation 15.

The output from the squaring means 77, and the output from the filter network 89 are summed by the summing amplifier 86, the squaring means output conductor 84 being joined by a conductor 114 at a junction 116 and the conductor 114 being joined to the output conductor 95 of the filter network 89 at a junction 118. A resistor 120, to provide a finite gain to the amplifier 86, is connected across the amplifier 86 by a conductor 122 joining the conductor 95 at a junction 124, a conductor 126 joining the conductor 128 at a junction 130, and the conductor 128 joining an output conductor 132 from the summing amplifier 86 at a junction 134. The amplifier 86 is further connected at other input and output terminals to a grounded conductor 87.

The summed output of the amplifier 86 at the output conductor 132 is coupled to an amplifier 138 through the conductor 132 being joined at the junction 134 by the conductor 128, a resistor 136 and a conductor 140 leading to an input of the amplifier 138. The amplifier 138 acts to modify the signal polarity so as to relate the input provided by the conductor 140 to the output provided by a conductor 142 by a -1 value. Amplifier 138 is connected at other input and output terminals to a grounded conductor 144, while a gain control resistor 146 is connected across amplifier 138 by a conductor 148 joining output conductor 142 at a junction 150, and a conductor 152 joining the conductor 140 at a function 154.

The output of the summing amplifier 86 is connected through the conductor 132 to the negative side of a linear potentiometer 156, and the output of the amplifier 138 is connected through the conductor 142 joining a conductor 158 at the junction 150 to the positive side of the linear potentiometer 156. The potentiometer 156 is provided with a center tap ground conductor 160 to reverse the polarity of the incoming signal, and has a control arm 157 which is manually adjustable for varying values ω_s of the vehicle spin rate, as heretofore explained. The potentiometer output, now proportional to the compensation torque ΔM_i, as shown by Equation 15, is coupled to the gain amplifier 162, for purposes of intensifying the signal, through a conductor 161, a resistor 164 and an input conductor 166. A gain control resistor 168 is connected across the amplifier 162 by a conductor 170 joining the input conductor 166 at a junction 172 and a conductor 173 joining an output conductor 174 of the amplifier 162 at a junction 176. The amplifier 162 is further connected at other input and output terminals to a grounded conductor 178.

The feedback loop is completed by the amplified potentiometer output, coupled through the conductor 174, being supplied as an input to a control winding 38B of a conventional two-phase torquer motor 32. The control winding 38B is arranged in cooperative relation with a rotor 38 of the inner gimbal torquer 32, said winding being grounded at a point 180.

A fixed phase winding 38A of the torquer 32 is coupled to the input supply 50 by the conductor 54 leading to one end of the winding 38A while an opposite end of the winding 38A is grounded by a conductor 184. The inner gimbal torquer 32, thus excited, provides a compensating torque ΔM_i, causing a precession of the outer gimbal 4 of FIGURE 1 in a sense rendering a reduction in the error e_ϕ in the measured vehicle angular displacement.

The outer gimbal synchro 36 has a stator winding 43, shown in FIGURE 3, inductively coupled to a rotor winding 42A carried by a rotor 42 affixed to the outer gimbal shaft 12. The rotor winding 42A is connected at one end to the input alternating current supply 50 by a grounded conductor 186 and at an opposite end through a conductor 187, joining the conductor 54 at a junction 182. The output of the outer gimbal synchro 36 provides a signal which is a measure of the angular position of the gimbal 4 and is proportional to the sine of the angular deviation V_o of the outer gimbal about the axis X—X, and is also proportional to the sine of the vehicle angular displacement $\omega_s t$ in inertial space. This output from the synchro 36 may be coupled, as shown by way of example in FIGURE 3, to an amplifier means 188 through conductors 190 and 192, with the output of the amplifier means 188 being connected to a grounded conductor 194 and further connected through a conductor 196 to a computer means 198 of conventional type and having another input terminal grounded by a conductor 200. The output signal from the synchro 36 may be utilized in the computer means 198 to provide a measure of the attitude of the spinning space vehicle 7 for effecting a control or indicating function as may be desired.

Operation

The present invention provides for a feedback loop around the inner gimbal 6 of a conventional two-degree of freedom gyroscope. This feedback loop provides novel means of improving the accuracy of the gyroscope when the gyroscope is used to measure the attitude of a steadily spinning vehicle 7 in the presence of an unknown misalignment angle between the spin axis O—O of the vehicle 7 and the gyroscope output axis X—X. Operationally, the present invention converts a voltage signal proportional to the angular misalignment of the gyroscope output axis X—X and the spin axis O—O of the vehicle 7 into precessional movement of the outer gimbal 4 about the axis X—X in order to compensate for such angular misalignment. Although for purposes of example, the angular misalignment has been taken to be in one direction only, similar means of compensation could be developed for angular misalignment in other directions.

A mathematical analysis of the novel means embodied in the present invention indicates initially an expression of the kinetic energy of the gyroscope system in terms of the respective angular deflections of the inner and outer

gimbals, as shown in Equation 4. This kinetic energy is further translated in terms of the angular deflection of the gyroscope outer gimbal axis of rotation from the vehicle spin axis, as shown in Equation 5. With the expressions for kinetic energy being expressed in terms of torque as shown in Equations 7 and 8, the error due to the misalignment of the outer gimbal axis and the vehicle spin axis may be represented as shown in Equation 11. A simplified expression for this error is shown in Equation 3, and when this expression is compared to Equation 2, a reduction in the misalignment error can be seen to depend on increasing the exponent of the small angular misalignment.

The foregoing mathematical analysis is implemented in the circuitry shown generally in FIGURE 2 and in detail in FIGURE 3. A voltage signal proportional to the angular misalignment is provided by the inner gimbal synchro **34** and coupled through the illustrated electrical means to provide an output voltage signal from the potentiometer **156** which is proportional to a computed torque. When this voltage signal is applied to the inner gimbal torquer **34**, a torque is evolved which causes a precession of the outer gimbal in compensation for the angular misalignment.

It will be seen from the foregoing that there has been provided by the present invention novel means for compensating for the misalignment of a vehicle spin axis O—O and the outer gimbal axis X—X of a gyroscope when the gyroscope is used to measure the attitude of the space vehicle.

The arrangement may be adapted to any conventional two-degree of freedom gyroscope where the errors due to such a misalignment must be kept to a minimum. The novel means described herein is of particular value when these errors must be minimized in a satellite type vehicle, spinning about its own axis and simultaneously rotating about an earth centered axis.

Although only one embodiment of the invention has been illustrated and described, various changes in the form and relative arrangements of the parts, which will now appear to those skilled in the art may be made without departing from the scope of the invention. Reference is, therefore, to be had to the appended claims for a definition of the limits of the invention.

What is claimed is:

1. In a gyroscopic control system for a spinning space vehicle, a vehicle having a spin axis, a two degree of freedom gyroscope having a first gimbal and a second gimbal, said gimbals having axes of rotational freedom in orthogonal relationship; means for mounting the gyroscope in the vehicle so that the axis of the first gimbal is in nominal alignment with the spin axis of the vehicle, but has a misalignment error angle with respect to said spin axis, a first synchro operatively controlled by said first gimbal to provide an output signal as a measure of the attitude of the space vehicle, a torquer having a rotor element and a stator element, said stator element being mounted on said first gimbal, means to rotatably mount said rotor element relative to said stator element and to operatively connect said rotor element to said second gimbal on an axis parallel to the pivotal axis of the second gimbal so that angular movement of the second gimbal will be effected by movement of the rotor element relative to the stator element, a second synchro having a rotor element, a stator element and an electrical output, said stator element being mounted on said first gimbal, means to rotatably mount said rotor element of the second synchro relative to said stator element of the second synchro and to operatively connect said rotor element to said second gimbal on an axis parallel to the axis of the second gimbal so that angular movement of the second gimbal will adjustably position the rotor element relative to the stator element to vary the electrical output of the second synchro, a feedback means for converting the electrical output of said second synchro to a signal proportional to the torque required to compensate for said misalignment error angle of the axis of the first gimbal with respect to the spin axis of the vehicle, and a means to apply said signal to said torquer to produce a torque causing a precession of the first gimbal in a sense to compensate the output signal of the first synchro for said misalignment error angle.

2. In a gyroscopic control system for a spinning space vehicle, having a spin axis, a two degree of freedom gyroscope having an inner gimbal and an outer gimbal, said gimbals having axes of rotation in orthogonal relationship; mounting means for mounting said gyroscope in said vehicle so that the outer gimbal axis is nominally aligned along the spin axis of the vehicle, but has a misalignment error angle with respect to said spin axis, a torquer having a rotor element operatively connected to the inner gimbal, and a stator element mounted on said outer gimbal, means to adjustably mount said rotor element relative to said stator element and on an axis parallel to the axis of rotation of the inner gimbal, a synchro having a rotor element operatively connected to the inner gimbal and a stator element mounted on said outer gimbal, means to adjustably mount said rotor element relative to said stator element and on an axis parallel to the axis of rotation of the inner gimbal, the output of said synchro being proportional to the misalignment error angle of the outer gimbal axis with respect to the vehicle spin axis, a feedback means converting said output of said synchro to a signal, and a means to apply said signal to said torquer to produce a torque causing a precession of the outer gimbal to compensate for said misalignment error angle.

3. The combination defined by claim **2** in which said feedback means includes electronic control means to provide a nonlinear relationship between the output of said synchro and the output of said electronic control means, said electronic control means output being proportional to the square of the sine of the misalignment error angle of the outer gimbal axis with respect to said vehicle spin axis, electronic network means to extract a direct current portion of said electronic control means output, electronic control means to sum said output and the extracted direct current portion thereof, and an electronic control means to convert said sum to an output voltage signal for causing said torquer to precess the outer gimbal to compensate for said misalignment error angle.

4. The combination defined by claim **3** in which said electronic control means to provide said output voltage signal includes a manually adjustable means to compensate for changes in the spin rate of said spinning vehicle.

5. In a gyroscopic control system for a spinning vehicle, a vehicle having a spin axis, a two degree of freedom gyroscope having an inner gimbal and an outer gimbal, said gimbals having axes of rotational freedom in orthogonal relationship; mounting means for mounting said gyroscope in said vehicle so that the outer gimbal axis is nominally aligned along the spin axis of the vehicle, but has a misalignment error angle with respect to said spin axis, sensing means operatively connected between said inner and outer gimbals to generate a first signal proportional to said misalignment error angle, electronic control means to convert said first signal to a second signal variable with the spin rate of said spinning vehicle, a torquer operatively connected between said inner and outer gimbals, and an electronic conversion means including said torquer to convert said second signal to a torque causing a precession of said outer gimbal in compensation for said misalignment error angle.

6. In a gyroscopic control system for a spinning vehicle, a vehicle having a spin axis, a gyroscope including a gimbal having an axis of rotation; mounting means for mounting said gyroscope in the vehicle so that the axis of rotation of the gimbal is nominally aligned with the spin

axis of the vehicle, but has a misalignment error angle, means to generate a signal proportional to said misalignment error angle, operator-operative means to convert said signal generated by said means to a signal variable with the spin rate of the spinning vehicle, and torquing means responsive to the signal generated by the operator-operative means to cause a precession of said gimbal to compensate for said misalignment error angle.

7. In a gyroscopic control system for a spinning vehicle, a gyroscope having an axis of rotation, mounting means for mounting said gyroscope so that the axis of rotation is nominally aligned with the spin axis of the vehicle but has a misalignment error angle with respect to said spin axis, means to generate a signal proportional to said misalignment error angle, a converter means to convert the misalignment error angle signal into a signal proportional to a compensating torque and including means manually adjustable to compensate for changes in the spin rate of the spinning vehicle, and a torquer responsive to said converted signal to apply the torque to precess said gyroscope about said axis to compensate for said misalignment error angle.

8. The combination defined by claim 7 in which said converter means includes means to demodulate said signal proportional to said misalignment error angle, said signal having an absolute value and a carrier, and said demodulating means acting to separate the absolute value of said signal from the carrier, squaring means to affect the magnitude of said demodulated signal so that the output of said squaring means is proportional to the square of the input thereto, filter means acting to extract a direct current portion of the output of said squaring means and to provide the direct current portion so extracted with a time delay constant, a summing means to sum the output of said squaring means and the output of said filter means, an adjustable potentiometer means, said summing means having an output operatively connected to said potentiometer means, said potentiometer means being adjustable in accordance with the spin rate of the spinning space vehicle so as to convert said summed signal to a signal proportional to a torque to compesnate for said misalignment error angle.

9. The combination defined by claim 8 in which said squaring means includes a first plurality of resistors having nonlinear characteristics, and a second plurality of resistors having linear characteristics, and said first and second pluralities of resistors being cooperatively arranged so as to square the magnitude of said demodulated signal.

10. The combination defined by claim 8 in which said filter means includes a capacitor and a pair of resistors, said resistors cooperating with said capacitor to extract the direct current portion of the output of said squaring means, and to provide the direct current portion so extracted with a time delay constant.

11. The combination defined by claim 8 in which said summing means includes an amplifier and a resistor, said resistor being cooperatively arranged with said amplifier so as to provide said amplifier with a finite gain operative to effect a summation of the output of said squaring means and the output of said filter means.

12. The combination defined by claim 8 in which said potentiometer means includes an operator-operative means adjustable so as to effect an output of said potentiometer variable as to the rate of rotation of the vehicle relative to inertial space.

13. A converter to compensate for a misalignment error angle between the axes of rotation of two structurally connected rotating bodies comprising first means to generate a first signal responsive to the attitude of one of said bodies about its axis of rotation, second means to generate a second signal proportional to said misalignment error angle, operator-operative means adjustable for variance in speed of rotation of said bodies to convert said second signal to a third signal, and a torquer responsive to said third signal to apply a torque to said one body to compensate said misalignment error angle.

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