

Implementation and Design of Inertial Sensor using the estimation of error coefficient method for sensing rotation

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Abstract

We studied the Implementation and design of inertial sensor that enables to improve performance by reduce the noise of rotor which Angle of inclination. Analyze model equation including motion equation and error, signal processing filter algorithm on high frequency bandwidth with eliminates error using estimation of error coefficient method is was designed and the prototype inertial sensor showed the pick off noise up to 0.2 mV and bias error performance of about 0.06 deg/hr by the experiments. Accordingly, we confirmed that the design of inertial sensor was valid for high rotation.

Keywords: *inertial sensor, rotor, estimation of error coefficient method, re-balance loop control, bias factor, scale factor, angle of slop, torque, pick off*

1. Introduction

The inertia sensor that measures the amount of rotation is a necessary sensor for acceleration, stabilization/attitude control, and inertial navigation control device. [1] Past inertia sensor mainly used for either military or civilian use of inertia navigational control device which requires high precision. Existing inertia sensor can be distinguished into two categories; using optical property and using mechanical property.[1-2] Sensor signal frequency bandwidth error factor can be distinguished into low frequency band and high frequency band. Long term error of low-frequency band is definitive and irregular. Short term error of high-frequency band is error by noise factor. [3] The main method in this study is the minimization of sensor noise and error by using the proposed algorithm method. Mechanical modeling of inertia sensor in the industry field that requires precise performance has been enhanced with existing inertia sensor by applying the proposed algorithm to improve its performance. Also, the results of the angle extraction frequency noise component are found to increase angular velocity error, thereby reducing sensor performance. [4] The performance analysis uses the proposed algorithm for error in the noise of frequency bandwidth through measurement and analysis of noise factor, which occur during rotation of

rotor, to demonstrate the excellence of the angular acceleration and to implement the desired inertia sensor. In this paper, we proposed efficient performance improvement by considering the error characteristics of sensor. Based on the error coefficient estimation method, the high frequency band signal processing filter algorithm of the rotor and its performance proved experimentally through inertia sensor implementation. The composition of this paper is as follows: Chapter 2 refers to the principle and composition of an inertia sensor. Chapter 3 presented the signal processing filter algorithm derived based on the modeling of the presented motion equation and estimation error, and the validity of the performance was verified through experiment. Chapter 4 is concluded through performance experiments with the implemented inertia sensor.

2. Principles and design

2.1 Inertia sensor operation principle

The Inertia sensor is an essential part of the inertial navigation system which is some sort of sensor that measures either angle of rotation or angular velocity by using the inertia of the spinning object. Inertia sensors are the sensor which can measure an input angular velocity. Since it is a compact size and has strength of implement the 2 axis inertia sensor at the same time, it is still continuously used by industry aviation field. [5-6] Inertia sensor is an electric-electro-mechanical system Inertia sensor cannot be properly controlled unless if accurate modeling is not preceded because it is a sensor of measuring the input of two axis. Inertia sensor is a 2 degree of freedom inertia sensor which once was found in the 1906s but not developed until the 1970s due to the difficulty of mechanical machining. [8] However, in the 1970s, the importance of a compact size, light-weight, cheap and precision sensor came to the fore as the development regularized. Later on, huge progress has been made continuously, and in these days, it is applied into real system especially with Laser inertia sensor in dynamic range system. [12]

2.2 Composition of Inertia Sensor

Inertia sensor can be divided into mechanical part such as case, drive motor, rotor, gimbal, suspension and electrical part such as hysteresis motor, re-balance loop, torque generator, pick off and electronics part such as re-balance loop controller. In order to design of the inertia sensor, access to a system level is necessary. Since Inertia sensor motion is guaranteed only if re-balance controller is designed that combination of both electric-electronic part and mechanical part, as shown in Figure 1 and Figure 2

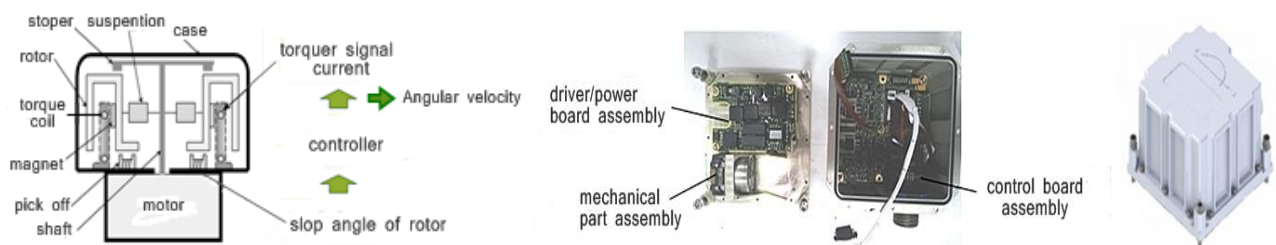


Figure 1. System structure of inertia sensor Figure 2. Picture of inertia sensor sample

3. Algorithm Design and Verification

3.1 Implementation Modeling

In this study, we study to model of motion of inertia sensor. [13-14] The factor for sensor performance improvement is reducing the occurrence of error when inertia sensor is activated. Added to the motion equation to analyze the effects of various noise and error factors is perform a performance improvement of inertia sensor. Total 3 coordinate systems are required for the equation of motion. Inertial coordinate system {i} is the coordinate system that stays stable in inertial space. Case coordinate system {c} is the coordinate system that stays solid to case. Lastly, rotor coordinate system {r} is along the x, y-axis that is plain and the z-axis is identical to a shaft and also the coordinate system that does not rotate along with the motor rotation.

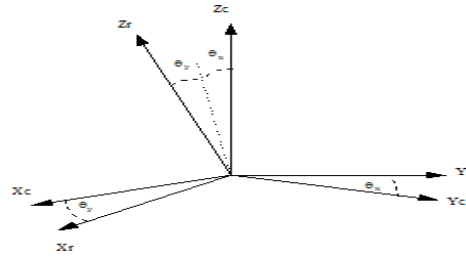


Figure 3. Rotor and case coordinate system

The angular velocity (ω_{ir}^r) of the inertial and rotor coordinate is express in the rotor coordinate by the sum of the angular velocity (ω_{ic}^r) of the inertial and case coordinate and the angular velocity ($\dot{\theta}_{cr}^r$) of the case and rotor coordinate, as shown in formula (1~2). Where C_c^r is matrix of cosine between case and rotor coordinate system.

$$\omega_{ir}^r = \omega_{ic}^r + \dot{\theta}_{cr}^r = C_c^r \omega_{ic}^c + \dot{\theta}_{cr}^r \quad (1)$$

$$\omega_{ir}^r = \begin{bmatrix} 1 & 0 & -\theta_y \\ 0 & 1 & \theta_x \\ \theta_y & -\theta_x & 1 \end{bmatrix} \begin{bmatrix} w_x \\ w_y \\ w_z \end{bmatrix} + \begin{bmatrix} \dot{\theta}_x \\ \dot{\theta}_y \\ \dot{\theta}_z \end{bmatrix} \quad (2)$$

The angular momentum(H) generated by the rotation of the rotor may be express in matrix form as shown in formula (3) by the multiplication of the inertial moment and angular velocity of the rotor. Where I_i is the moment of inertia of the i-axis, and if the x, y-axis of the rotor is symmetry, I_x and I_y have the same value as.

$$H = \begin{bmatrix} I_x & 0 & 0 \\ 0 & I_y & 0 \\ 0 & 0 & I_z \end{bmatrix} \begin{bmatrix} \omega_{ir-x}^r \\ \omega_{ir-y}^r \\ \omega_{ir-z}^r \end{bmatrix} \quad (3)$$

Rotating rotor's moment(M_r) with the speed of ω_{ir}^r is as express formula (4). Thus, applying this case coordinate can be expressed as formula (5).

$$\mathbf{M}_r = \dot{\mathbf{H}}_r + \omega_{ir}^r \times \mathbf{H} \quad (4)$$

$$\mathbf{M}_c = C_r^c \mathbf{M}_r = \begin{bmatrix} 1 & 0 & -\theta_y \\ 0 & 1 & \theta_x \\ \theta_y & -\theta_x & 1 \end{bmatrix}^T \mathbf{M}_r = \begin{bmatrix} M_{rx} + \theta_y M_{rz} \\ M_{ry} - \theta_x M_{rz} \\ M_{rz} - \theta_y M_{rx} + \theta_x M_{ry} \end{bmatrix} \quad (5)$$

Moment of formula (5) is only necessary to keep the rotor motion. The moment required by the z-axis is provided by the motor drive and the moment required by the x, y-axes shall be provided by the torque. Also the sum of all externally moments must be equal to those moments by the rotor as a reaction, so the moment to be generated by the torque generator can be expressed as in formula (6). In formula (6) Main section and error factor can be divided into 3 categories; main section related to sensor motion, a section influenced by different axis, and error section caused by driving power and error. Among these, the main section is correlated with motion and other sections can be considered as error section. [7-8, 13-14]

$$\mathbf{M}_T = \mathbf{M}_c + \mathbf{M}_d + \delta_r \mathbf{M}_r \quad M_{Tx} = M_{x1} + M_{x2} + M_{x3} \quad (6)$$

$$M_{x1} = A(\ddot{\phi}_x + \dot{\theta}_x) + H(\dot{\phi}_y + \dot{\theta}_y)$$

$$M_{x2}$$

$$= A(-\theta_y \ddot{\phi}_z - \dot{\theta}_y \dot{\phi}_z) + H(\theta_x \dot{\phi}_z) + (C - A)(\dot{\phi}_y + \dot{\theta}_y + \theta_x \dot{\phi}_z)(\dot{\phi}_z + \theta_y \dot{\phi}_x + \theta_x \dot{\phi}_y)$$

$$-C\dot{\alpha}_t(\dot{\phi}_y + \dot{\theta}_y + \theta_x \dot{\phi}_z) + C(\ddot{\phi}_z - \ddot{\alpha}_t)\theta_y$$

$$M_{x3} = H \frac{N_0 - (\dot{\alpha} + \dot{\phi}_z)}{F_m} \theta_x + \frac{H}{\tau} \theta_y + M_{1N} \pm HR_\theta \dot{\phi}_{2N} + H\delta_{Ty} \dot{\phi}_x \quad (7)$$

This paper proposes a method to compensate for errors by modelling the error components caused by frequency noise that the most frequently caused by the tilt of the rotor, as in M_{x3} section.

3.2 Error Compensation Algorithm Design Verification

A performance indicator that can determine the performance of inertia sensor is to expand the input angular velocity and the bandwidth to obtain the dynamic range of the sensor. It is derived from controlling the input angular velocity and the torque to balance the input angular velocity by generating torque to keep the angle of slope at zero. This allows the estimation of input angular velocity by measuring torque, possible more stable operation for large dynamic inputs. In this paper, a method applied to eliminate errors due to angle detection noise caused by tilt of rotor with signal processing filter algorithm. Therefore, it is necessary to apply method to eliminate the critical error components from the signal processing process. In this study, studies on the estimation error coefficient method, which identifies and compensates for the factors of slope angle detection noise error that significantly affect inertia sensor performance. This proposed filters algorithm should effectively eliminate the noise at that frequency, while also minimizing the time delay within the frequency bandwidth. Because of the time delay that occurs in the frequency band eventually, it is a reduction in frequency bands. Therefore, the proposed filters algorithm is implement to compensate for errors in the passband to minimize time delay and to eliminate only generated frequency noise. To implement these proposed algorithms, the frequency response of

the filter is shown from Figure 4 to meet the desired specification with a phase delay of 100 Hz to approximately 17 degrees, and the cutoff rate of that frequency is also -60dB .

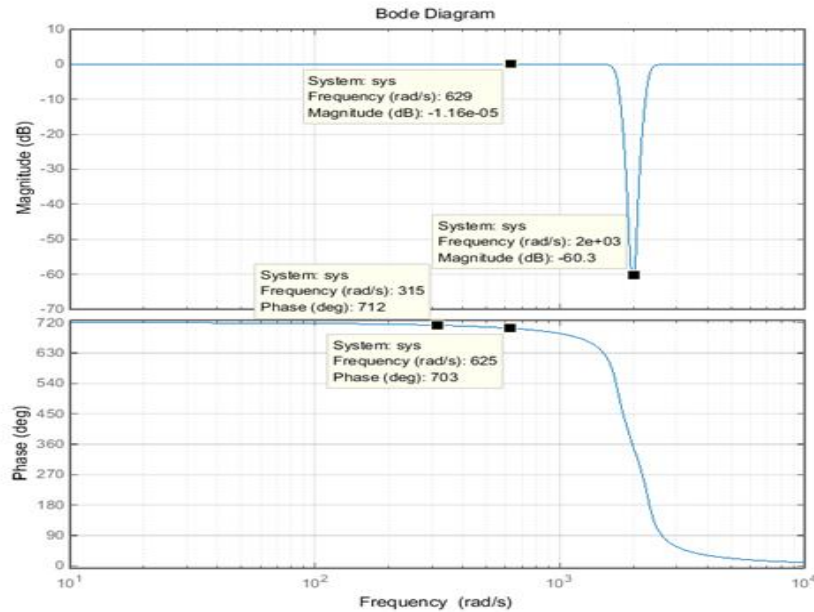


Figure 4. Frequency response of proposed filter

Figure 5 is a frequency response for step input, overshoot decreases due to high-level filter. This indicator shows the stability of filter and indirectly show that this filter stable even more.

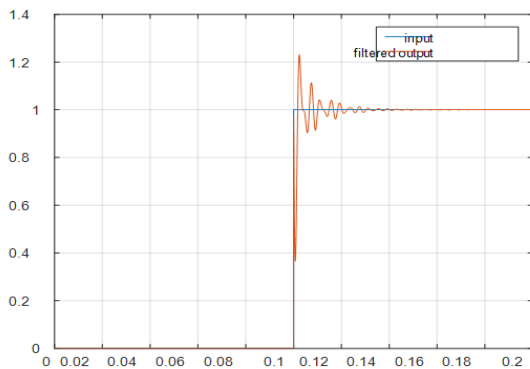


Figure 5. Pulse response of proposed filter

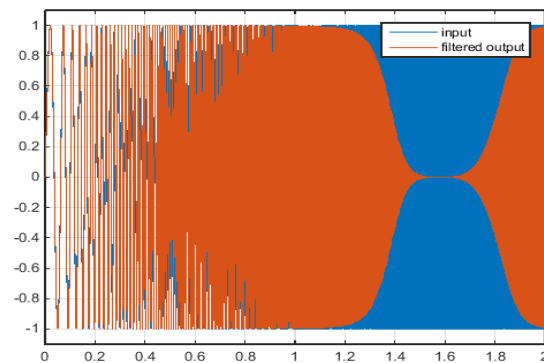


Figure 6. output through frequency change

Figure 6 uses magnified picture of variable bandwidth in designed filter. It confirms that this filter effectively eliminates the noise and minimizes the time delay during the processing.

4. Performance Test and Results

This study is implement software with controllers and filters that prove to be capable and effective through simulation. Software is implements through C++ code, the bugs of code is modified and optimized and the control

algorithm was implemented in the FPGA with the implemented sensor and tested in the field. Based on the research on development of inertia sensor, the research on SW implementation of controllers was carried out so that errors can be kept smaller in the process of linearization, and the controller including error coefficient estimation algorithm is design into inertia sensor modeling taking into account the error factor to realize error compensation. Modeling design and simulation of inertia sensor used a simulation tool based on MATLAB Simulink. Figure 8 show that the result of error factor to maintain the performance of the inertia sensor is a measurement of the performance of the controller, which is robust against to noise, removes noise and maintains bandwidth at around 100 Hz.

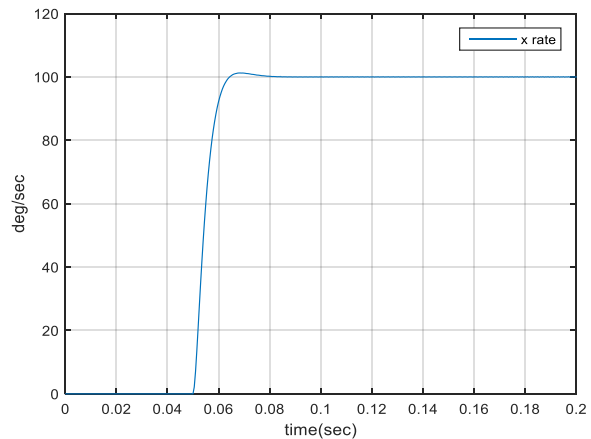
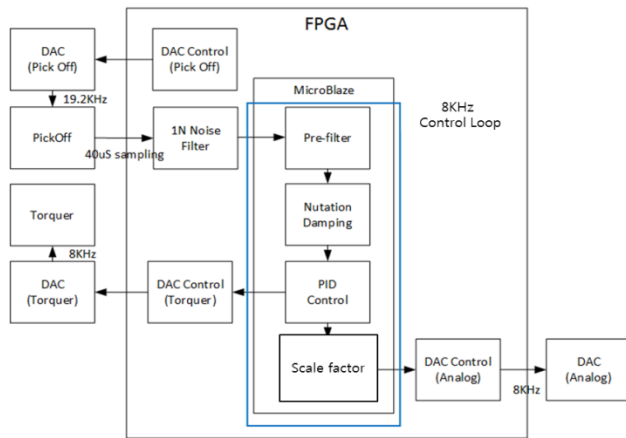


Figure 7. Diagram of a re-balance loop controller **Figure 8. Result of simulation the controller**

This modeling describes motion of inertia sensor by calculating the slope angle for each input angular velocity and the simulation torque current. This enabled to predict the performance of the basic inertia sensor and to analyses the effects of errors in each part on the performance of the inertia sensor. Developed simulation tools include: The angle generated by the model with the input angular velocity of the x, y axes can be measured at the pick-off, and the control signal generated by the re-balance loop acts to the torque to zero the slop angle, thereby maintaining the performance of the synchronizer. In this study, simulation performs by changing the sampling time to check the robustness of the controller with the determinative error factor. Simulation results showed that the controller could be configured to have a more than 3 kHz of sampling frequency allowing guarantee the stability of the system. Based on IEEE standard to test the performance of inertia sensor, we measured bias stability, conversion factor, frequency bandwidth and maximum input angular velocity.

5. Conclusion

Through this study, we figured out inertia sensor error factor with detail and analyzed effects of noise from an angle of slop. This frequency noise must be eliminated because it causes significant effect on inertia sensor control and bias stability. In this study, we confirmed how frequency noise extracted from an angle of slop can effect on bias stability and proposed signal processor algorithm based on estimation error coefficient method to eliminate this effect. We able to obtain a satisfied result from applying proposed algorithm. Proposed algorithm calculates the slope angle for each input angular rate and performs a simulation of the torque current accordingly to modeling the motion of inertia sensor. For error analysis, this study modelled inertia sensor and a study on signal processing algorithm to design an optimal controller for expand limited bandwidth and based on these studies the results of

attenuating the noise at level of 10 mV to 0.2 mV. Thus, applying this algorithm method reduces bias errors to under 0.06deg/hr state. This increases the likelihood of successful implementation as inertia sensor and ensures stability. This performance improvement development study will help in the future mass production and test evaluation of inertia sensor, and will enable successful inertia sensor development if further research is carried out in the future.

References

- [1] LAWRENCE, Anthony. "Modern inertial technology-Navigation, guidance, and control", STIA, 1993, 93: 39795. Bibcode : 1993STIA...9339795L
- [2] P.H. Savert, "Gyroscope: Theory and Design", McGraw-Hill, 1961.
- [3] CARTA, G., et al. "Gyro-elastic beams for the vibration reduction of long flexural systems. Proceedings of the Royal Society A: Mathematical", Physical and Engineering Sciences, 2017, 473.2203: 20170136. DOI: <https://doi.org/10.1098/rspa.2017.0136>
- [4] NARASIMHAPPA, Mundla; SABAT, Samrat L.; NAYAK, Jagannath. "Fiber-optic gyroscope signal denoising using an adaptive robust Kalman filter". IEEE Sensors Journal, 2016, 16.10: 3711-3718. DOI: 10.1109/JSEN.2016.2535396
- [5] SUN, Boqian, et al. "Decoupling control of micromachined spinning-rotor gyroscope with electrostatic suspension". Sensors, 2016, 16.10: 1747. DOI: <https://doi.org/10.3390/s16101747>
- [6] SADEGHI-EMAMGHOLI, Amin; AZIZI, Askar; NOURISOLA, Hamid. "Modeling and design of appropriate compensation for DTG (Dynamically Tuned Gyroscope) and improving sensor response using a Kalman filter". In: 2016 4th International Conference on Robotics and Mechatronics (ICROM). IEEE, 2016. p. 202-209. DOI: 10.1109/ICRoM.2016.7886847
- [7] CRAIG, Robert JG. "Theory of operation of a two-axis-rate gyro". IEEE transactions on aerospace and electronic systems, 1990, 26.5: 722-731. DOI: <https://doi.org/10.1109/7.102707>
- [8] KANG, Taesam; LEE, Jang Gyu; PARK, Chan Gook. "Performance improvement of a dynamically tuned gyroscope using an input compensator". Journal of guidance, control, and dynamics, 1992, 15.2: 404-409. DOI: <https://doi.org/10.2514/3.20850>
- [9] ANGÉLICO, Bruno Augusto, et al. "On guaranteeing convergence of discrete LQG/LTR when augmenting it with forward PI controllers." IEEE Access, 2017, 5: 27203-27210. DOI: 10.1109/ACCESS.2017.2768160
- [10] ALESSIO, Silvia Maria. "Sampling of Continuous-Time Signals". In: Digital Signal Processing and Spectral Analysis for Scientists. Springer, Cham, 2016. p. 133-152. DOI: https://doi.org/10.1007/978-3-319-25468-5_4
- [11] KWAK, No-Sang; MÜLLER, Klaus-Robert; LEE, Seong-Whan. "A convolutional neural network for steady state visual evoked potential classification under ambulatory environment". PloS one, 2017, 12.2: e0172578. DOI: <https://doi.org/10.1371/journal.pone.0172578>
- [12] SKALSKÝ, Michal; HAVRÁNEK, Zdeněk; FIALKA, Jiří. "Efficient Modulation and Processing Method for Closed-Loop Fiber Optic Gyroscope with Piezoelectric Modulator". Sensors, 2019, 19.7: 1710. DOI: <https://doi.org/10.3390/s19071710>
- [13] Song Jin-woo, "design of digital re-flat loop for DTG" master degree of the paper Department of Control Measurement Engineering at Graduate school of Seoul National University, 1997.
- [14] FERRIOL, M., et al. "Thermal degradation of poly (methyl methacrylate)(PMMA): modelling of DTG and TG curves". Polymer degradation and stability, 2003, 79.2: 271-281. DOI: [https://doi.org/10.1016/S0141-3910\(02\)00291-4](https://doi.org/10.1016/S0141-3910(02)00291-4)