Modeling and Simulation of Low Cost MEMS Gyroscope Using MATLAB (SIMULINK) for UAV Autopilot Design

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***Abstract*— Micro-Electro-Mechanical systems (MEMS) are widely used in applications ranging from consumer electronics to aerospace. Gyroscopes are commonly used sensors for measuring angular velocities in many areas of applications such as homing missiles, Unmanned Ariel Vehicles (UAVs), and stabilized platforms. On the other hand to properly design autopilots of UAVs; a six degree of freedoms (6DOF) simulation model is usually built, and to accurately tune the autopilot parameters the feedback sensors should be well modeled. Toward that, this work is intended to accurately model a low cost MEMS gyroscope. Angular rate tests are used for calibrating the biases, scale factors, and non-orthogonal ties of gyroscope of (MPU6050 from Invensense) used as a case study. The linearization of the designed gyro model is required for designing and analysis of linear control system. The validation of the designed simulated model with the real raw data of the MEMS gyroscope is given which confirms the accuracy of the simulated model.**

Keywords—MEMS gyroscope, modeling, simulation, Matlab (SIMULINK).

I. Introduction

Gyroscopes are the most essential and necessary part of inertial navigation systems or any guidance system [1], [10]. Gyroscope is defined as a system which contains a heavy metal rotor [14], which is mounted so that it has three degrees of freedom. This definition seems to be good for gyroscopes of earlier days. Present days, gyroscopes, like MEMS type, vary in construction but the principle of working remains the same [16], [13]. Applications as important as monitoring the orientation of an aircraft, to stabilizing the pictures that we click using our cameras [6], to be used in many critical applications like guiding an unmanned Arial vehicle during flight [7], fire control systems abound ships [10], satellite navigation[11]. Micro-Electro-Mechanical system gyroscopes have a widely popularity for use as an angular rate sensors in commercial applications because of their cheap cost, small size and its low power consumption when they are compared to the other traditional ones. All tools of Simulation for MEMS represent important needs when designers and researchers start to develop technology to high levels Gyroscope history in order to discuss MEMS gyroscopes we must first understand gyroscope in general, and what role it plays in science. Actually, a gyroscope is any device that can measure angular velocity. As early as the 1700s [12], spinning devices (gyroscopes) were being used for navigation in sea in foggy conditions. The more traditional spinning gyroscopes were introduced in the early 1800s [13], in the early of 1900, gyroscopes were used on ships. And also used in aircraft where it is still widely used nowadays beside Unmanned Ariel Vehicles (UAVs) [14]. In the early of 20th century scientists made great improvements on the gyroscope. And also in the early of 1960, optical gyroscopes which use laser technique were invented and soon introduced to find commercial success in military applications [15]. In the last ten to fifteen years, MEMS gyroscopes have been submitted and many improvements have been made to produce mass-produced successful products with many advantages over traditional macro-scale devices [16]. Traditional Gyroscopes function differently depending on their type. In this paper all types of errors of gyroscopes are presented. In this paper by using modeling of the gyroscope some of these errors are reduced to get high performance of MEMS gyro and accurate data because it is used in complex application like guided missile and autopilots. The structure of this paper is as follow: section II exposes to errors associated with MEMS sensors. Section III discusses MEMS gyroscope principle of operation. Section IV discusses MEMS gyroscope calibration. Section V illustrates gyroscope modeling with Simulink and simulation results. Section VI represent linear model of gyroscope. Finally, the conclusions of this paper are given in section VII.

II. MEMS Gyroscope Errors

Errors are classified into two categories; systematic and stochastic (random) errors. The calibration and characterization procedures became essential manner to improve the performance of MEMS accuracy [20], [21]. MEMS IMU calibration can be defined as the operation and processing technique at which the output data of sensors are compared with known reference data then the coefficients in the output equation can be calculated , that agree to the reference information and used to compensate systematic errors [17], [18], [20], on the other hand the stochastic errors contains unpredictable random processes which appear on the output as a noise or a slow change of parameters in time these errors has to be modeled using different techniques which are widely used as Power Spectral Density (PSD), Allan Variance (AV) and the Autocorrelation Function (ACF).

A. Systematic(deterministic) errors

- Bias offset: It is defined as the output of the sensor when there is no input, this term often varies slowly with time so it is also called drift.
- Scale factor: It is the deviation of the input-output ratio from unity. The accelerometer output error due to scale factor is proportional to the true specific force along the sensitive axis, while the gyroscope is proportional to the true angular rate.
- Non-orthogonality error: It occurs when any of the axes of the sensor triad deviated from mutual orthogonality during the manufacturing.
- Misalignment Error: It is the deviation between the sensitive axes of the inertial sensors and the orthogonal axes of the body frame due to mounting imperfection.

B. Stochastic (Random) Errors

- Angle/Velocity Random Walk (A/VRW): It is a high frequency noise term that has a correlation time much shorter than the sample time and defined as additive white noise component on the sensor output [21].
- Quantization Noise (Q): It is strictly due to the digital nature of sensor output, obtained when sampling analog input signal using Analog to Digital (ADC) [18].
- Flicker Noise (Bias Instability) (B): It is mainly due to noise in electronics components and because of its low frequency nature it shows up as the bias fluctuation in the data.
- Angular Rate Random Walk (RRW): It is random process of uncertain origin, it needs a long periods of collecting data in order to be able to observe it, usually output sensors affected by ambient temperature variation and spoils the RRW line on the AV, so it is recommended to run AV test in constant environmental condition [11].
- Rate Ramp Noise(R): It is more of deterministic error Rather than stochastic noise, it shows due to a very slow periodic change of the sensor intensity persisting over a long period of time. It could be also due to a very small acceleration of the platform in the same direction and persisting over a long time period.
- Sinusoidal Noise: A low frequency source could be the slow motion of the test platform due to periodic environmental changes.

III. MEMS Gyroscope Principle of Operation

Great and significant progress towards high performance and low power Consumption of MEMS gyroscopes are accurately made [2], [3], [4]. A mass production of low cost MEMS gyroscopes with small form factor to suit the consumer electronics market are widely produced nowadays. For measuring the angular rate of MEMS gyroscopes the Coriolis Effect is used, as shown in Fig. 1.

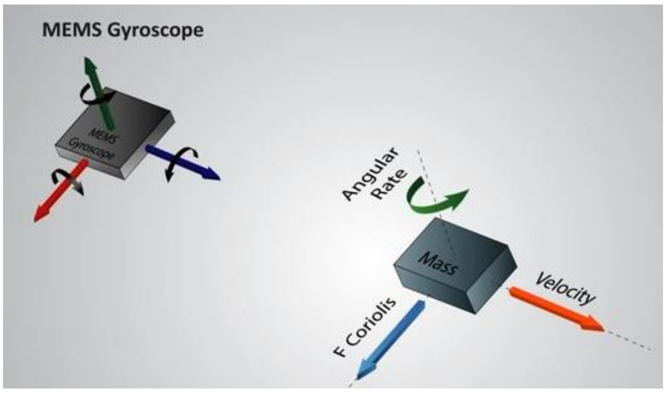

Fig. 1. Coriolis force

Moving the body in the direction of velocity (v), the Coriolis force causes physical displacement; a capacitive sensing structure can sense these resulting physical displacements. Most available MEMS gyroscopes use a tuning fork configuration. as shown in Fig. 2. Two masses vibrate and move in opposite directions.

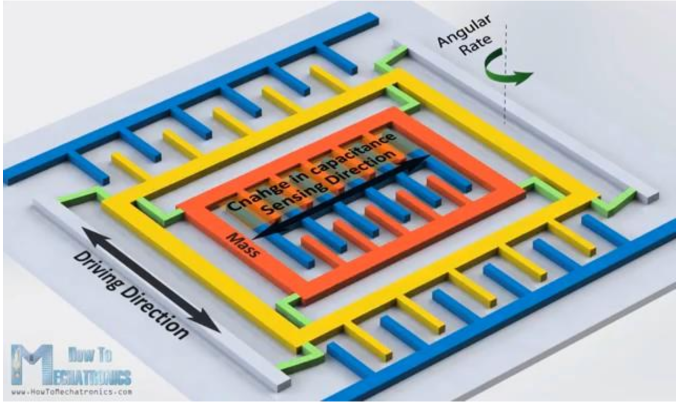

Fig. 2. Effect of applying angular velocity

A MEMS gyroscope has a small vibrating mass and when an angular rate is applied this mass experiences a small coriolis force which displaces the vibrating mass from its original path as shown in fig. 2. This displacement can be sensed using a capacitance and the output is proportional to number of counts

IV. MEMS Gyroscope Calibration

The angular rate tests used for calibrating the biases, scale factors, and non-orthogonal ties of gyroscopes for automotive-grade navigation systems. Tests of the rates are typically performed using an accurate rate turntable [21], by rotating the unit through given turning rates and the outputs of the gyroscopes are compared to these references, the biases, scale factors, and non-orthogonal ties are estimated. This is typically accomplished by rotating the table through a defined angular rate in both clockwise and counterclockwise directions. Applying rates from 0 up to ±90[deg/sec], the rate can be used to calculate bias, scale factor, and misalignment errors. For obtaining bias and scale factor for the gyroscope the curve fitting method is used and misalignment errors obtained by rotating the turn table and observing the measuring values of the gyro sensitive axis then taking the average of the actual value of the gyro corresponding to the desired rate of the table and then plotting one to one graph with y-axis representing the desired rate applied to the table and the x-axis is the actual value measured by the gyro[18], this process repeated for the three sensitive axis of the gyro. The row data of the rate gyro of (MPU6050) with x-axis as sensitive axis and turntable desired rate command is [90, 72, 54, 36, 18, 0,-18,-36,-54,-72,-90] with approximately 3 minutes for each desired rate is shown in Fig. 3.

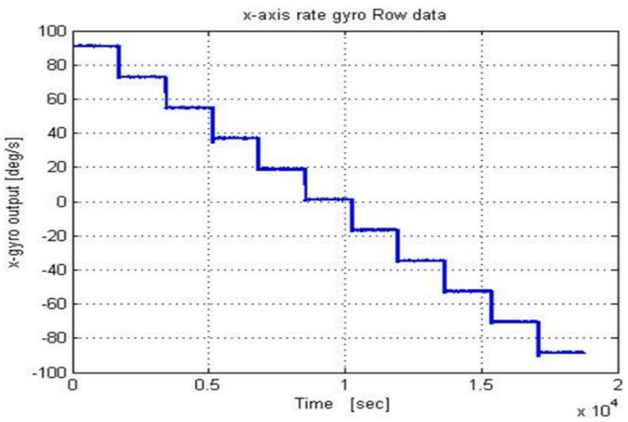

Fig. 3. X-axis Rate Gyro Row Data

The output of the X-axis gyro is noisy, and to determine the noise characteristic the linear fitting is applied .The calibration curve used to determine the bias and scale factor of the x-axis rate gyro is shown in Fig. 4. The bias=0.7164, the scale factor=0.9953. The stochastic noise of the x-axis rate gyro can be modeled by white Gaussian noise with zero mean.

$$Measured = 0.9953 * desired + 0.7164$$

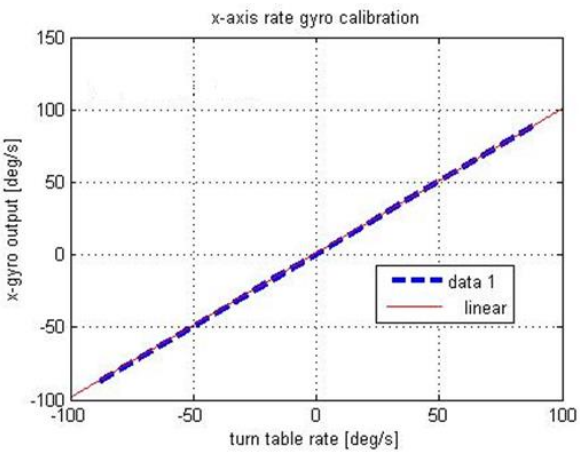

Fig. 4. X-axis Rate Gyro Calibration Curve

V. Gyro Simulink Model and Simulation Result

Real world angular rate is the gyroscope input, counts or any value that can be represented by 16-bit integer is the gyroscope output, The dynamics of the gyro approximately represented by 2nd order system [5], [6], [7]; in addition to the deterministic error model for the gyro as inertial sensor; the calibrated gyro bias added to simulate the real gyro measurement data. Moreover, stochastic error is represented by white Gaussian noise, the scale factor is used as a simple conversion from deg/sec (which is the gyro input) to a count (which is the gyro output), and its value is given from the data sheet. Finally, designing low path filter at the output of the measured data after using a limiter to constrain the gyro measurements between upper and lower rates; the simulated gyro model is shown in Fig. 5.

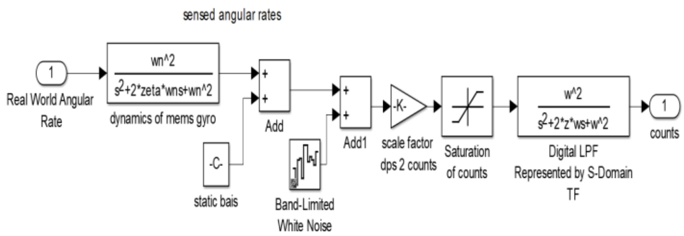

Fig. 5. Gyroscope Simulink Model

the real row data of the MEMS gyro is acquired with the serial port of the microcontroller to the MATLAB; The real data of stationary gyro from x-axis is shown in Fig. 6. It’s expected that the output will be zero but as shown in figure gyroscope’s output is noisy that’s why bias and white Gaussian noise blocks are added to the gyro-SIMULINK model.

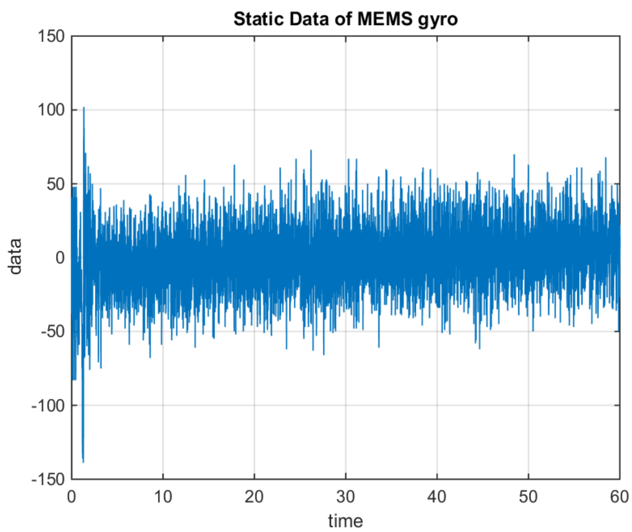

Fig. 6. Real Gyro Data

By removing the bias and scale factor which estimated from gyro calibration; moreover, the white Gaussian noise with cut of frequency 12 Hz from the data sheet of the gyro. As a result, the band limited white Gaussian noise remains constant before the cut of frequency and starts to fall of quickly beyond this frequency as shown in Fig. 7 with the vertical axis represent the amplitude of the real gyro data transformed by fast Fourier function and the j=horizontal axis is the frequency.

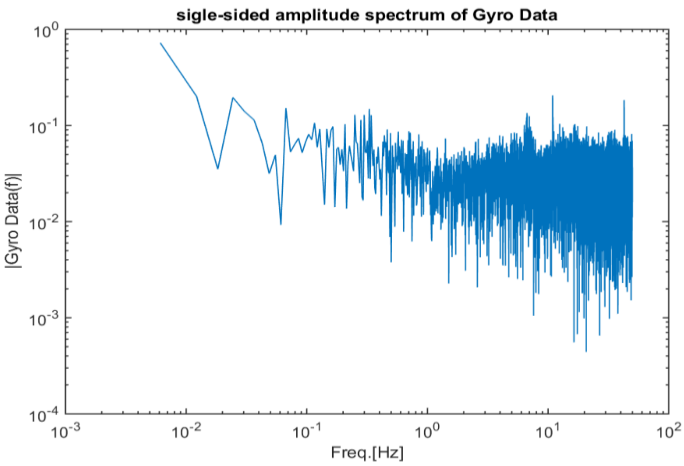

Fig. 7. Frequency Response of Real Gyro Data

Results of designed gyro model validation starting by comparing the designed model response to the real gyro data with zero rate level. Deterministic and stochastic errors model of the gyro (bias and the white Gaussian noise) are added to emulate the reality of the gyro under measurement, this gyro SIMULINK model is shown in Fig. 8. With replacing input by constant with zero value and the output by simGyro which will appear in Workspace to be compared with the real acquired data.

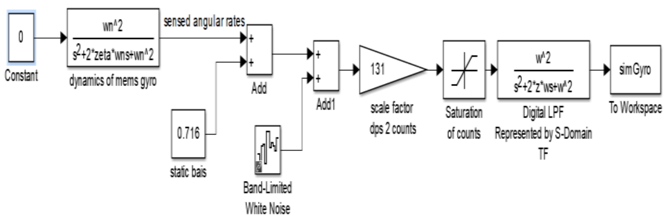

Fig. 8. Simulink Model of Zero Rate Level gyro

The amplitude of simulated output data of the gyro transferred by Fourier transform with the frequency without bias error is shown in Fig. 9.

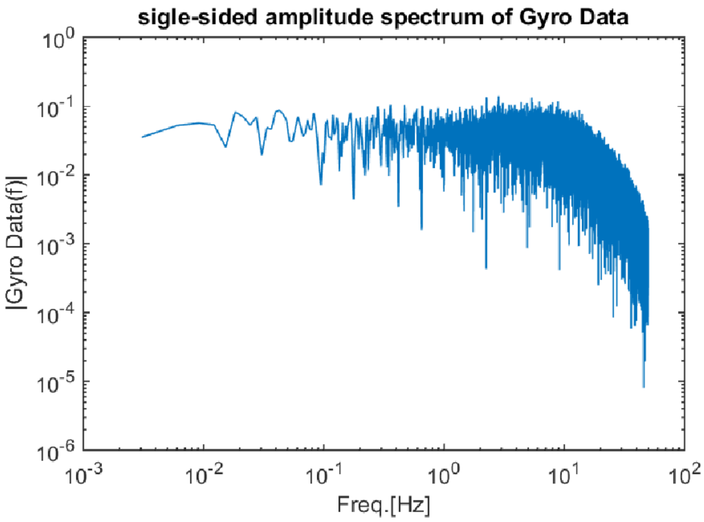

Fig. 9. Frequency Response Simulated Gyro Data

The degree of the designed gyro model accuracy is confirmed by comparing the response of the model to real gyro data acquired through the serial port and the simulated input rate from Simulink with the same amplitude input; the proposed gyro model response to both real and simulated angular rate is shown in Fig. 10.

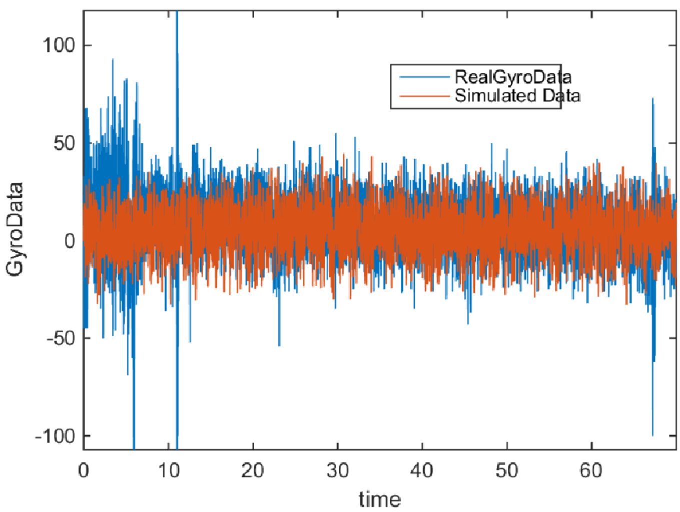

Fig. 10. Real and Simulated Data

Furthermore, the frequency domain analysis for the designed gyro model to both real and simulated data is shown in Fig.11.

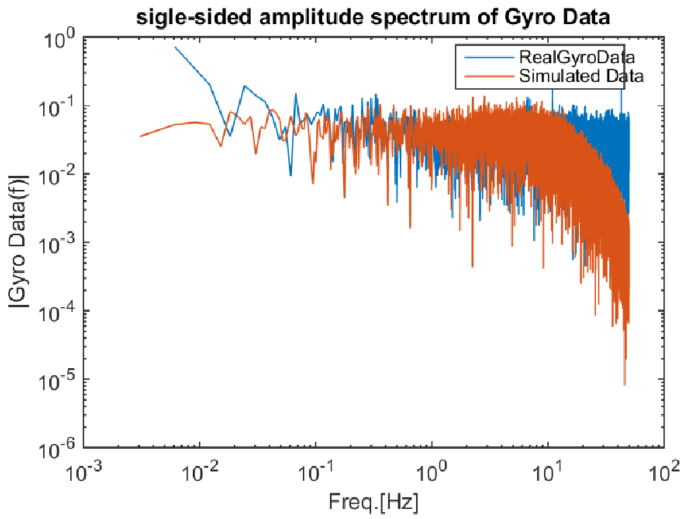

Fig. 11. Frequency Response of Real and Simulated Data

VI. Linearization of the Gyroscope

The process of linearizing nonlinear system is important, by linearizing nonlinear gyro model it is possible to apply numerous linear analysis methods that will produce information on the behavior of nonlinear system. The complexity of the designed nonlinear gyro model made the analysis of the closed loop control system more difficult due to the existence of the gyro as a feedback measurement sensor. As a result the linearization of this designed model is strongly required but with little accepted response to the same signal. Based on the calibrated data from the gyro under discusses the static error model of the nonlinear model (bias, scale factor) is compensated in the feedback signal. Using low path filter will cutting all high frequency of the dynamic of the designed gyro model, moreover, the white Gaussian noise is removed as it is nonlinear with zero mean In addition to the saturation block, also removed as we assume working within the range of the gyro model. The general block diagram of the closed loop control system with designed linearized gyro model as a feedback sensor is shown in Fig. 12.

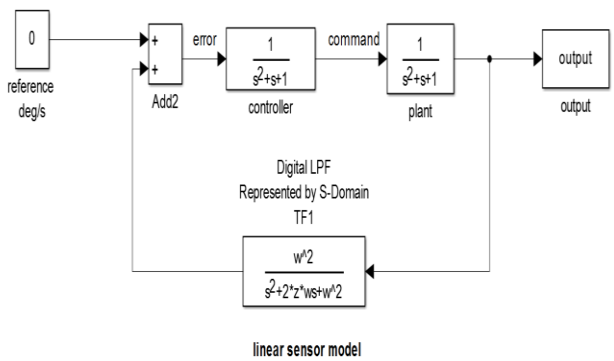

Fig. 12. Linear Model Gyroscope in Feedback Control loop

The simulated gyro model can be used for the Autopilot of UAV simulation, from the previous results, the gyro Simulink model works as and give approximately the same outputs in time and frequency domains so that the simulated model can be used for modeling of autopilot of UAVs as shown in fig. 13.

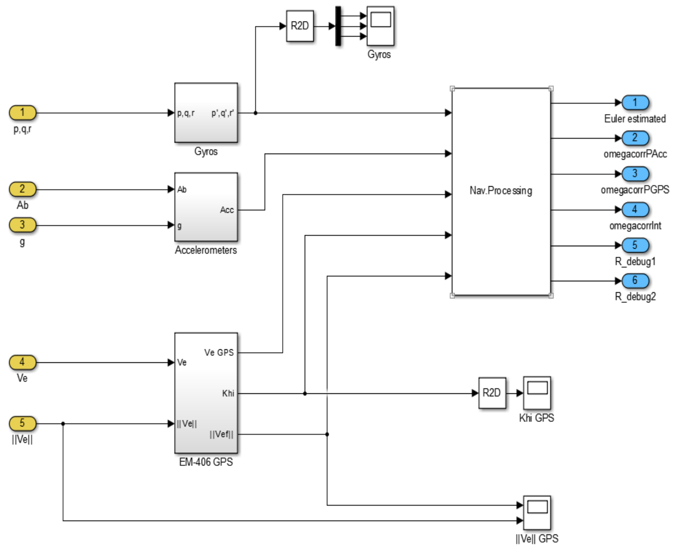

Fig. 13. Model of UAV's autopilot Navigation system

The Simulink model of UAV's systems which consist of sensor subsystem (gyroscope, accelerometer and GPS), the output of these sensors is processed by the data processing and introduced to the NGC subsystem which generate the guidance commands and control signals which keep the desired path to be between the four corner points by using UAV's actuator subsystem as shown in fig. 14 . The simulation result of the UAV's Simulink model is shown in fig. 15.

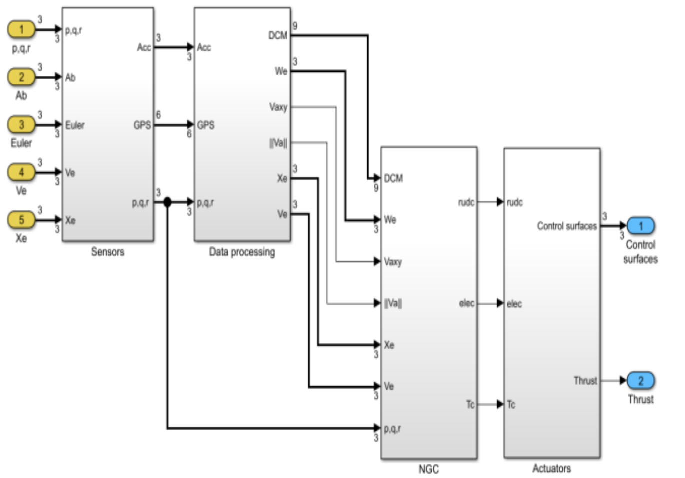

Fig. 14. UAV's Subsystems

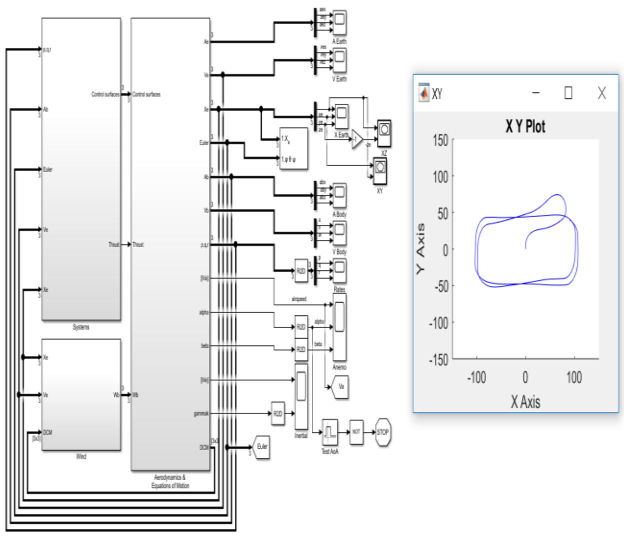

Fig. 15. Simulation of UAV's Simulink model

VII. CONCLUSION

This paper present MEMS Gyroscope model by Simulink, The simulation results increase our knowledge and help us to understand the behavior of the MEMS gyro and the natural phenomena associated with its simulation, errors of the Gyroscope can be evaluated like, bias error and band limited noise to increase the performance of the Gyroscope, the real output data of the Gyroscope is evaluated and drawn, the accurate simulated output data of the Gyroscope is obtained and drawn, comparison between the real data and the simulated one gives us how much the MEMS Gyro work efficiently. Finally, the simulation of the UAV's Simulink model is presented after introducing the block diagram of the Gyro in a linearized block diagram.

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