Project for the Minor in Space Technologies

Autumn 2007

Phase B/C

ADCS Gyroscopes

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RECORD OF REVISIONS

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2/0	21/12/2007	Draft Report	Rakesh Chandra Prajapati
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PROJECT: SwissCube Satellite **PHASE: C**	**WP REF: 4612**
WP Title: SwissCube ADCS gyroscopes **Responsible:** LMTS **Collaborator/assistant:** Herbert Shea, Hervé Péter-Contesse **Student:** Rakesh Chandra Prajapati **Start date:** 18-09-07 **End date:** 21-12-07 **WP Manager:** M. Noca, H. Péter-Contesse	**Sheet 1 of 3** **Issue Ref: 1** **Issue Date:** **17-09-07**

Introduction

This Work Package summarizes the work expected from the student during phase C (semester's project) of the SwissCube Project. The expected duration of the work is as stated above.

The objectives of this task will be four fold:

- Review the task description;
- Plan a schedule for your work, and review it with your project assistant;
- Perform the tasks and keep the project informed of the status;
- Provide the outputs and deliverables listed at the end of this document.

The student will report for all technical matters to the Lab assistant (when applicable) and project system engineer (assistant) assigned at the beginning of the semester.

The student will have to participate in the design meetings related to his topic (mechanical, electronics, data).

Deadlines are summarized here:

Kick-off meeting (mandatory):	September 21, 17h00 in ELD 010
Mid-term review:	October 31, time TBD ELD 010
Draft report due:	December 2 (for EPFL students)
Final report due:	December 9
Final review/presentation:	January 10

Deadlines related to the technical work will be given at the kick-off meeting.

Task Description:

During last semester project, the hardware (sensors, actuators and controller) for the SwissCube attitude determination and control system (ADCS) has been selected, and preliminary tests have been made. The goal of this project is to finalize and test the ADCS integrated gyroscopes: test the functionality in space conditions (vacuum, temperature), develop compensation and recalibration methods (software) on microcontroller for the temperature and drift.

This task includes :

- ☐ Review all documentation regarding the ADCS subsystem
- ☐ Find a better solution than the actual gyroscopes
- ☐ Do the first tests with the new solution; develop a test platform and PCB if needed
- ☐ Characterize operations; especially thermal, offset and drift characteristics
- ☐ Develop compensation and calibration methods and a gyroscope model; program the ADCS microcontroller
- ☐ Characterize operations with the ADCS microcontroller and validate the compensation and calibrations methods
- ☐ Provide recommendations and document all activities.

Inputs:

- "SwissCube Phase B-C Mission and System Overview" (S3-B-C-SET-1-2-Mission_System_Overview.pdf);
- "SwissCube ADCS Specifications Document" (S3-C-SE-2-0-Level_4_ADCS.pdf);
- S3_Phase_B-C-ADCS-1-3-ADCS_HW_and_System.pdf;
- S3_Phase_B-C-ADCS-1-3-Gyroscopes.pdf;
- SwissCube document templates;
- Reference: "Space Mission Analysis and Design", Larson & Wertz

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Outputs:

- Detailed performance model of gyroscopes;
- Compensations methods.

All analyses should include documentation of the assumptions.

Deliverables:

- A final report including a short description of all outputs.
- A presentation at the final review at the end of the semester.
- A disk containing all analysis and documentation files for records.

INTRODUCTION

The project "ADCS Gyroscope" is a part of SwissCube Project at EPFL, which is carried out for the fulfilment of minor course in Space Technologies of 8ECTS credit hour. SwissCube is the first Swiss pico-satellite based on CubeSat concept. The project ADCS Gyroscope is a subsystem of Attitude Determination and Control System (ADCS).

In general ADCS system has two functions, attitude control for the maintenance of a desired orientation of a satellite within a given tolerance, and attitude determination to provide knowledge of the satellite's orientation within a given tolerance. The functions of SwissCube ADCS are to determine the direction of the payload before taking night-glow picture, and to control the satellite spin rate at minimum value to prevent from blur picture, and during launch into the space.

Gyroscope will provide precise spinning rate measurement of the satellite in all 3-axes, which will help the ADCS system to determine the orientation of the satellite. Gyroscope senses rotational rate, not attitude.

Currently, the ADCS-Gyroscope is in the Phase B/C. Sufficient analysis and design of gyroscope is explained, and basic anticipated interface sub-system is presented. Refined design requirement document for the part of gyroscope is listed.

This report reviews the types of MEMS gyroscopes suitable for SwissCube and comments on the selection of a new gyroscope ADXRS614, and short list of gyroscopes used in past CubeSat project is collected. Some primary tests, like rate sensitivity, temperature sensitivity, bias test, were carried out with the new gyroscope, to support an evidence of applicability of ADXRS614 in SwissCube, hence, the results were compared with the design requirement of the SwissCube. A small test PCB for gyroscope was built which can be mounted in ADCS board.

Report Outline: This report begins with an introduction of ADCS system and its functions, with short description of aim of Gyroscope in SwissCube. It begins with Design Requirements in first chapter, and second chapter defines the design and working assumptions, interface and methodology to achieve the target design requirements. After selection of new gyroscope, the technical description of the gyroscope and PCB design is detailed in chapter three. To conform that the new gyroscope fits to the refine design requirements, test set-up and test performed were explained in chapter four, and the test results and design requirements were also compared. Recommendation for further refine test results and limitations of ADXRS614 are made in chapter five. Chapter six, seven, and eight are Conclusion, References, and Acknowledgement respectively. Finally this report ends with Appendixes, where different types of gyroscopes are compared, calculation for the calibration of the revolving table is done, also list of the CubeSat projects which had used gyroscope are collected, and a short details about the test steps which were being followed during the project work was explaind.

1 DESIGN REQUIREMENTS

The following design requirements, Table 1 for the ADCS Gyroscope have been extracted from the report *S3_Phase_B-C-ADCS-1-0-System_Engineering* by Hervé Péter-Contesse, January 2007, EPFL [R3]. The table summarises constrains and basic requirements for Gyroscope selection, and design.

Gyroscopes			
	Main power supply	3.3±0.23	V
	Power consumption (mean)	<90	mW
	Temperature range	-30 to +60	°C
	Measurement range	±15	°/s
	Resolution	<0.01	°/s
	Accuracy	<0.04	°/s
	Measurement Rate	≤2 (2 nominal)	Hz
ADCS board			
	Main power supply	3.3±0.23	V
	Power consumption (standby mode)	<30	mW
	Power consumption (sensor mode)	<90	mW
	Power consumption (nominal mode)	<250	mW
	Peak current	<150	mA
	Mass (whole ADCS)	<120	g
	Mass (ADCS board)	<34	g
Payload			
	Max angular vel. (payload)	1.25	°/s
	Determination precision (3 axis)	<12	°

Table 1 ADCS Gyroscope Design Requirements

Previously used gyroscope IDG300 was discarded for it does not satisfy the above requirements, mainly due to low resolution. The above design requirements plays crucial role while selecting a new gyroscope. Based on CubeSat concept, gyroscope has to be selected with mass, power, and size constrains, while satisfying required resolution and accuracy, in addition the gyroscope must be easily available and cheaper for academic research project.

One of the main objectives of this project is to find a new gyroscope, which satisfies the above stated requirements. MEMS gyroscope best suit the design requirements, mainly due to its low mass, small size, and minimum power consumption advantage. But the use of MEMS gyroscope has one common problem, as most of the MEMS gyroscope operates at 5V supply, whereas the SwissCube ADCS board has 3.3V supply. For the temperature drift measurement it is better to have an inbuilt temperature sensor in the gyroscope itself for precise measurement.

Accuracy and resolution are the other most important parameters of the gyroscope. Without accruing the needed resolution of the gyroscope, the gyroscope will not be able to give precise measurement of the rotational rate, thus resulting poor determination of SwissCube's orientation. Otherwise, Sun-sensor and Magnetometer can be used to estimate the satellite rotational rate, but it has to be more accurate.

2 DESIGN ASSUMPTIONS AND APPROACH

2.1 Design Assumptions

A simple test PCB for ADXRS614 was fabricated, Figure 1 . The test and measurement will be carried out to find if this new gyroscope will satisfy the design requirements. To make the test simple, the following design assumptions were made:

- 5V supply will be available in the SwissCube for the Gyroscope ADXRS614, therefore, test were carried out using a 5V DC power supply.
- 16bit ADC will be present between ADCS board and Gyroscope ADXRS614 interface, so that it will result high resolution.
- Additional external RC filter (R=22kΩ, C=0.1µF, thus fc=70Hz) were used to reduce the high frequency noise (can be external and internal source), thus an additional hardware or equivalent software filter will be used before acquiring gyroscope data.
- In built temperature sensor of ADXRS614 was used for sensor's temperature measurement, therefore, no additional temperature sensor for gyroscope will be needed.

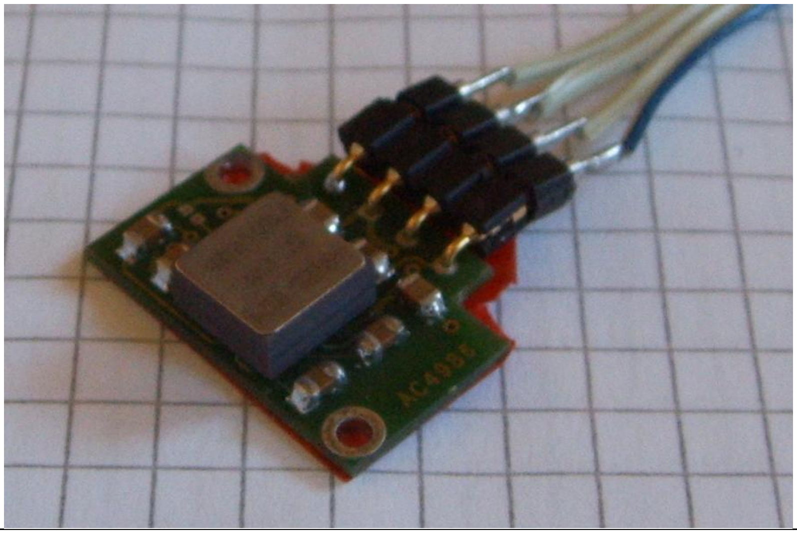


Figure 1 Test PCB of ADXRS614

2.2 Working Assumptions

As explained in the design assumptions, the peripheral components (5V supply, 16-bit ADC, and external filter) are suppose to be compatible and work properly. As reported in [R1] IDG-300 gyroscope could not give the required sensitivity, and IDG-1000 is unavailable. Therefore, for the better solution a list of MEMS gyroscopes were searched, and under the guidance of Mr. Hervé Péter-Contesse, a new gyroscope ADXRS614 (from Analog Device, Inc.) was selected, for detail refer Appendix A. The gyroscope ADXRS614 was selected for it has high sensitivity to measure the small rotational rate; in addition it has light weight and small size. The following Table 2 presents the characteristics of ADXRS614:

S.No.	Characteristics	ADXRS614
1.	Sensitivity	25mV/deg/sec
2.	Full scale range	+/- 75deg/sec
3.	Zero rate out	2.5V
4.	Bandwidth	DC to 2kHz
5.	Noise	0.04deg/sec/√Hz
6.	Non-linearity	0.1% of FS
7.	Temperature Sensor	Yes
8.	Supply Voltage	4.75V to 5.25V
9.	Supply Current	3.5mA
10.	Temperature range	-40°C to +105°C
11.	Axis	single-axis (perpendicular to the package top)
12.	Start up time	50msec
13.	Size	7mm*7mm*3mm (BGA package)
14.	Weight	<0.5gram

Table 2 Characteristics of ADXRS614 [from datasheet [R4]]

FUNCTIONAL BLOCK DIAGRAM

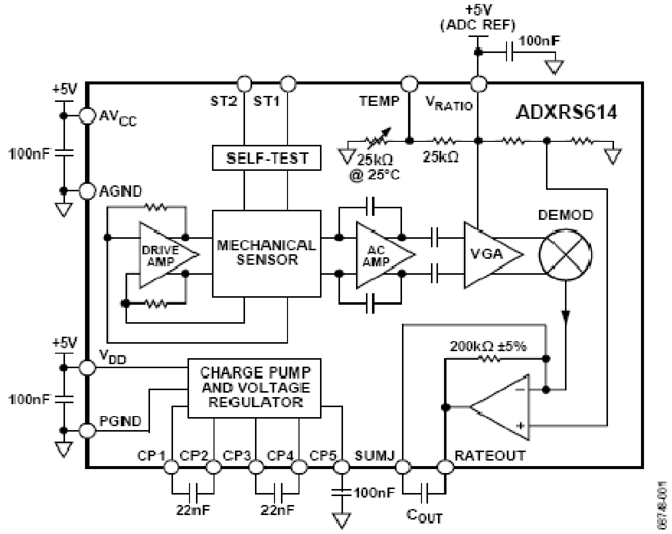


Figure 1. ADXRS614 Block Diagram

Figure 2 Functional Block-Diagram of ADXRS614 [R4]

As shown in functional block-diagram of ADXRS614, Figure 2, ADXRS614 has rate output (Vrate) which measures the rate of angular speed with respect to the axis perpendicular to the device package, and it has temperature output (Vtemp) which measures the temperature of the device.

An external 15nF capacitor was added to the rate output, to form a low-pass filter (C=15nF, R=200kΩ, thus fc=50Hz), to suppress the internal high frequency noise of 14 kHz. During testing, it was observed that some noise from the test-bed was coupled to the gyroscope output; therefore, an additional external RC filter was added, which helped to reduce the noise.

ADXRS614 has its own inbuilt temperature sensor, which can be used for the compensation of drift in the rate measurement due to the change in temperature. The temperature characteristics of the gyroscope can be modelled and lookup table can be used to mitigate the error in Vrate caused by temperature variation.

The Vratio terminal of ADXRS614 can be connected to reference input of supply ratiometric analog-to-digital converter (ADC), thus any variation in Vrate voltage, due to fluctuation in supply voltage, will be compensated as Vref of ADC will also changes proportionally with changes in supply voltage.

2.3 Interface of ADXRS614 in ADCS System

The main drawback of ADXRS614 for ADCS system is its power supply standard. ADXRS614 operates in 5V supply, whereas 3.3V is the standard supply in SwissCube. Also, the output of the gyroscope is analog, therefore it has to be digitalized before feeding its output to ADCS microcontroller. Thus, for the interface of ADXRS614, it is required to have 5V power supply unit, and ADC converter to convert analog output into digital.

For ADC converter, AD7795 Analog to Digital Converter (ADC) from Analog Device has been proposed for the gyroscope and ADCS microcontroller interface. AD7795 was selected because it is a low noise 16 bit ADC and it has 6 channels inputs, which are required by 3 gyroscopes with 2 outputs (Vrate and Vtemp) each.

An external 16-bit ADC was used instead of using already available 12-bit ADC on the microcontroller, because the use of higher bit ADC increases the resolution of the gyroscope to the design requirement. In addition, it can be directly communicated to ADCS microcontroller through SPI interface. The gyroscope resolution is given by

$$Gyroscope\ Resolution(\delta) = \frac{Vref\,ADC}{2^{number\ of\ bit\ ADC} \times gyroscope\ sensitivity}$$

Therefore, δ is 0.001525 °/sec/LSB.

As the ADC will be operated at 5V, the output won't be compatible to feed into ADCS microcontroller, which is operating at 3.3V. But the output from the microcontroller is compatible to the input of the ADC chip. Therefore, it is suggested to use two clamping diodes in anti-parallel pair, to limit the node (I/O pins) voltage of the microcontroller within the 3.3V power supply.

For power supply to the gyroscope, a combination of DC-DC converter and LDO regulator is proposed. LTC3459 DC-DC converter has efficiency greater than 85% in wide range, the operating frequency is also very high at 1.75MHz, and it comes in small package SOT-23. LTC1761 LDO regulator is proposed for the fix 5V supply at the gyroscope. Refer [R3] for complete interface schematic.

2.4 Methodology

To explain the methodology in detail it is divided into the time zones from the start up to this date into different phases, because the methods followed were different at different time epoch. The progress in the phases also indicates the development of the project work and the level of understanding of the subject.

Before starting to design and construct any system, both theoretical and practical knowledge and understanding regarding the topic should be gained. Therefore, the project was started with Literature Survey, with the documents provided along with work-sheet. Literature survey is a continuous process starting from the beginning to the end.

Next period was to identify problem with the previous gyroscope, and suggest new gyroscopes. For that, the basic design requirements for ADCS gyroscope were considered while identifying new gyroscopes. After identifying a gyroscope, it was ordered and a test PCB was constructed for SwissCube applicability testing. PCB was made very simple and small for the testing purpose.

Test bed was set-up, and calibrated. Types of tests to be performed were identified, and outputs of the test results were defined. The test results were compared with the design requirements, and final recommendation was made.

The following are the main steps followed during the project work.

- Literature Survey
- Finding the Types of Gyroscopes used in CubeSat Projects
- Gyroscope Search and Selection, and Order
- Gyroscope PCB Design and Fabrication
- Test-Bed Set-up and Calibration
- Listing Types of Tests to be performed on the new Gyroscope
- Defining Input and Output parameter in Test procedure
- Testing and comparing the Results with the Design Requirements
- Define Interface unit for the new Gyroscope with the ADCS system
- Recommendation after testing

For the detail description how test were carried out, refer Appendix D Test Procedure, and for the list of Test being performed refer Chapter 4 Tests.

3 TECHNICAL DESCRIPTION

3.1 Design of ADXRS614 PCB and Circuit

This chapter concentrates on the PCB design and characterisation of ADXRS614. ADXRS614 is single axis gyroscope, so it will require 3 of them to be placed at perpendicular planes on SwissCube to measure rotational rate at all 3-axes. A small PCB for ADXRS614 was fabricated, which will be mounted on two mutually perpendicular aluminium plates screwed on the ADCS board, and third gyroscope will be on the ADCS main-board. Thus, three gyroscopes will be placed mutually perpendicular, to measure rotational rate for all 3-axes. Refer [R3] for detail placement of the three gyroscopes.

According to the datasheet of ADXRS614, all external capacitors were predefined. For the output filter, an external capacitor of 15nF was selected, so that the -3dB frequency is set at 50Hz, with an internal resistor of 200kΩ.

In the Figure 3 circuit diagram for ADXRS614 is shown. In the final test PCB, the self-test pins were left open; therefore the resistor is not soldered.

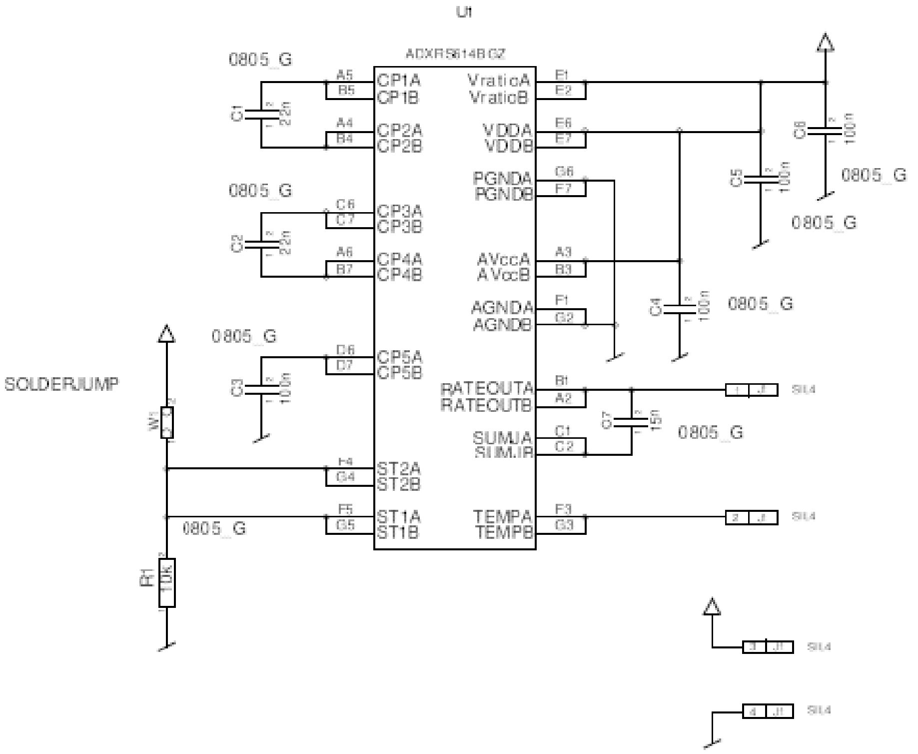


Figure 3 Circuit Diagram for ADXRS614

The circuit design has, two outputs for Vrate (measures the rotational rate by the gyroscope and gives proportional voltage), and Vtemp (measures the temperature by inbuilt sensor in the gyroscope and gives proportional voltage), thus keeping the PCB as small and simple as possible for test purpose. This simple and small PCB can also be mounted on ADCS board easily with only four connecting terminals between the gyroscope PCB and the ADCS board.

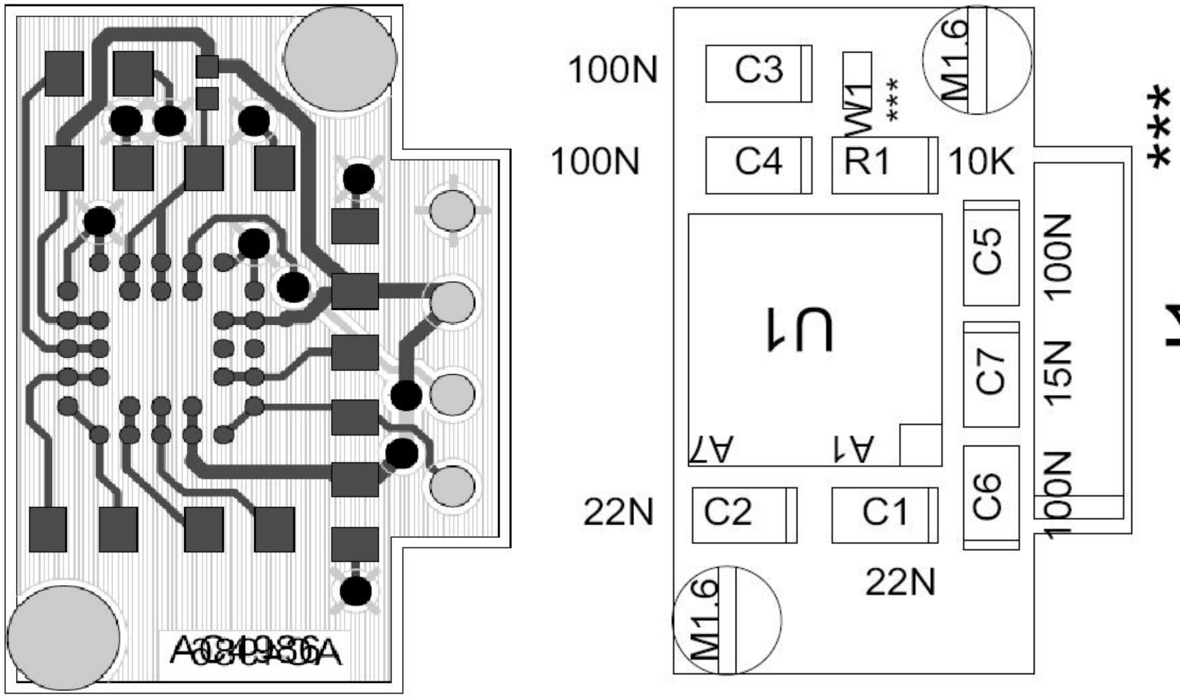


Figure 4 PCB Layout and Component Layout for ADXRS614

Figure 4 depicts the PCB layout and component placement of ADXRS614. Since ADXRS614 is available in Ball Grid Array (BGA) package, care should be taken when the gyroscope is soldered. It is suggested to use BGA socket if test has to be carried out for many gyroscopes before finally being used in SwissCube. A cheap BGA socket for the gyroscope costs around 100CHF.

BGA sockets are available from Advanced Interconnections, USA (www.advanced.com). While ordering BGA socket, the following BGA Socket Characteristics should be mentioned, ball-count (32), pitch (0.8mm), and device size (7mm*7mm*3mm). Other requirements like, operating temperature, and maximum bandwidth are also to be referred. For local distributer, contact:

Abacus Deltron France

69 Rue du Chevaleret

Paris, 75013 FRANCE

Phone : 33 (0) 1 44 23 20 39, Fax : 33 (0) 1 45 82 10 12

Email : sales@deltronfrance.com

4 TESTS

MEMS gyroscope ADXRS614 was selected for the SwissCube project, and was tested to match with the requirements for SwissCube ADCS Gyroscope subsystem. The test result will help to decided if the selected gyroscope will be suitable to be used in SwissCube, or next better solution has to be search.

The tests were performed to measure ADXRS614 gyroscope's sensitivity and find output linearity with rotational rate. Other important tests performed were Bias Test, Temperature Sensitivity, Transverse Sensitivity, Power Consumption, and Rise Time. At the end, the test results were compared with the requirements for SwissCube.

The test procedure and test list were followed form [R1], where the writer had performed the similar tests for the initially selected gyroscope (IDG-300). Using the same test setup, testing for the new gyroscope ADXRS614 was carried out at LMTS, Neuchatel.

A test PCB for ADXRS614 was made, it consists of two connection pins for Vcc and GND, and two output pins for Rotational Rate measurement (Vrate [V]) and Temperature measurement (Vtemp [V]). Vrate gives the output voltage proportional to rotational rate, and Vtemp gives voltage proportional to sensor environment temperature.

For the testing purpose, the fixed 5V was supplied directly from a variable DC power supply. And the PCB was mounted on the rotating disk.

For testing and measurement of the gyroscope output signal, equipments like digital multimeter, data acquisition card with LabView, and digital oscilloscope were used.

4.1 Test Setup

For rotational measurement, the gyroscope was place on the rotation table and the output Vrate was measured for 0~90°/sec rotational speed. The test measurement was carried out at 5V supply at room temperature.

For temperature sensitivity measurement, temperature chamber was used to vary temperature. The output at Vrate and Vtemp were measure to characterise the gyroscope at different operating temperature. The gyroscope was place inside temperature chamber in static position.

The rotational table, Figure 5, can be used for controlling the speed of the revolving disk, where gyroscope is placed. It has two mode of speed selection [fast/slow] which can selected be by altering the position of rubber chain on the larger and smaller radii groves. It has feed-through cables to prevent wires from entangling while rotating the gyroscope. The input power supply at the speed controller helps to vary the speed of the revolving disk, for the measurement of the rotating disk speed, the voltage at tachometer output (Vtacho [V]) can be used, which is proportional to the speed. From empirical measurement the speed controller output was calibrated as 0.84V/1000rpm at Vtacho. The motor used on the rotational table has gear ratio of 160:1. Also, the radii of the larger and smaller wheels were measured 18cm and 3cm respectively. Therefore, the final gear down speed of the disk is mathematically calibrated with reference to the Vtacho as: for 1°/sec revolution in slow mode the Vtacho measures 1.377V, and for 1°/sec revolution in fast mode the Vtacho measures 0.0378V.

Figure 5 Rotational Table (Gyroscope is place on the right; fast mode in the picture) [photo from [R1]]

The temperature chamber, Figure 6, with manual program it can be used for the controlled temperature setting (ramp/constant) with time. The chamber was programmed to ramp temperature from -20°C to 50°C in one hour, and decrease linearly from 50°C to -20°C in half-hour. The above temperature variation between -20°C and 50°C simulates linear approximated cyclic temperature variation as in the space at an orbit ranging between 100km to 700km [R1]. As mentioned in [R3] according to the new requirement, the orbit is between 400km to 1000km, and the temperature inside the SwissCube can vary between -30°C and 60°C, which includes a margin of 20°C.

Figure 6 Temperature Chamber (Gyroscope is place inside the chamber) [photo from [R1]]

4.2 Test Performed and Its Objectives

The following Table 3 gives the list of test being carried out, and its objective. The following basic test will help to characterise the gyroscope and will assist to decide 'Go/No Go' decision for the ADXRS614.

S.No.	Test List	Input/ Output Parameters	Objective
1.	Sensitivity Test	in: 0~90°/sec varying rotational rate out: Vrate measured	Characterisation for rotational speed with Vrate
2.	Transverse Sensitivity Test	in: 0~90°/sec varying rotational rate out: Vrate measured	Find dependence of transverse axis rotation on Vrate
3.	Bias Test	in: 0~5V varying bias voltage out: Vrate, Vtemp measured	Find Vrate, Vtemp with function of supply voltage
4.	Temperature Sensitivity	in: -20°C~50°C varying temperature out: Vrate, Vtemp measured	Find Vrate, Vtemp with function of temperature
5.	Power Consumption	in: current, voltage out: power measured	Find power consumed by ADXRS614
6.	Start-up Time	in: power on out: time to +/- 0.5°/sec of final	Find a possibility of ON/OFF operation for power saving

Table 3 List of Test Performed

4.2.1 Sensitivity Test

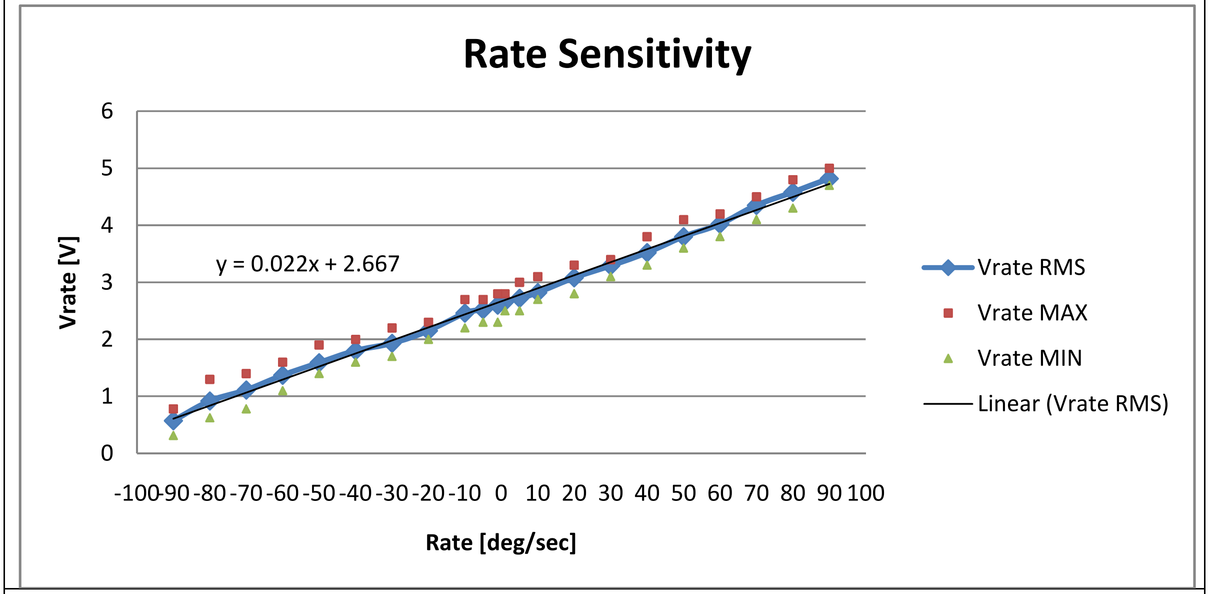
The measurement of sensitivity of the gyroscope will help to find out the minimum detectable rotational speed of the gyroscope. This test will also check linearity of the sensitivity, and compares the measured value with the specification given in the datasheet.

Two measurements were carried out, one for small range of sensitivity test and other for higher range up to 90deg/sec. For smaller rate measurement the rotating table was operated in slow mode, and for rate measurement up to 90deg/sec the table was rotated in fast mode. The speed control of the rotating disk was done by manual tuning of the input voltage at the speed controller.

The voltage measurement at Vtacho is proportional to the speed of the rotating disk. At slow mode the secondary disk rotates at 1°/sec for 1.377V Vtacho. At fast mode, the secondary disk rotates at 1°/sec for 0.0378V Vtacho. For detail calculation refer Appendix B Gear Calculation and Calibration of the revolving table.

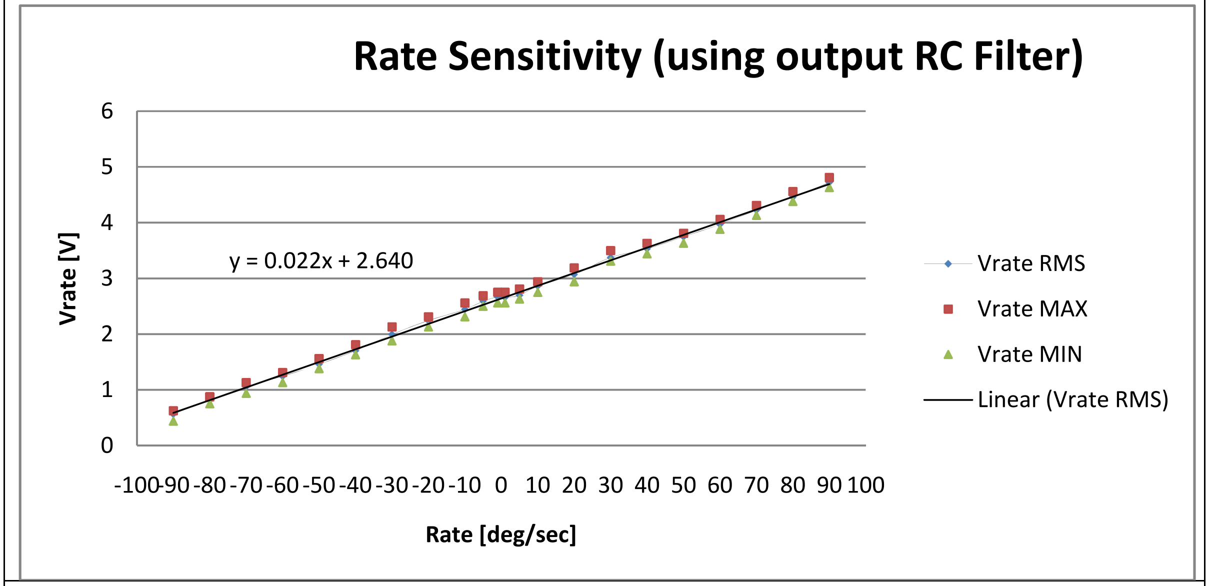
4.2.1.1 Fast Rate Mode

The following graph, Graph 1, reveals the rate sensitivity characteristics measured at 22°C, for angular speed variation of 0deg/sec to 90deg/sec, in both clock wise (CW) and counter-clock wise (CCW) directions. The positive deg/sec magnitude represents CW rotation, and vice-versa.



Graph 1 Rate Sensitivity. [with Vrate MAX and Vrate MIN ranges]

From the graph, the sensitivity of the gyroscope (slope of the linear Vrate RMS line) as obtained by the linear fit of Vrate RMS data is 22mV/deg/sec. According to the datasheet of ADXRS614, the specified rate sensitivity is 25mV/deg/sec, and at static position, 0deg/sec, the Vrate is 2.5V.



Graph 2 Rate Sensitivity (RC Filter used). [with Vrate MAX and Vrate MIN ranges]

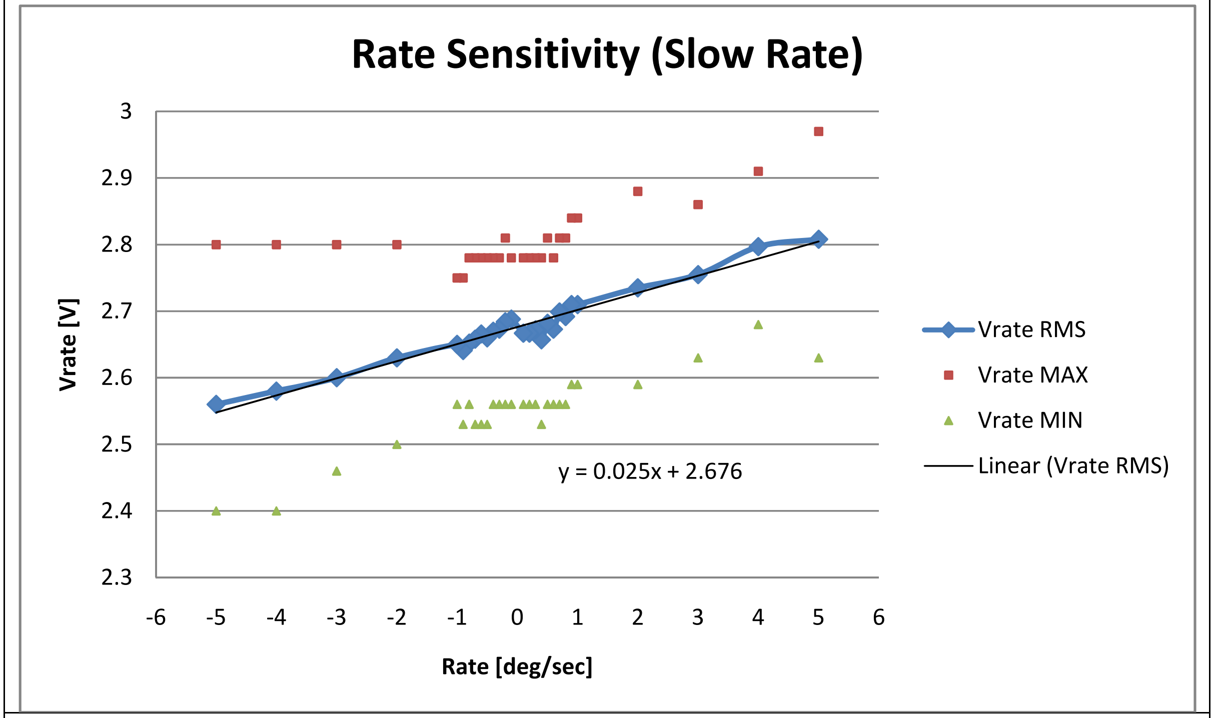
In Graph 1 the fluctuation in the Vrate output within the range of the Vrate MAX and Vrate MIN is due to the noise produce by the speed controller circuit. The noise produced by the speed controller is of frequency ranging from 2.7MHz to 3.2MHz, and the peak noise is about 150mV.

The Graph 1and Graph 2 can be a good comparison, the use of external RC filter with cut-off frequency 50Hz (R=22kΩ, C=0.1μF which gives fc=72Hz) has greatly reduced the noise RMS, which measure about 5mV. Note, while selecting external RC filter the cut-off frequency has to be consistent with rate of ADCS measurement rate. According to the design requirement, the ADCS gyroscope measurement rate is 2Hz; therefore, the sampling rate of ADCS must be at least twice of 2Hz. Hence, ADCS measurement frequency should be at least 4Hz, but in practical case, it should not be less than 5Hz, which allows having external RC filter with cut-off frequency of 50Hz.

The effect of the noise due to the speed controller is more possible to degrade the Vrate signal in the slow rotational speed rate characteristics, as discussed in the following paragraph, Graph 3.

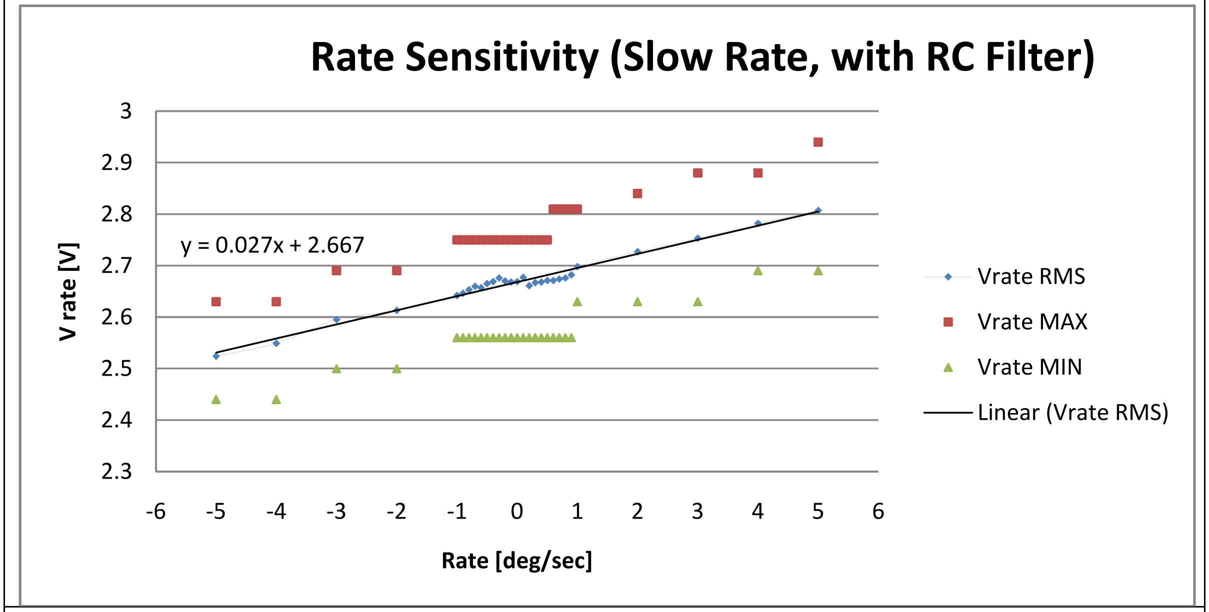
4.2.1.2 Slow Rate Mode

The following graph, Graph 3, depicts the slow rate characteristics for range below 5deg/sec at 22°C. It is clear that as the disk starts to turn, as away from 0deg/sec, the noise produced by the controller is dominating the output Vrate RMS. The Vrate MAX and Vrate MIN are moving far from its RMS value as the speed of the rotation is increased.



Graph 3 Rate Sensitivity for Slow Rate. [with Vrate MAX and Vrate MIN ranges]

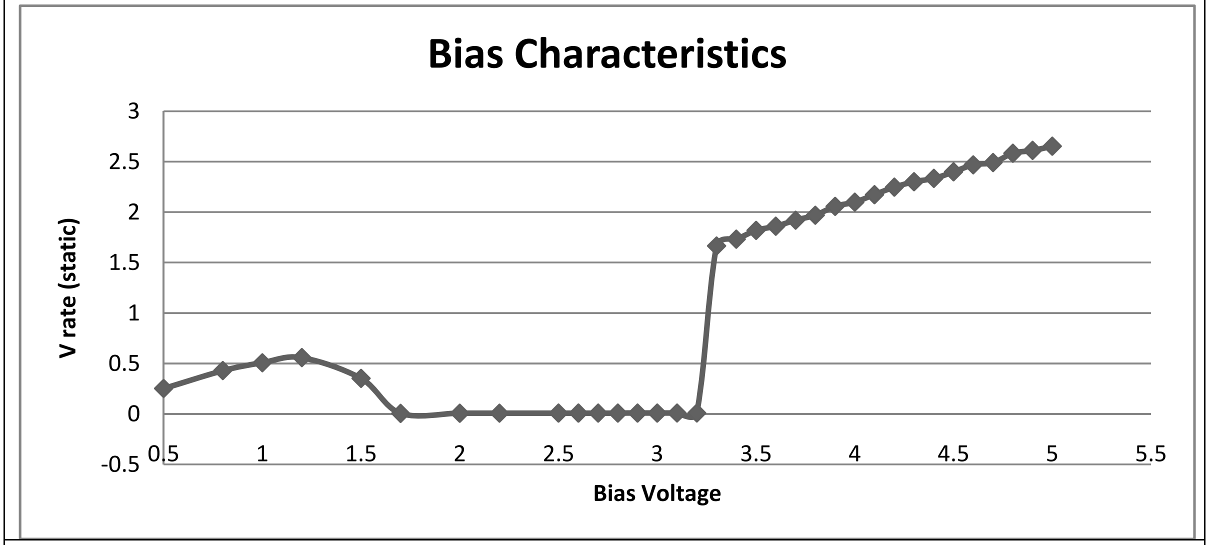
Similarly, like in the fast mode, an external RC filter was used at the output of gyroscope at slow mode also. As shown in the Graph 4, the result is promising; it has greatly reduced the noise, which is about 30mV.



Graph 4 Rate Sensitivity for Slow Rate (RC Filter used). [with Vrate MAX and Vrate MIN ranges]

4.2.2 Bias Test

Bias test was carried out to locate the suitable operating voltage range for the gyroscope, and to find the dependency of Vrate on the supply voltage. Bias voltage was varied from 0V to 5V, and output Vrate at static condition was measured.



Graph 5 Bias Characteristics.

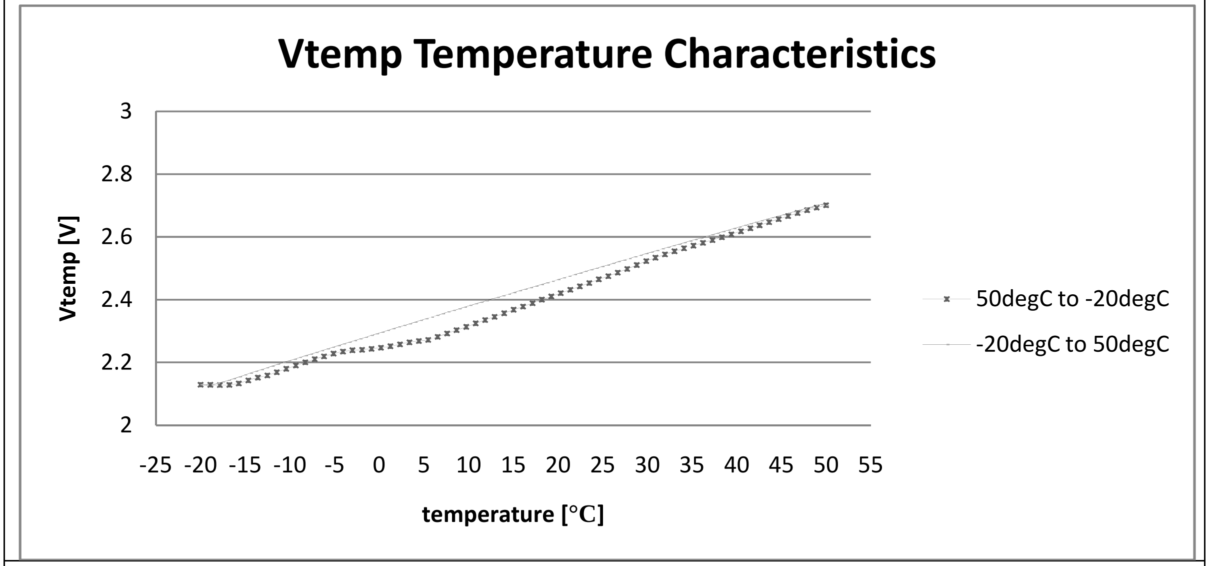
The Graph 5 was obtained for static bias characteristics at 22°C. As seen from the Graph 5 the change of Vrate is linear with the change in bias voltage from 3.5V to 5V range. The dependancy of Vrate on the bias voltage can be a limiting factor to detect minimum angular speed of SwissCube without error. The unit variation in bisa volatge will result delta of 0.576V in Vrate [from the slope of the cureve between 3.3V and 5V bias], thus, a variation of 1V in bias level can result an error of +/-20°/sec, in the linear reason from 3.3V to 5V bias characteristics.

4.2.3 Temperature Sensitivity

This experiment will help to find how Vrate changes with temperature, and to characterise the inbuilt temperature sensor of ADXRS614. From the output temperature characteristic, it can be used to define compensation technique for any fluctuation on Vrate due to temperature changes, which is measured by inbuilt temperature sensor Vtemp.

For temperature sensitivity test, the gyroscope was placed fixed inside the temperature chamber and the temperature was set to vary from 50°C to -20°C and vice versa. The temperature chamber was programmed to ramp temperature from 50°C to -20°C in 30 minutes, and to ramp from -20°C to 50°C in 1 hour, thus making one loop. The above temperature setting was chosen according to the explanation in [R1] of the temperature cycle in outer space at 100km to 700km altitude orbits.

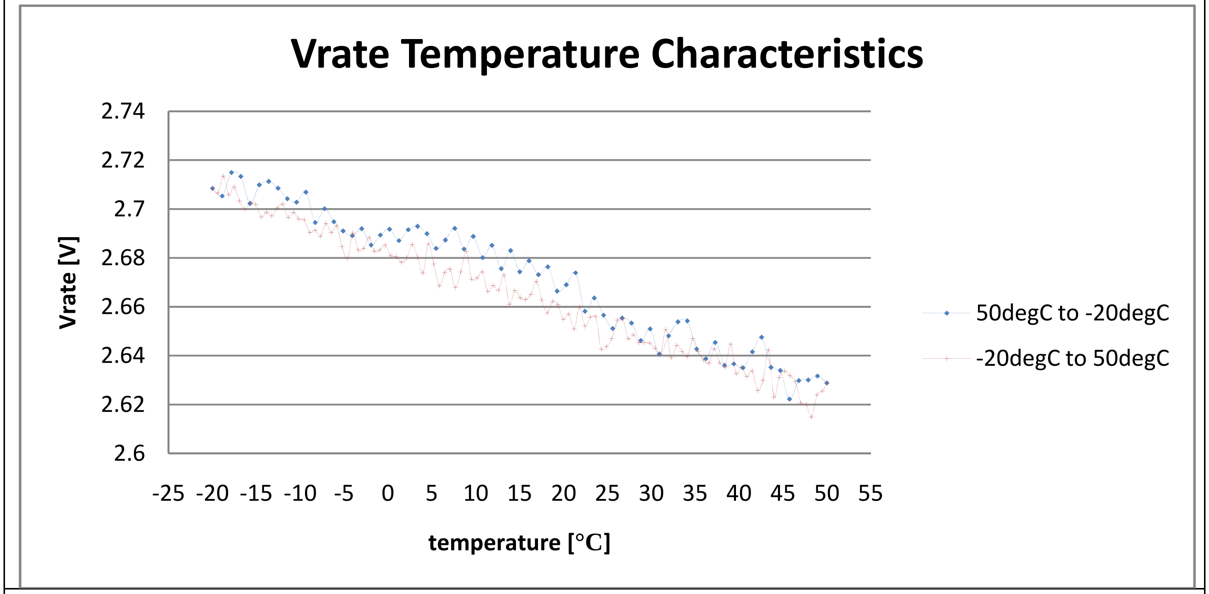
The following measurement was found on the Vtemp output, which is as shown in the Graph 6.



Graph 6 Temperature Characteristics of Vtemp output.

Small hysteresis loop was found during temperature cycle. The maximum deviation of about 67mV was measured at 5°C, at other temperature values the hysteresis deviation as from the above graph is below 67mV. From the slope of the curve, the average temperature sensitivity for Vtemp was found to be 8mV/°C, according to the datasheet it is 9mV/°C. The above temperature characteristics were measured without using output buffer/voltage follower at the output terminal of the Vtemp. It is suggested to use buffer in [R4], probably it might help to get more linear and mitigate the hysteresis.

Similarly, Vrate output was also measured for the temperature sensitivity. The following Graph 7 depicts the temperature characteristics of Vrate output. It is clear from the graph that for temperature change within 50°C to -20°C the Vrate fluctuates within 2.62V to 2.72V, which is of 0.1V band. The slope of the both curve are almost alike with shift in Y-interceptions. From the slope of the linear fit of the curves, it is found that the temperature sensitivity of Vrate is 1mV/°C. Therefore, the maximum error due to unit change in temperature in the rotational rate measurement is 0.04deg/sec. The gyroscope was placed fixed inside the temperature chamber, so it can be concluded, the Vrate decreases linearly as temperature increases, and vice-versa. But it is unclear the existence of wavy noise superimposed in the linear line. However, the reading were taken without using an external RC filter, it is assumed that the use of an external RC filter will smooth the curve.



Graph 7 Temperature Characteristics of Vtemp output.

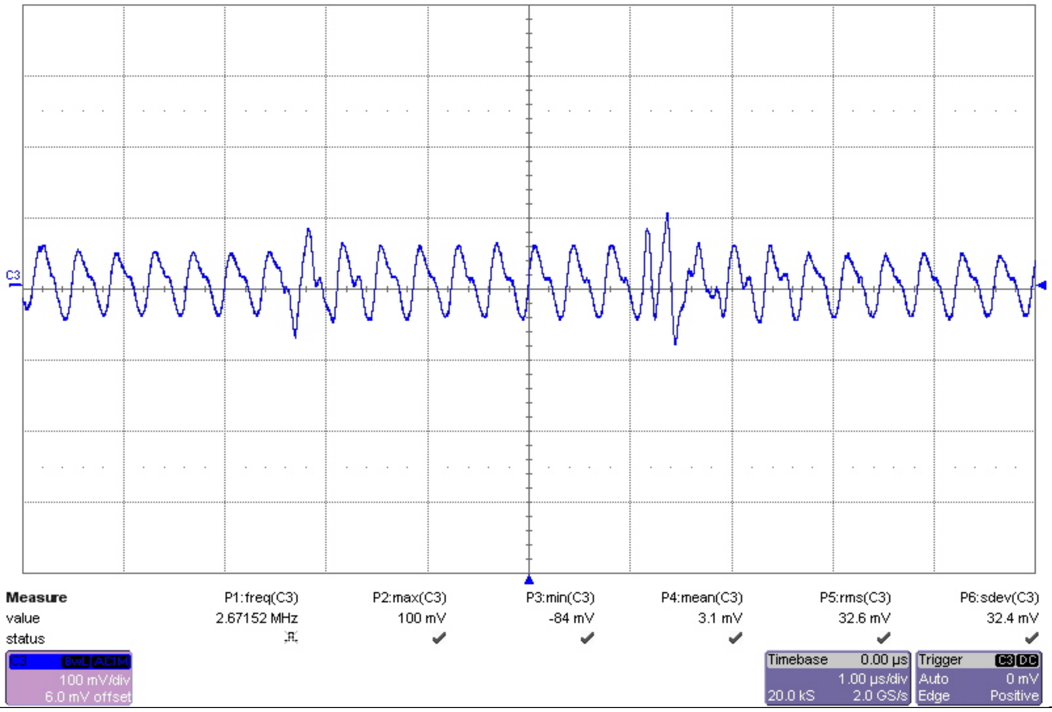
4.2.4 Noise Measurement

It is found that most of the noise in the gyroscope output is due to the external motor controller circuit. Even, the grounds were isolated between the gyroscope and motor controller; there was still noise at the gyroscope output, which might be due to capacitive coupling at very high frequency. As the controller has to be turned on for rotational measurement, the noise was unavoidable.

The following Figure 7 shows the time-base measurement of noise present in Vrate output (without using output external RC filter), and Figure 8 shows the same output with output RC filter. The channels were set to AC 1MΩ coupling, as the dc component of the Vrate is proportional to the rotational rate and for static case it is about 2.5V. The ac signal present in the Vrate is due to noise. The measurement was carried out at the static mode, and motor speed controller was turned on.

From the comparison of the figures, it is clear that the use of external filter has reduced the noise amplitude. Notice, the graphs are in different time scale.

One of the reasons for noise might be long wires, though they were twisted, and wires on the controller were also twisted and shielded with aluminum foil.



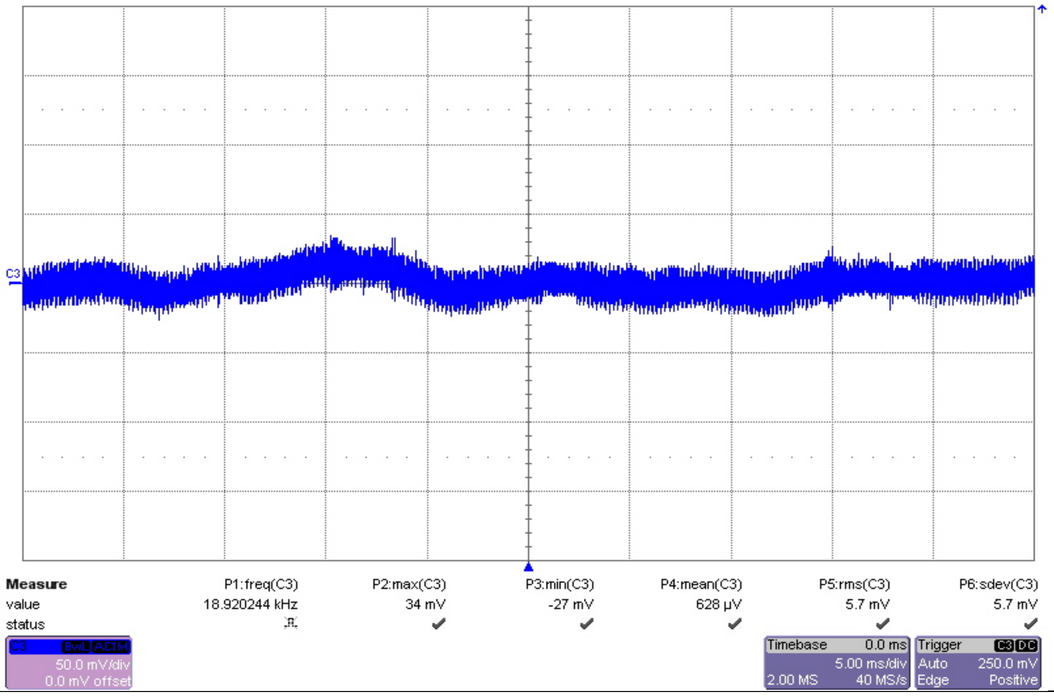
Measure	P1:freq(C3)	P2:max(C3)	P3:min(C3)	P4:mean(C3)	P5:rms(C3)	P6:sdev(C3)
value	2.67152 MHz	100 mV	-84 mV	3.1 mV	32.6 mV	32.4 mV
status	⎍	✓	✓	✓	✓	✓

C3 BwL AC1M
100 mV/div
6.0 mV offset

Timebase 0.00 µs
1.00 µs/div
20.0 kS 2.0 GS/s

Trigger C3 DC
Auto 0 mV
Edge Positive

Figure 7 Time-base Measurement of Noise (without using external RC filter)



Measure	P1:freq(C3)	P2:max(C3)	P3:min(C3)	P4:mean(C3)	P5:rms(C3)	P6:sdev(C3)
value	18.920244 kHz	34 mV	-27 mV	628 µV	5.7 mV	5.7 mV
status	⎍	✓	✓	✓	✓	✓

C3 BwL AC1M
50.0 mV/div
0.0 mV offset

Timebase 0.0 ms
5.00 ms/div
2.00 MS 40 MS/s

Trigger C3 DC
Auto 250.0 mV
Edge Positive

Figure 8 Time-base Measurement of Noise (using external RC filter)

4.2.5 Auxiliary Tests

Some basic tests were carried out to measure the power consumption, turn on time, and transverse sensitivity. It was found that gyroscope draws 3.506mA current at 5V supply. For 3 gyroscopes the total power consumption will be 53mW. Turn on time was measured to be around 14ms for output to reach ± 0.5°/sec of final. Transverse sensitivity was carried out to find if gyroscope has any sense while rotating the gyroscope perpendicular to its rate axis. It was measured that it has null effects on the output voltage. Average transverse null voltage was 2.666V for 0deg/sec to 90deg/sec rotation rate.

4.3 Test Results and Design Requirements

This chapter compares the test results with the design requirements of SwissCube, ADCS system. According to the design requirements

- Gyroscope shall be able to measure at resolution of 0.01°/sec.
- Gyroscope shall perform well within temperature range -30°C and 60°C.
- Gyroscope shall be able to provide measurement range within ± 15°/sec.
- Gyroscope measurement rate will be 2Hz.
- Gyroscope mean power consumption will be less than 90mW.

From the *sensitivity test*, it was found that the sensitivity of the gyroscope is about 22mV/°/sec, but for slow rate mode the sensitivity was measured about 27mV/°/sec, but at the same time very high noise should also be kept on mind. Even with the worst values of sensitivity (22mV/°/sec) the gyroscope resolution is equal to

$$Gyroscope\ Resolution(\delta) = \frac{Vref ADC}{2^{number\ of\ bit\ ADC} \times gyroscope\ sensitivity}$$

Which gives the worst case δ= 0.001733°/sec/LSB, the resolution value is high enough to fulfil the design requirement.

From the *temperature sensitivity*, it is found that the gyroscope can perform well within the temperature range of -20°C and 50°C, which lies within the lower bound of the design requirements [-30°C and 60°C]. Even after the temperature sensitivity test, the gyroscope was performing well in rate sensitivity test and other measurement in the later days, thus the sensor can perform within the design requirement temperature range. The inbuilt temperature sensor found to be linear and has a small hysteresis which can be modelled, and the temperature dependency of Vrate is also linear hence, it must be easy to mitigate the effect of the temperature variation.

From the *bias test*, it is found that the gyroscope output is linearly dependent to the supply voltage within the range of 3.3V to 5V. Therefore, the use of ratiometric ADC will easily compensate the bias dependent output, as explained in section *2.2 Working Assumptions*.

From the *auxiliary test*, the turn on time is 14ms [maximum 50ms from datasheet [R4]], which leave enough room for ON/OFF mode for power saving, but during this design phase it had been considered to keep the gyroscope ON all the time. Power consumption for one gyroscope is 18mW, therefore for 3 gyroscopes the total power consumption will be 54mW, which is much lower than the maximum value as assumed in [R3] of 81mW. Therefore, the power consumption limit for whole gyroscope unit must be within the design requirements. Finally, for gyroscope measurement rate of 2Hz, the use of 50Hz cut-off low pass filter has enough bandwidth.

5 RECOMMENDATIONS

The current rotating disk setup is not sensitive enough for small rotational rate measurement, like below 5deg/sec, also the motor controller itself is producing noise in the measurement. Therefore, it is suggested to put the controller kit as far as possible and be kept inside a metal box, but not opened and close to the test area as in the current structure.

EMI due to motor controller was observed, even common ground was avoided. Therefore, in a compact structure like SwissCube, it can't be said that there won't be such EMI interference in the gyroscope output. Also, the gyroscope has resonant frequency at 14 kHz, which can result EMI interference to other circuits in the SwissCube.

It is recommended to use an extra external hardware or software filter of 50Hz cut-off frequency, to reduce the noise [internal resonant frequency, and external EMI high frequency] at the gyroscope output. The use of compensation method, like, lookup table mapped with Vtemp output, and an external RC filter can reduce the effect of variation in Vrate with temperature change. The use of external RC low pass filter can result smooth Vrate curve with temperature dependent. It is strongly recommended to use inbuilt temperature sensor of ADXRS614 for temperature measurement and compensation, as it will help to increase the accuracy of the ADXRS614.

Test was more emphasised on Rate Sensitivity and Temperature Sensitivity, but to simulate outer space environment, other tests like vacuum test, radiation test must also be carried out.

Current test was done on only one Gyroscope, though the results were found as specified in the datasheet of ADXRS614, some more gyroscopes have to be ordered and tested, and characterised for the final flight in SwissCube.

ADXRS614 uses 5V power supply for its operation, therefore, it is recommended to find solution for its power supply management and its interface with other units. In this report, some technique with specific electronics components for 5V power supply unit and ADC system has been proposed, but it needs to be tested. Therefore, it is recommended to construct a new test PCB with 16-bit ADC, step-up and LDO. As characterisation has to be done with many, for easy and quick testing, it is suggested to include BGA socket for ADXRS614 in the PCB.

It was realised at the end the importance of ADXRS614 noise characterisation, as the information will be used for the software simulation of ADCS model. Thus, the noise present in the gyroscope output has to be measured and statistical data like variance should be computed. A quick [static mode] measurement was taken, and it was found the variance of the noise present at the Vrate is about 20.76µV.

The only drawback of using ADXRS614 is it uses 5V power supply. All SwissCube ADCS sub-systems were designed to operate under 3.3V. As ADXRS614 has only one axis measurement, it will require three gyroscopes on each three perpendicular planes.

Gyroscope gives direct measurement of angular speed which Sun Sensor and Magnetometer cannot! Also, the gyroscope measurement is more precise than the estimation made by Sun sensor alone. Therefore, it is recommended to use gyroscope for the fulfilment of SwissCube design requirement.

6 CONCLUSION

High sensitivity gyroscope is needed for the precise detection of the SwissCube rotational rate. It is found that ADRS614 is well suited for the SwissCube application. It has very high sensitivity of 25mV/deg/sec [measured 22mV/deg/sec] in comparison to the previously selected gyroscope IDG300 [2mV/deg/sec]. Also the sensitivity curve is linear. Further, the gyroscope resolution can be increased by using a 16-bit ADC [AD7795], but the accuracy of the ADC is higher than that of the gyroscope, thus the gyroscope limits the overall accuracy of the angular rate measurement. The ADXRS614 is small BGA package (7mm*7mm*3mm), light weight (0.5g), consumes less power (max 25mW), thus ADXRS614 fulfils the SwissCube design requirements.

The drift in rate voltage output due to temperature variation is also found to be very small [0.04deg/sec per unit change in temperature], which is more stable and liner in comparison to test result for IDG300 gyroscope.

The effect of bias voltage variation on Vrate was found to be linear in comparison to IDG300, within supply voltage range between 3.3V and 5V; thus, the error due to the bias instability can be cancelled out by using a supply ratiometric type ADC, where Vrate of the gyroscope is connected to the Vref of the ADC, here, 5V.

A simple and small PCB for gyroscope has been made, that can be easily inserted to the main ADCS Board for interfacing.

7 REFERENCES

[R1] Kaspar Jenni, *S3_Phase_B-C-ADCS-1-3-Gyroscopes,* EPFL, June 2007

[R2] Hervé Péter-Contesse, *S3_Phase_B-C-ADCS-1-3-ADCS_HW_and_System*, EPFL, June 2007

[R3] Hervé Péter-Contesse, *S3_Phase_B-C-ADCS-1-0-System_Engineering*, EPFL, January 2007

[R4] ADXRS614 *Datasheet,* Analog Deveice, Inc. 2007

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Last but not the least, thanks goes to Muriel Noca and Hervé Péter-Contesse for checking through the draft version of the report, and their valuable suggestions.

APPENDIX A GYROSCOPES COMPARISONS

The following table lists some of the gyroscopes being manufactured, and is compared with ADXRS614.

	Gladiator Tech GA10	Micro Aerospace MAS IMU01	Analog Devices ADXRS614	Systron Donner QRS11	Systron Donner LCG50	BEC Navigation BP-3G-150H
Sensitivity	12 mV/deg/sec	-------------------	25mV/deg/sec	25mV/deg/sec	16mV/deg/sec	Digital output
Size	18*18*18 cm^3	30*26*16 mm^3	7*7*3 mm^3	40mm dia.	14*14*5mm^3	16*16*16 mm^3
Weight	27 gm	40 gm	0.5 gm	60 gm	12 gm	4 gm
Power	55mW	600mW	18mW	800mW	40mW	50mW
Supply	5V	5 ~ 12 V	+5V	+5V and -5V	5V	5V
Axis	Z	X-Y-Z	Z	Z	Z	X-Y-Z
Interface	Analog output	RS 485 Serial	Analog output	Analog output	Analog output	I2C Serial

Gyroscopes Characteristics Comparison

From the above table, it is clear that, ADXRS614 has the smallest sized, weight, and consumes least power, plus it has high sensitivity. Thus, it ADXRS614 is the best choice for the SwissCube where size, power and weight is a critical parameter. ADXR614 measures only one axis gyroscope, it will require three of them for SwissCube.

From the consideration of axis measurement, BP-3G-150H is good for SwissCube, as it has small size and consumes less power, and only one of it will work. Thus, leaving more space in SwissCube, with compare to 3-ADXRS614 with all the interfacing circuits. But BP-3G-150H has one drawback as it uses I2C interface, but ADCS microcontroller has only one I2C interface which is already being used for the satellite main bus for interconnection between all subsystems. Also, BP-3G-150H was not readily available.

APPENDIX A GEAR CALIBRATION AND CALCULATION

The revolving table has to be calibrated before carrying any rotational measurement on it. The table consist of Motor Speed Controller, DC Motor with gear ratio of 1620:1, and the motor drives a wheel (primary wheel) directly coupled with axis and the wheel drives another wheel (secondary wheel) coupled with a rubber band chain.

There are two modes while driving secondary wheel by the primary wheel. Both wheels have groves cut at large radius (R) of 18cm, and small radius (r) of 3cm. Therefore, the chain-pulley combination of 18cm radius primary wheel and 3cm radius secondary wheel will run at Fast Mode, and the combination of 3cm radius primary wheel and 18cm secondary wheel will run at Slow Mode.

The voltage output of tachometer has unknown Volt/rpm ratio. From the product datasheet, it was found that two possible calibrations were listed for Vtacho, either 0.84V/1000rpm or 1V/1000rpm. Therefore, empirical measurements were carried out to calibrate the Vtacho of Motor Speed Controller, as shown in the following table.

Number Rotation of Primary Disk	Vtacho (Vt)	Time (t)	RPM of Primary Disk (RPMpd)	RPM of motor (RPMm)	Converted RPM per 1Volt	Converted RPM per 0.84Volt
formula			*(60/t)*	*(RPMpd*1620)*	*(RPMm/Vt)*	*(RPMm*0.84/Vt)*
1	2.48	33	1.818	2945.16	1187.56	997.55
1	3.49	23.38	2.566	4156.92	1191.09	1000.51
1	3.71	21.83	2.74	4438.8	1196.44	1005.00
1	5.1	15.92	3.76	6091.2	1194.35	1003.25
1	7.44	10.96	5.47	8861.4	1191.04	1000.47
1	9.6	8.41	7.13	11550.6	1203.18	1010.67
1	2.76	29.3	2.04	3304.8	1197.39	1005.80
1	1.73	46.7	1.28	2073.6	1198.61	1006.83
1	0.45	78	0.337	546.06	1213.46	1019.30

From the above table it is clear that tachometer calibration can be considered as 0.84V/1000rpm.

For Fast Mode:

At Vtacho= 0.84V, secondary disk rpm is $(\frac{R}{r}*\frac{1000}{1620})$ = 3.703 rpm, that is 22.218°/sec at 0.84Vtacho.

Therefore, for 1°/sec rotational increment Vtacho must be increased by 0.0378V.

For Slow Mode:

At Vtacho= 0.84V, seconday disk rpm is $(\frac{r}{R}*\frac{1000}{1620})$ = 0.10288 rpm, that is 0.61°/sec at 0.84Vtacho.

Therefore, for 1°/sec rotational increment Vtacho must be increased by 1.377V.

APPENDIX C TYPES OF GYROSCOPES USED IN CUBESAT

The following are the list of CubeSat Projects which had used gyroscope in ADCS system.

Gyroscopes Used in Past CubeSat Project

1. CUTE-I by Tokyo Institute of Technology, Japan (2003)
    - Piezoelectric Vibrating Gyroscopes
2. CUTE-1.7 + APD by Tokyo Institute of Technology, Japan (2006)
    - ADXRS 150 (single axis gyro, used 3 gyros)
3. SEEDS by Nihon University, Japan (2006)
    - no more information found
4. AAUSAT-II by Aalborg University, Denmark
    - Gyro from Analog Device (ADXRS401)

The following are the list of CubeSat Projects which are planning to use gyroscope in ADCS system.

Gyroscopes planed to be used in Future CubeSat Project

1. BeeSat by Technical University of Berlin, Germany
2. ITUpSAT-I by Istanbul Technical University, Turkey
3. HIT-SAT by Hikkaido Institute of Technology, Japan
4. SwissCube by EPFL, Switzerland

APPENDIX D TEST PROCEDURE

The aim of this annex is to provide a short detail for a reader to be able to repeat or replicate the test and measurements.

Sensitivity Test:

1. Use rotational table
    a. Apply voltage (range 0V to 35V) at *Alim* to control the desire rotational speed
    b. Take volt measure from *Tacho* for rotational speed measurement [refer Appendix B Gear Calculation and Calibration for relation between Vtacho and angular speed]
2. Place the gyroscope on the secondary rotating disk.
    a. Place rotational axis perpendicular to the ADXRS face/package with sticking tape
    b. Provide fix 5V supply using variable DC power supply to the gyroscope using feed-through cables
    c. Bring Vrate and Vtemp outputs wire to the panel [rotational table] using feed-through cables.
3. Manually control the voltage at *Alim* to rotate the gyroscope at desire speed
4. Measure voltage reading at Vrate and Vtemp using digital multi-meter or multi-channel oscilloscope, at different rotation speed (range ±90deg/sec) [direction: clock wise positive(+), counter clock wise negative (-)]
5. Flip the gyroscope face to change the [CW and CCW] direction of rotation

Transverse Test:

1. Place the gyroscope face parallel to the axis of rotation, use L-shape any supporting frame
2. Repeat the steps [from 1 to 4] as described in *Sensitivity Test*

Bias Test:

1. Vary gyroscope bias/supply voltage from 0V to 5V using variable DC power supply
2. Take Vrate measurement for each step changes in bias voltage

Temperature Sensitivity:

1. Use temperature chamber
    a. Program the chamber to ramp for -20°C to 50°C in one hour, and 50°C to -20°C in half hour [refer manual the temperature chamber]
    b. Place the gyroscope inside the chamber, pass wires through a hole passage and cover with a rubber block [for details refer manual of the temperature chamber]
2. Use digital multi-meter interfaced with LabView and DAQ card set-up to acquire and store the data into a computer [acquisition time interval used was 30 seconds]
3. Acquire data from Vrate and Vtemp

Power Consumption:

1. Turn ON the gyroscope
2. Use digital multi-meter to measure the voltage across the gyroscope, and current passing through the gyroscope

Start-Up Time:

1. Connect Vrate output to oscilloscope and set the oscilloscope to acquire data when triggered
2. Capture the signal when power supply is connected
3. Count the time taken to rise Vrate up to ±0.5°/sec of final steady-state