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Direct Axis Control of Torque Rebalance Loop fora Two Degree of Freedom Gyroscope

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ABSTRACT: This paper explains the development and implementation of a control loop consisting of direct axis and cross axis components for a Two Degree of Freedom Dynamically Tuned Gyroscope. In a DTG, as the angular rate inputs are applied, the spinning rotor of the gyroscope is displaced from its initial position with respect to the gyro case. A rebalance loop is an electronic circuit or device used to re-align the spinning rotor of the gyroscope back to the null position so that the gyroscope remains in its range of measurement. A control loop which uses signals from X-axis Pickoff coils to apply torque to the Y-axis torquer coils and vice versa is called the cross axis loop. A control loop which uses the X-axis pickoff signals to apply current to the X-axis torquer coils is called the direct axis loop. In this paper, a direct axis control loop is developed in conjunction with the existing cross axis loop for improved performance.

KEYWORDS: DTG; Direct Axis Control; Rebalance Loop

I. INTRODUCTION

A gyroscope is an instrument used for sensing the orientation of an object in space. Gyroscopes are used in applications to sense either the angle turned through by a vehicle or a structure or its angular rate of turn about some defined axis. Gyroscopes are the most important part of an inertial navigation system or any guidance system. A mechanical gyroscope based on spinning rotor is one of the first types of gyroscopes. Currently, for space navigation and flight path sensing application, a DTG is most commonly used. The DTG is also a gyroscope based on spinning rotor technology. Nowadays, various types of gyroscopes with different resolutions are available. Some of them being the NMR Gyro, Ring Laser Gyro, Fiber Optic Gyro, MEMS Gyro, etc… Due to the compact size and reasonable accuracy the DTG provides, it is still widely used sensor for space craft applications. In a DTG, during operation, when a rate input is given to one of the input axes, the spinning rotor displaces in the axis perpendicular to the spin axis and the axis to which the rate was applied. To rebalance the rotor, torquer currents are applied. Suppose the gyroscope rotor is spinning in the Z-axis. Then, X and Y-axes are the input axes. The deflection of the gyro rotor from the initial position, or null position is detected by pickoff coils. If the spinning rotor is subjected to a rate input along X-axis, the rotor displaces to the Y-axis. So, a current has to be applied to the Y-axis torquer coils so that the rotor can be brought back to the null position and the gyroscope can sense any further change in orientation. It has to be taken care that the gyro rotor does not hit the gimbal stops because if it does, the inertial reference will be lost. A control loop which makes use of the pickoff signals from one axis and uses it to apply torqueing signals to the other axis and is called the Cross Axis loop. This paper explains the development of a Direct Axis control loop which uses the pickoff signals from one axis and uses it to apply torquer current to the same axis itself. Usually, the Cross Axis loop alone is used in Inertial Reference Units and it satisfies the typical performance requirements. However, the addition of the direct axis control loop should improve the performance of the rebalance loop. This paper explains the development of a Direct Axis control loop in conjunction with the already existing Cross Axis loop. The rebalance loop is developed from the transfer function model derived from the equations of motion of a DTG.

II. EQUATIONS OF MOTION

The transfer function of a Dynamically Tuned Gyroscope can be derived from the equations of motion of the sensor. The rotor is considered to be spinning about the z-axis for this derivation. The anti-spring may be observed in the equations of motion resulting from the gimbal action. These open loop equations of motion are:

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$$\left[A+\frac{A_g}{2}\right]\ddot{\theta}_x+(C+A_g)N\dot{\theta}_y+\left[K_x-\left(A_g-\frac{C_g}{2}\right)N^2\right]\theta_x+D\dot{\theta}_x+T_D\theta_y$$
$$=-\frac{1}{2}\left[A_g\ddot{\theta}_x+2A_gN\dot{\theta}_y-(2A_g-C_g)N^2\theta_x\right]\cos 2N$$
$$-\frac{1}{2}\left[A_g\ddot{\theta}_y-2A_gN\dot{\theta}_x-(2A_g-C_g)N^2\theta_y\right]\sin 2N+G_x$$

And,

$$\left[B+\frac{B_g}{2}\right]\ddot{\theta}_y+(C+B_g)N\dot{\theta}_x+\left[K_y-\left(B_g-\frac{C_g}{2}\right)N^2\right]\theta_y+D\dot{\theta}_y-T_D\theta_x$$
$$=\frac{1}{2}\left[B_g\ddot{\theta}_y-2B_gN\dot{\theta}_x-(2B_g-C_g)N^2\theta_y\right]\cos 2N$$
$$-\frac{1}{2}\left[B_g\ddot{\theta}_x-2B_gN\dot{\theta}_y-(2B_g-C_g)N^2\theta_x\right]\sin 2N+G_y$$

Where,

A and B are the transverse inertias of the rotor
C is the polar inertia of the rotor
A_g and B_g are the transverse inertias of the gimbal
C_g is the polar inertia of the gimbal
K_x and K_y are the torsional stiffness of the flexures
θ_x and θ_y are the rotor deflections with respect to shaft about x & y axis respectively
G_x and G_y are the rate inputs along x and y axis respectively
N is the spin speed of the shaft
D is the viscous damping
T_D is the rotor to case drag coefficient

Since the DTG is a dry type instrument, the viscous damping, D can be neglected from the equations. Also, the rotor to case drag coefficient is negligible as the rotor is only subjected to motions of very small angular displacements.

The terms lying in the RHS of the two equations, except the rate inputs G_x and G_y are grouped together and are denoted as higher order terms in the following equations. Therefore, the equations of motion can be further simplified as follows.

$$\left[A+\frac{A_g}{2}\right]\ddot{\theta}_x+(C+A_g)N\dot{\theta}_y+\left[K_x-\left(A_g-\frac{C_g}{2}\right)N^2\right]\theta_x+(higher\ order\ terms)=G_x$$
$$\left[B+\frac{B_g}{2}\right]\ddot{\theta}_y+(C+B_g)N\dot{\theta}_x+\left[K_y-\left(B_g-\frac{C_g}{2}\right)N^2\right]\theta_y+(higher\ order\ terms)=G_y$$

The higher order terms are neglected as they are very small and do not affect the normal operation of the DTG and hence, they do not contribute much to the transfer function model.

III. TUNING CONDITION

In the above equations, the dynamic anti-spring terms $-\left(A_g-\frac{C_g}{2}\right)N^2$ and $-\left(B_g-\frac{C_g}{2}\right)N^2$ are always negative because A_g and B_g must be greater than $\frac{C_g}{2}$. If the spring constant equals the anti-spring term, torque free operation is obtained and the gyro is said to be tuned. At the tuned speed, the positive flexure stiffness is equal to the dynamic spring stiffness.

That is; $K_x=\left(A_g-\frac{C_g}{2}\right){N_0}^2$
$K_y=\left(B_g-\frac{C_g}{2}\right){N_0}^2$

Solving these two equations for ${N_0}^2$ gives:

$${N_0}^2=\frac{K_x+K_y}{A_g+B_g-C_g}$$

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Normally, by design, the spring rates for both the axes are equal.
That is;

$$K_x = K_y = K$$

Also, the transverse inertias of gimbal are assumed to be the same.
That is;

$$A_g = B_g$$

Therefore, applying these assumptions in the equation for ${N_0}^2$ gives,

$${N_0}^2 = \frac{K}{A_g - \frac{C_g}{2}}$$

$$N_0 = \sqrt{\frac{K}{A_g - \frac{C_g}{2}}}$$

Where N_0 is the tuned speed of the Dynamically Tuned Gyroscope.
At the tuned speed, the flexure generated torques are cancelled by the dynamic inertial effect. Under the tuned condition, the DTG equations of motion for the open loop conditions can be written as follows.

$$\left(A + \frac{A_g}{2}\right)\ddot{\theta}_x + \left(C + A_g\right)\dot{\theta}_y N_0 = G_x$$

$$\left(B + \frac{B_g}{2}\right)\ddot{\theta}_y + \left(C + B_g\right)\dot{\theta}_x N_0 = G_y$$

If the transverse inertia of the rotor is equal along both input axes (i.e. $A = B$), and if the polar inertia of the rotor is much greater than the transverse inertias of the gimbals (i.e.; $C \gg A_g, B_g$), the above equations can be written by neglecting A_g and B_g as;

$$J\ddot{\theta}_x + H\dot{\theta}_y = G_x$$

$$J\ddot{\theta}_y + H\dot{\theta}_x = G_y$$

Where,

J is the rotor transverse inertia and,
$H = CN_0$ is the angular momentum of the rotor.
The three important conditions for the DTG to make it an ideal free gyro are:

1. Spin speed should be equal to the tuned speed N_0.
2. The damping torque on the rotor should be zero.
3. The torque at twice the spin frequency should be zero.

The tuned speed N_0 should be precisely controlled to achieve the free gyro condition. In the design of DTG, it becomes necessary to reduce the slope of $-\left(A_g - \frac{C_g}{2}\right)N^2$ at the tuned speed. This is usually done by reducing the term $-\left(A_g - \frac{C_g}{2}\right)$ and keeping the spin speed as high as possible to generate the high angular momentum. If the DTG is operated away from the tuned speed, bias torque will be developed and thus, it will lead to bias drift, which is an undesired characteristic.

The torque acting on the rotor at twice the spin frequency cannot be eliminated with a single gimbal DTG. The single gimbal DTG suffers from $2N$ angular vibration and causes drift, where N is the spin frequency. This $2N$ angular vibration occurs from shaft bearings due to their imperfections producing a spectrum of radial wobble.

The transfer function of a two degree of freedom DTG can be derived by modifying the above equations and including the terms for the rate inputs along x and y axes and the angular rates of the gyro case. The equations can be written as:

$$J\ddot{\theta}_x + H\left(\dot{\theta}_y + \dot{\emptyset}_y\right) = G_x$$

$$J\ddot{\theta}_y - H\left(\dot{\theta}_x + \dot{\emptyset}_x\right) = G_y$$

Where,

θ_x and θ_y are the angular deflections of the rotor about the case-fixed axis
G_x and G_y are the externally applied moments
$\emptyset_x$ and $\emptyset_y$ are the angular rates of the gyro case resolved along case-fixed axis

Applying Laplace transform and re-arranging the above equations, we get:

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$$\theta_x(s) = \frac{G_x(s)}{Js^2} - \frac{H\theta_y(s)}{Js} - \frac{H\emptyset_y(s)}{Js}$$
$$\theta_y(s) = \frac{G_y(s)}{Js^2} + \frac{H\theta_x(s)}{Js} + \frac{H\emptyset_x(s)}{Js}$$

The terms $\emptyset_y$ and $\emptyset_x$ are neglected as they are significantly small and also, substituting $\frac{H}{J} = \omega_n$ in the above equations give:

$$\theta_x(s) = \frac{G_x(s)}{Js^2} - \frac{\omega_n\theta_y(s)}{s}$$
$$\theta_y(s) = \frac{G_y(s)}{Js^2} + \frac{\omega_n\theta_x(s)}{s}$$

Substituting $\theta_y(s)$ in Eq: and solving for $\theta_x(s)$ gives;

$$\theta_x(s) = \frac{G_x(s)}{(s^2 + \omega_n{}^2)} - \frac{\omega_n G_y(s)}{s(s^2 + \omega_n{}^2)}$$

Similarly, substituting $\theta_x(s)$ in Eq: and solving for $\theta_y(s)$ gives;

$$\theta_y(s) = \frac{\omega_n G_x(s)}{s(s^2 + \omega_n{}^2)} + \frac{G_y(s)}{(s^2 + \omega_n{}^2)}$$

These are the transfer functions of a two degrees of freedom Dynamically Tuned Gyroscope for both the axes. In the equation for $\theta_x(s)$, $-\frac{\omega_n G_y(s)}{s(s^2+\omega_n{}^2)}$ is the Cross Axis term and $\frac{G_x(s)}{(s^2+\omega_n{}^2)}$ is the Direct Axis term. Similarly, in the equation for $\theta_y(s)$, the Cross Axis component is $\frac{\omega_n G_x(s)}{s(s^2+\omega_n{}^2)}$ and the Direct Axis Component is $\frac{G_y(s)}{(s^2+\omega_n{}^2)}$.

IV. CONTROL LOOP DESIGN

The control loop for re-balancing the rotor of a Dynamically Tuned Gyroscope is developed from the transfer function model shown above. There are two input axes for a Dynamically Tuned Gyroscope and the two transfer functions for the same are derived in section III. The control loops developed for rebalancing the rotor may be called the x-axis loop and the y-axis loop respectively. The control loop in which the pickoff signal from one axis is used to apply torque to the other axis is called the Cross Axis Loop. For example, if the x-axis pickoff signals are used to rebalance the rotor along y-axis, or vice versa, then that control loop is called the Cross Axis Loop. The control loop in which the pickoff signal from one axis is used to apply torque signals to that axis itself is called the Direct Axis Loop.

Although the transfer function for the DTG consists of both the Direct and Cross axis components, only the Cross axis loop is implemented in practice. This is because the Cross Axis loop provides good rotor re-alignment due to the properties of the gyroscope. This project aims to implement the Direct Axis Loop along with the Cross Axis loop for improved performance of the entire rebalance loop. The addition of the Direct Axis loop should improve the performance of the re-balance loop especially when the gyro is subjected to rate inputs and acceleration inputs.

Figure 1 shows the open loop block diagram representation of a cross axis control loop. It consists of the Pickoff, Pre-Amplifier and Input Amplifier stages, a Demodulator Filter, Spin Notch and Nutation Notch Filters, the Cross Axis Transfer Function of the Gyro, the Output Amplifier and the Torquer Coil.

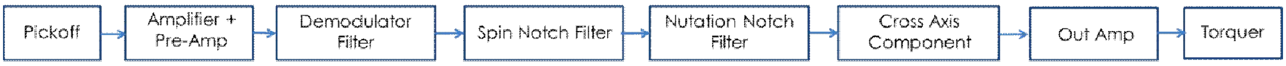

Fig. 1: Open Loop Block Diagram Representation of the Cross Axis Loop

The gyro pickoff coils produce the pickoff angle information in the form of an electric signal and modulates on a high frequency carrier signal. A desired characteristic in the torque rebalance loop frequency response is a good high frequency roll-off. A Low Pass Demodulator filter is used at the gyro output to eliminate the Low Frequency noise components.The major noise components in a Dynamically Tuned Gyroscope are the Spin Noise and the Nutation Noise components. The rebalance loop design requires the elimination of the spin noise at the gyro spin speed and the nutation noise which is present at 1.75 times the gyro spin speed. Notch filters are required to be used at this stage. This is because there are large amounts of noise signals at the spin frequency and the nutation frequency. These large noise components severely affect the performance of the gyro rebalance loop. Therefore, it is undesirable to contain this noise

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in the control loop.Fig. 2 shows the block diagram representation of a rebalance loop consisting of both the Direct and Cross Axis Components.

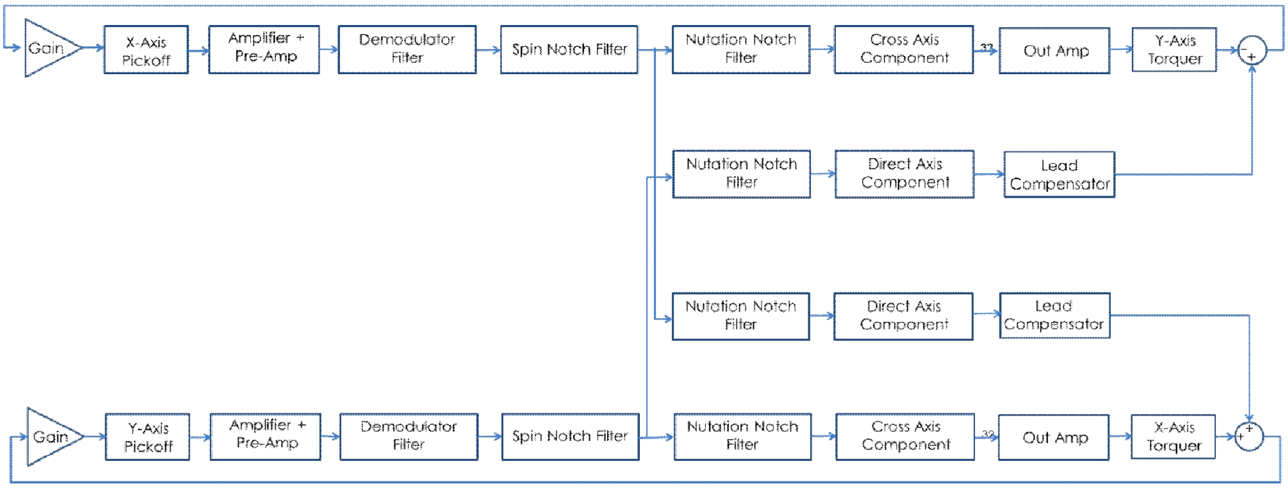

Fig.2 Closed Loop Block Diagram Representation of a Rebalance loop consisting of Direct and Cross Axis Components

V. RESULTS

The frequency response analysis of the re-balance loop is used in this project to analyse the stability and performance characteristics of this re-balance loop. Some of the tools used for analysing the performance characteristics are the Bode Plot, The Root Locus and Step Response.

The more uncertainties there are in the system, more margin must be designed for the system. The rebalance loop should be designed in such a way that there must be a Gain Margin of >6dB and a Phase Margin of at least 40°. This is the minimum stability margins that can ensure smooth operation of the system. Open Loop Bode plots can be used to assess the amount of margin that the control system has. This gives an idea about how the system will respond in closed loop form. On the control loop consisting of only the Cross Axis Loop, the gain margin is 23.9 dB and the Phase Margin is 34.6°. This can be seen in Fig.3. The open loop Bode plots for the re-balance loops designed in this paper are shown in figures 4 and 5 respectively. We can see that we have about 15dB gain margin and 45° phase margin for control loops of both axes.

These stability margins prove satisfactory for both the loops. There is an improvement in the Phase Margin of the control loops and we also have good Gain Margin compared to the control loop with Cross Axis loop only. These stability margins prove satisfactory for the proper functioning of the DTG rebalance loop.

The bandwidth of the control loop can be assessed by observing the closed loop Bode plots. The bandwidth of a system indicates how fast a system responds to its inputs. On observing the -3dB crossing point on the magnitude plot of the closed loop Bode Plots, we can analyse the bandwidth of the control loop. In the magnitude plots of both X-axis and Y-axis closed loop Bode Plots, we can find that the gain crosses the -3dB point at 50.16 rad/sec and 50.12 rad/sec respectively. These frequencies translate to about 8 Hz bandwidth, which is desired.

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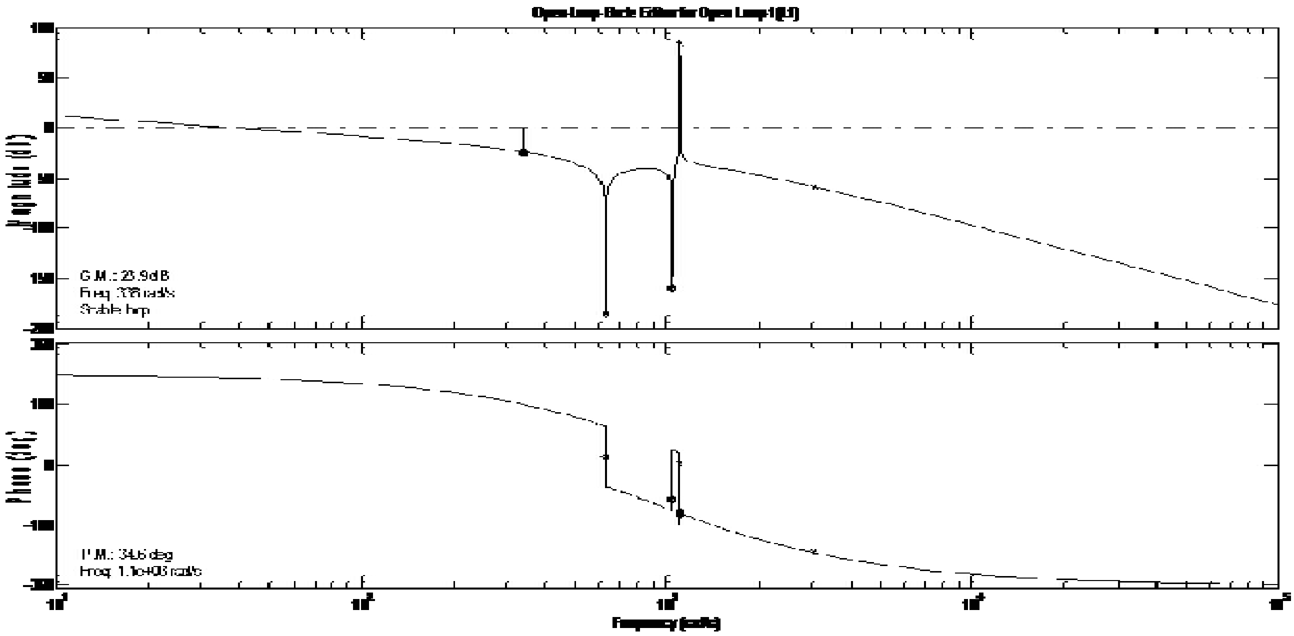

Fig. 3: Open Loop Bode Plot with Cross Axis Loop only

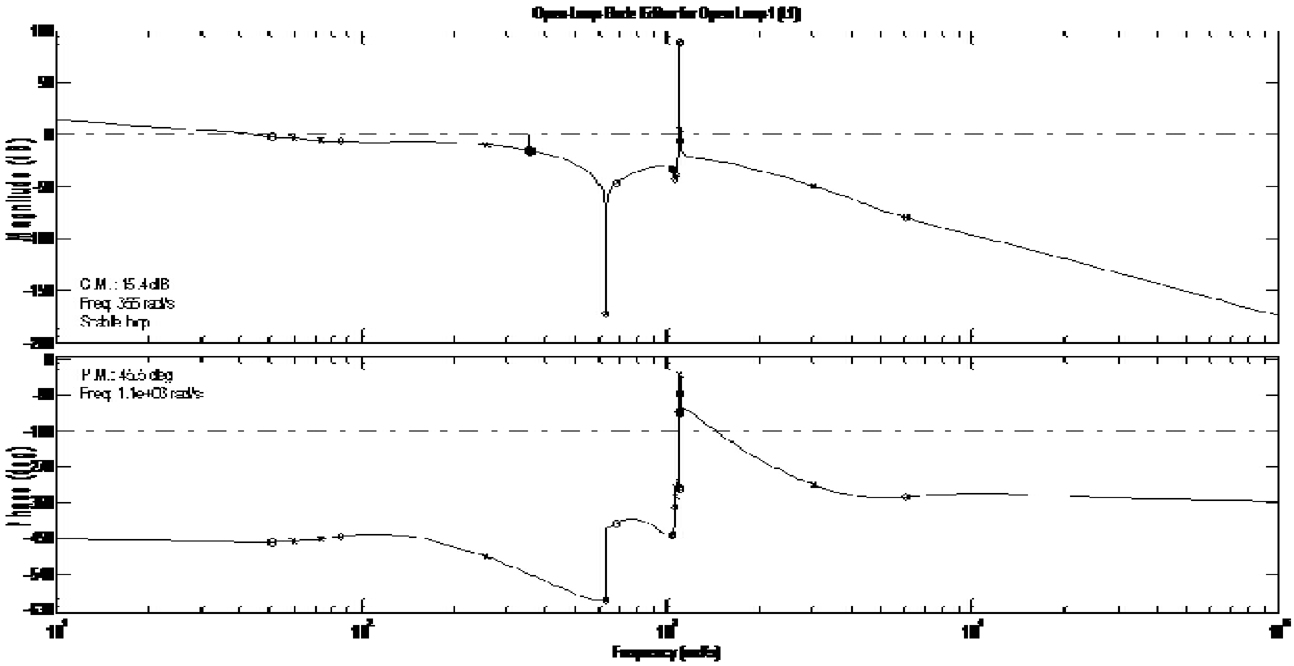

Fig. 4: Open Loop Bode Plot with Direct Axis and Cross Axis Loops

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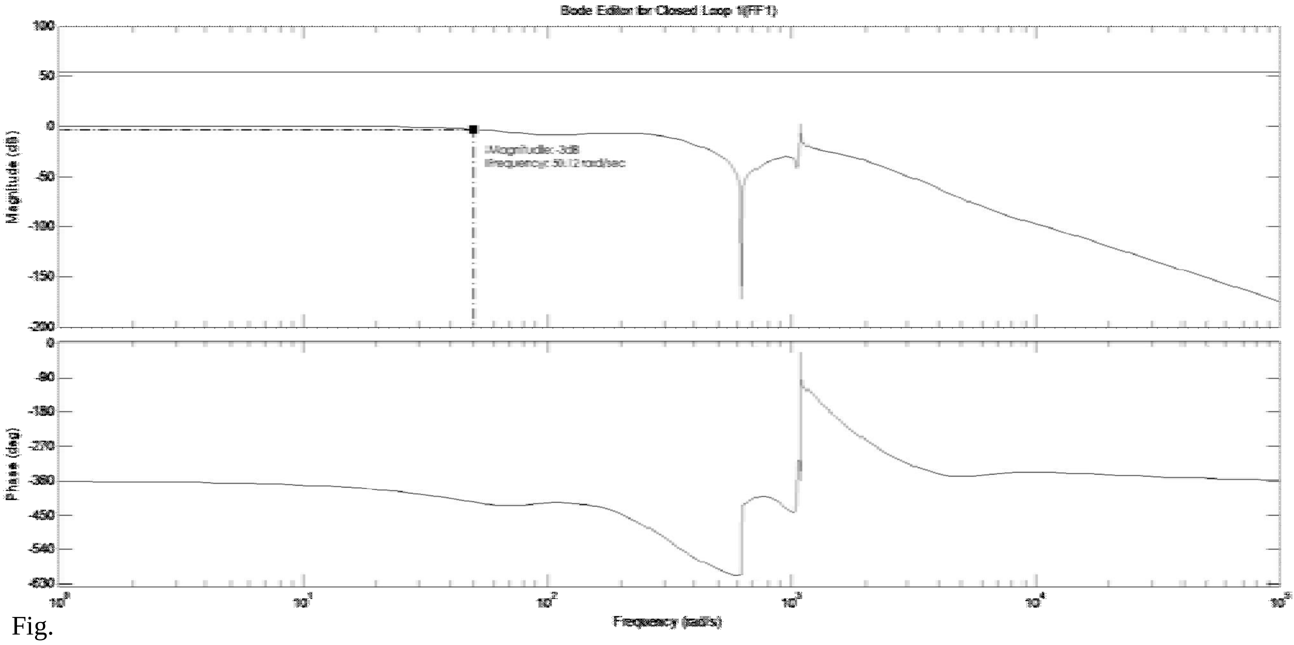

Fig. 5: Closed Loop Bode Plot of the Rebalance Loop with Direct and Cross Axis loops

The Root Locus is a powerful tool used for the analysis of control systems. From the root locus plot, we can analyse the stability of the control loop. If we observe the root locus of rebalance loop with both Direct and Cross Axis Loops, we can find that there are no closed loop poles on the right half of the s-plane. The poles of the gyroscope transfer function and poles and zeros of the nutation notch filters appears as the dominant poles and zeros on the root locus. From the root locus, we can observe that the addition of the Direct Axis loop added closed loop poles on the left half of the s-plane, and does not compromise on the stability of the control loop.

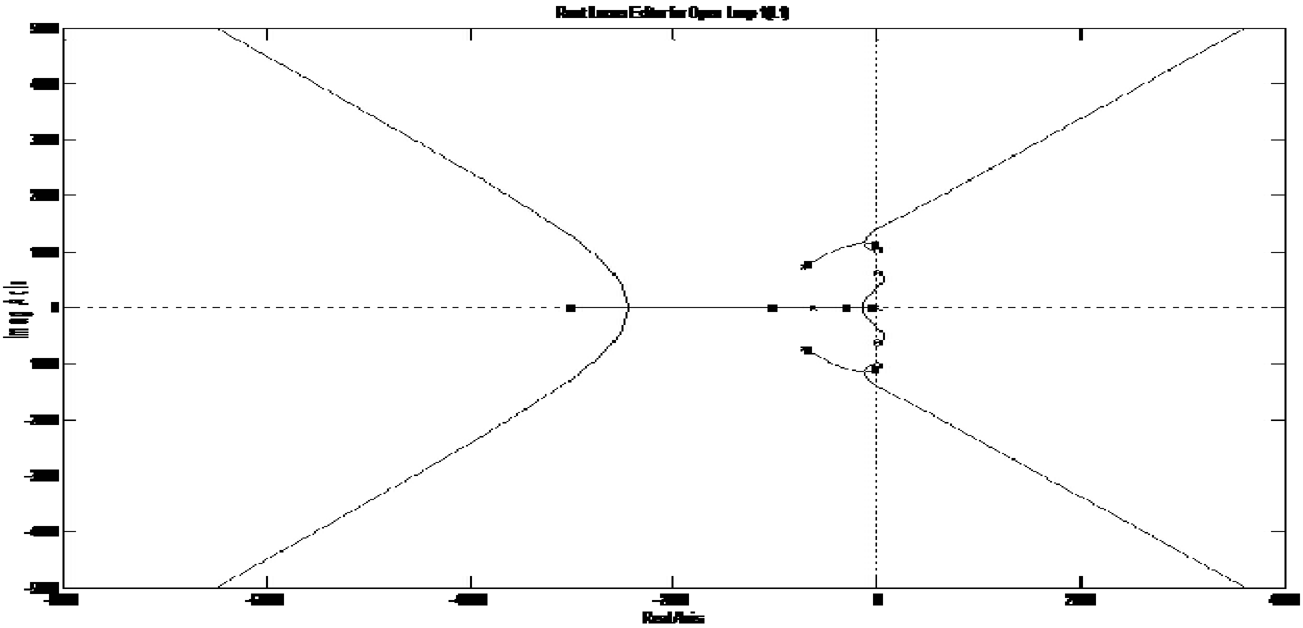

Fig. 6: Root Locus of the Rebalance Loop with Cross Axis Loop only

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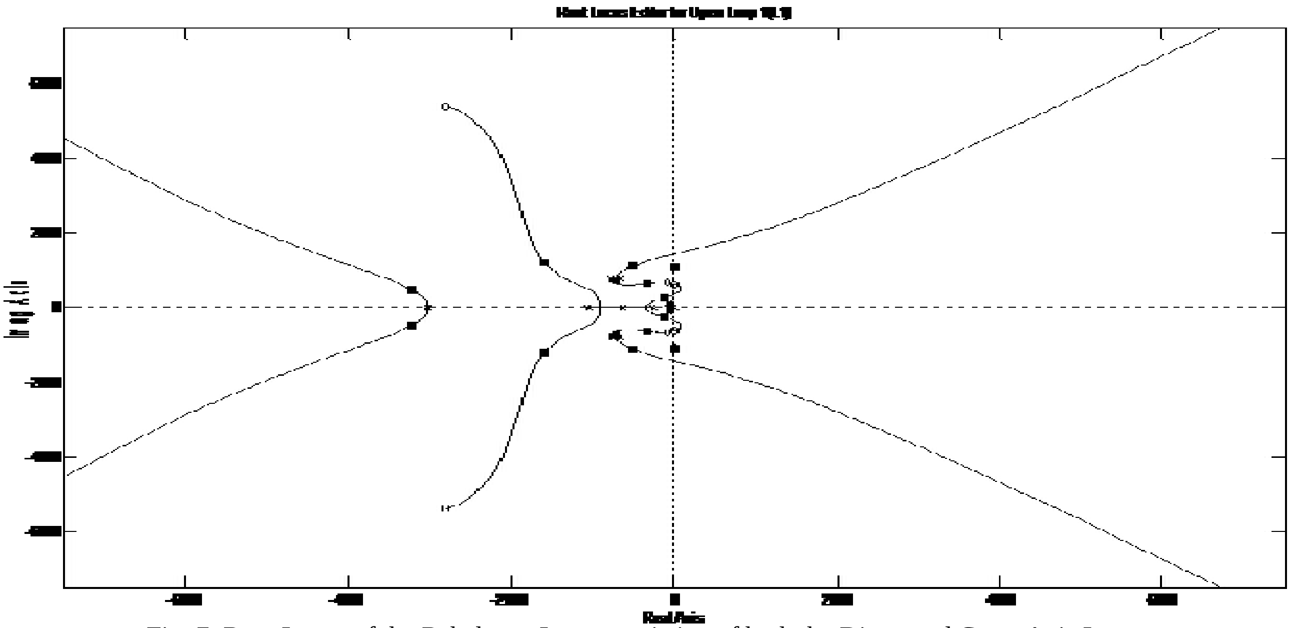

Fig. 7: Root Locus of the Rebalance Loop consisting of both the Direct and Cross Axis Loops

When a system is being designed and analysed, we cannot simply use any random signal to analyse or measure its performance characteristics. Instead, the system is tested by using simple reference functions. The step response is most frequently used to analyse systems. The Step Response of the control loop consisting of only the Cross Axis Loop is shown in Fig. 8. This control loop has a Rise Time of 0.0623 seconds and a Settling Time of 0.115 seconds.

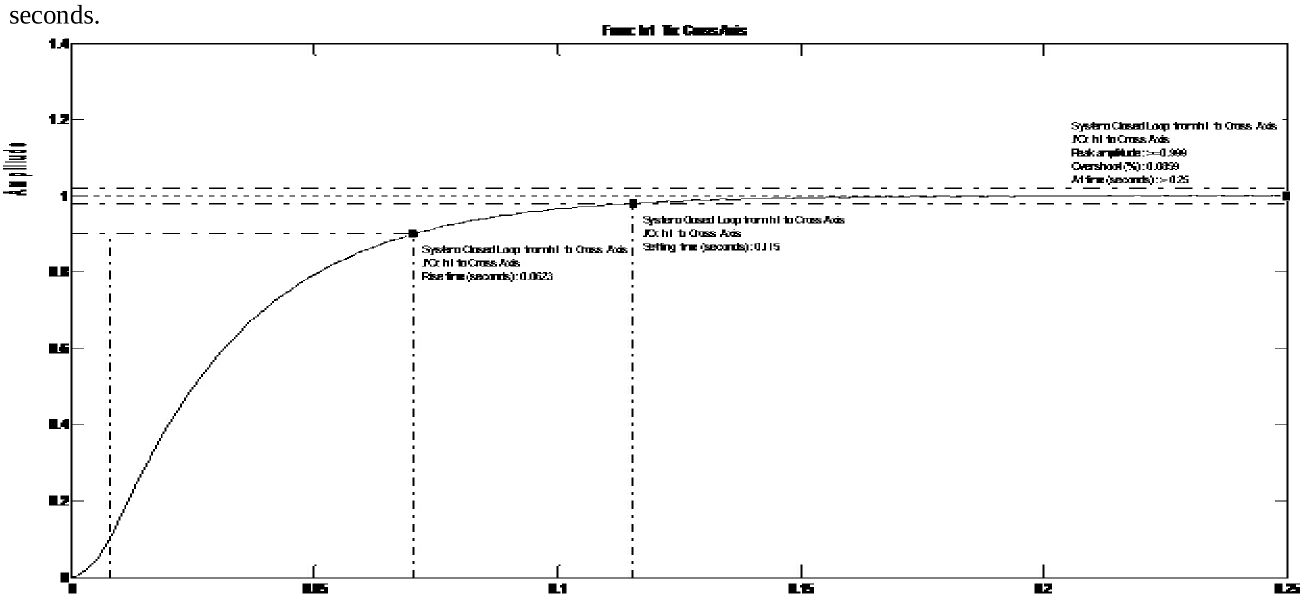

Fig.8: Step Response of Rebalance Loop with Cross Axis Loop only

The step responses of the rebalance loop consisting of the direct and cross axis components are shown in the Fig.9. On observing the step responses of the control loops with direct and cross axis loops, we can find that the control loop has a Rise time of about 0.0412 seconds and reaches a Peak Amplitude of 1.02 at 0.0817 seconds. This also indicates an overshoot of about 2.25%, which is very satisfactory. The desired overshoot was under 5% and is achieved. The step response also has a settling time of 0.0881 seconds. Thus, it can be found that the Rise Time and Settling Time of the control loop were improved with the combination of Direct and Cross Axis control loops.

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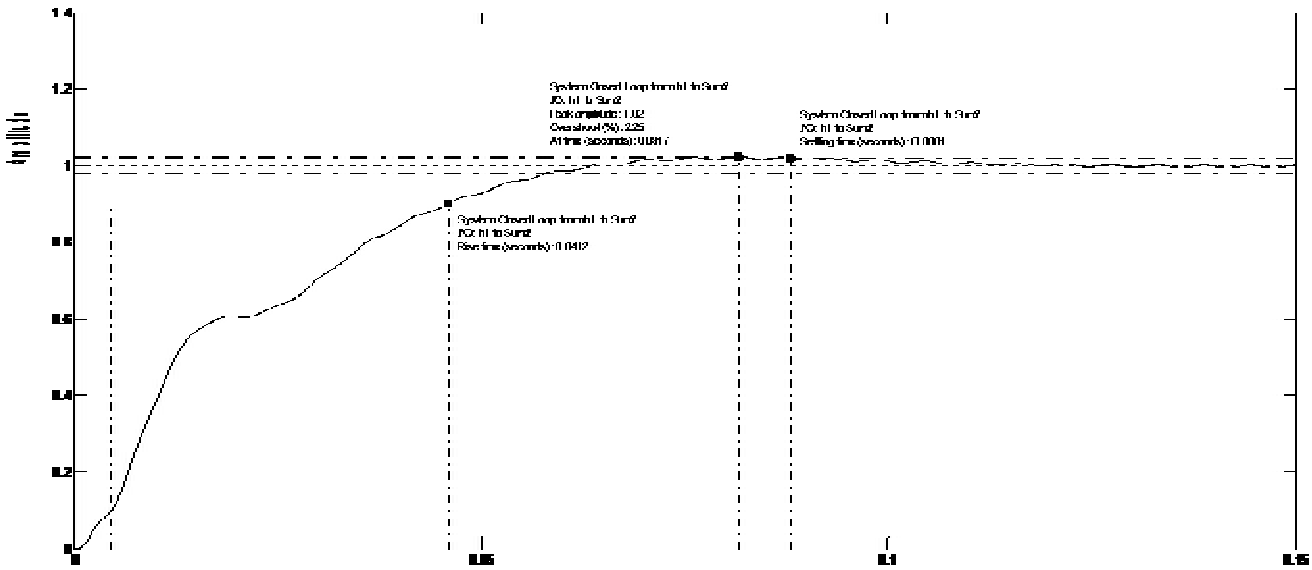

Fig. 9: Step Response of Rebalance Loop with both Direct and Cross Axis Loops

VI. HARDWARE REALIZATION

The DTG was interfaced to the control loop discussed above by using Hardware In the Loop (HIL) method. The hardware realization of the above designed control loop was implemented by using 'Real Time Windows Target' in Simulink. the Simulink model is interfaced to the hardware by using Real-Time Windows Target External Mode Execution. A data acquisition card is used to introduce the gyroscope to the control loop in Simulink. The data acquisition card used is the 'National Instruments PCI 6259'.

The Simulink model was interfaced to the gyroscope and control loop was found to be working as expected. First, the Simulink model with Cross Axis loop only was interfaced, and the gyroscope was found to be operating normally. The gyroscope was drawing normal currents after the loop close command was given. The gyroscope was also accepting rate inputs and the operation of the gyroscope was found to be satisfactory.

Then, the gyroscope was powered up again by interfacing the Simulink model consisting of both the direct axis and cross axis control loops. It was observed that the gyroscope was operating in normal conditions with the addition of the direct axis loop. Now also, the gyroscope was found to be operating normally, drawing normal currents even after the loop close command was given. It was observed that the gyroscope was able to accept higher rate inputs compared to when only the cross axis loop was interfaced. The Frequency Response Analysis (FRA) of the control loop during operation is shown in Fig.11.

During the operation of the gyroscope in the Inertial Reference Unit applications, the gyroscope is subjected to acceleration and rate inputs. Hence, the actual performance of the gyroscope is observed when the device is subjected to acceleration and rate inputs. Due to the limitations in the test conditions of the above developed rebalance loop, the device is tested only by applying rate inputs. From the FRA, we can observe that the bandwidth was about 11 Hz and the performance of the sensor was found to be satisfactory.

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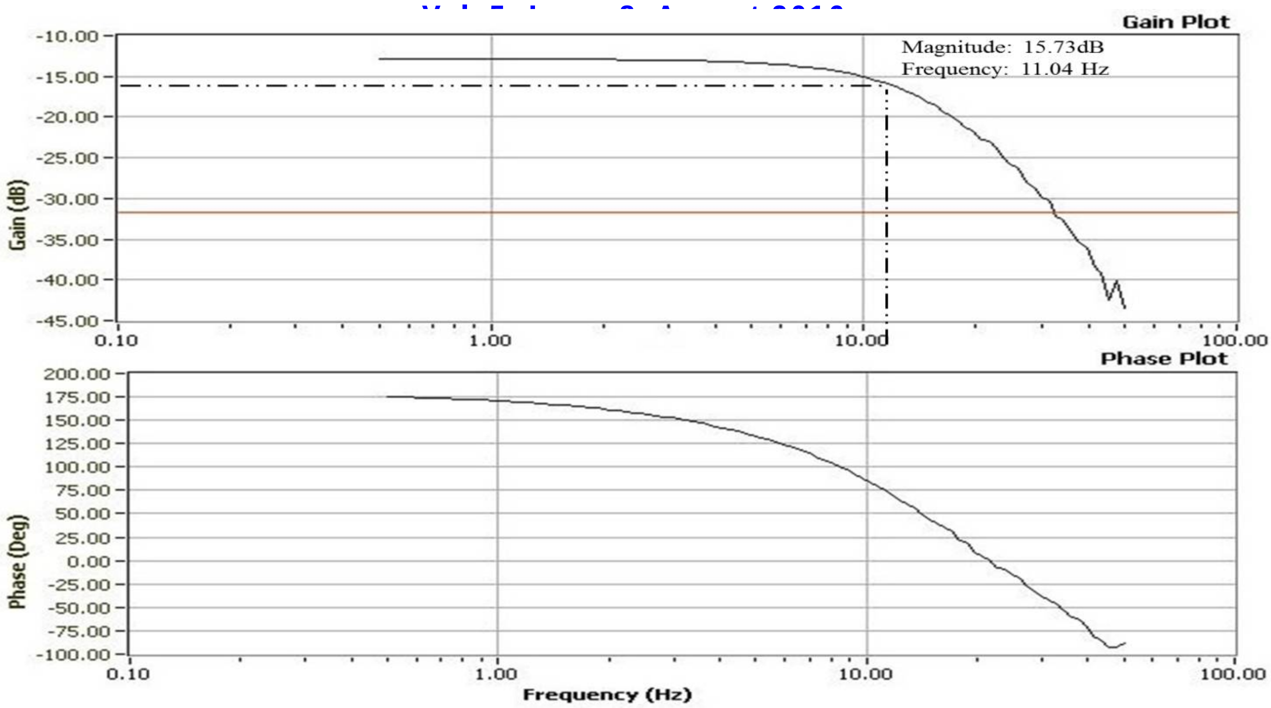

Fig. 11: Frequency Response of the system consisting of Direct Axis and Cross Axis loops

VII. CONCLUSION

Compared to the existing loop, the rebalance loop with direct and cross axis components had better stability margins, making it more immune to environmental conditions. Also, the bandwidth of the sensor was improved from 3Hz to 11Hz. This shows that the performance of the sensor was improved with the addition of the Direct Axis loop. During the actual operation of the gyroscope in the Inertial Reference Unit applications, the gyroscope is usually subjected to acceleration and rate inputs. Hence, the actual performance of the gyroscope is observed when the device is subjected to acceleration and rate inputs. Due to the limitations in the test conditions of the above developed rebalance loop, the device was tested only by applying rate inputs. The gyroscope fared well during test conditions. Thus, it can be concluded that the performance of the rebalance loop was improved and the working of the sensor was found to be satisfactory.

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