ASEN 3200 LAB A-1 Attitude Sensors and Actuators

Assigned: Tuesday, August 25, 2020
Report Due: Monday, September 14, 2020, 10PM

OVERVIEW

This experimental lab introduces a key attitude ***sensor*** – the rate gyro, and two types of attitude ***actuators*** – a reaction wheel (RW) and a control moment gyro (CMG). The rate gyro installed is a MEMS (Micro-electro-mechanical System) type integrated circuit board. The MEMS rate gyro and reaction wheel are mounted in a single axis spinning spacecraft mockup – i.e. the spin module hardware that you will use in the class. We will use this equipment again in Lab A-3 to implement a closed-loop control system for the spacecraft mockup. In lab A-1, we will start by simply making calibration measurements for the MEMS rate gyro and the reaction wheel on the spin module. We will also qualitatively explore the principles of operation of a separate hand-held physical rate gyro to understand how gyros work. Then, using a large inertia rim-loaded bicycle wheel, we will also explore the principles of operation of a control moment gyro (CMG) actuator where the students will play the part of the spinning spacecraft. Note: The hand-held physical gyro and CMG are separate hardware and not part of the spin modules.

OBJECTIVES

- Investigate the MEMS rate gyro and measure its capabilities for sensing angular velocity and position.
- Investigate the reaction wheel actuator and measure its angular momentum storage capability.
- Qualitatively understand how a physical rate gyro works.
- Operate and qualitatively understand how a control moment gyro works.

PRELIMINARY QUESTIONS

1. A rate gyro is mounted on the spacecraft mockup (spin module) with its input (sensitive) axis pointed up. Suppose you are given a data file containing rate gyro measurements at equally-spaced time increments of Δt sec. The measurements are in volts, and the gyro sensitivity is K [V/(rad/sec)]. How would you calculate the angular position of the spacecraft in [rad] from these data?
2. A spacecraft in low Earth orbit experiences a constant disturbance torque, M_d [Nm], due to aerodynamic drag. An onboard reaction wheel is angularly accelerated (spun up) to keep the spacecraft from tumbling. If the reaction wheel has a moment of inertia about its spin axis of $I\omega$ [kg m^2], what is the required angular acceleration (rate of change of the angular velocity) of the reaction wheel to fully compensate for the drag disturbance?
3. Imagine you are holding a spinning gyroscope in your hand. What do you think you'll feel as you slowly rotate your hand about different axes?
4. Imagine that you are sitting on a stool, free to rotate about the vertical, holding a spinning bicycle wheel in front of you with the spin axis horizontal. Describe how you would use the wheel as a CMG (i.e how would you move the spin axis of the wheel) to rotate yourself to the left on the stool.

EQUIPMENT

1. Spacecraft mockup (spin module) - with MEMS rate gyro, brushless base motor w/ encoder, brushless RW motor, reaction wheel, and LabVIEW VI
2. Hand held physical rate gyro box
3. Rim-loaded bicycle wheel (CMG), spin-up motor, low-friction platform

LAB TASKS

There are four parts to the experiment that can be done in any order. You should have enough time to get to all four parts during the available lab periods. There are up to 8 spacecraft mockups that will be set up at fixed lab stations and 2 bicycle wheel setups that you can work with. You are welcome to observe other groups working with the equipment while you wait for your turn.

The experiments with the gyro and reaction wheel on the spacecraft mockup involve collecting data using a LabVIEW VI. You are requested to use the following naming convention for your data files:

- G## – identify your Group number
  Unit## – identify your Spin Module Unit # (Located on the base plate)
- MEMSMANUAL/MEMSMOTOR/RWHEEL – for the type of run (see below)
  RUN## - sequential run number of all your experiments for this lab

For example, if you are group #40, working with Spin Module Unit #1, taking your third dataset from the MEMS gyro with manual control, the filename would be: **G40_UNIT01_MEMSMANUAL_RUN03**
Substitute MEMSMOTOR or RWHEEL when doing those types of experiments.

1) RATE GYRO MEASUREMENTS

The MEMS gyro can be used to measure the angular velocity of the spacecraft mockup. The brushless DC motor mounted to the base of the spacecraft has an encoder that provides a truth reference for the angular velocity of the spacecraft. Both the encoder velocity and the gyro output are recorded by the LabVIEW VI. (See separate procedure handout.)

a. Draw a block diagram of the experimental setup

The diagram can be hand drawn or done on a computer. Identify each of the key elements (gyro, power, signal conditioning unit, etc.) of the system, their input and outputs, and connections. Describe in one or two sentences the function of each.

b. Experiment with manual inputs

To start with you will rotate the spacecraft and observe the output relation. To get different velocities you can move the spacecraft back and forth by hand. Abrupt changes in angular velocity lead to non-linear effects in the gyro output which appears as “looping” in the relationship between true angular rate and gyro voltage.

With the VI set to “Manual Control”, experiment by moving the spacecraft in a gentle, sinusoidal manner so that a good linear relationship between voltage and angular rate can be observed on the VI. Observe how moving the spacecraft at different rates affects the data collection. Collect data for a minute or so. Take notes on performance of the gyro so you can discuss this in the report.

c. Measure the bias & adjusted scale factor, *K*, for the MEMS gyro using motor inputs

To measure the rate gyro bias and adjusted scale factor, we capture and compare the gyro output to the actual motor encoder velocity for a range of spacecraft angular velocities. To get different velocities we will now move the spacecraft back and forth using the base motor.

Set the VI to use the base motor to move the spacecraft for specified sinusoidal output. Parameters of frequency and amplitude of the output sine wave are given in the experiment section below. Collect data for a minute or so and save to an appropriately named file. Repeat at least two more times with different driving frequencies and amplitudes, saving files each time.

Import the data into MATLAB and plot the encoder velocity on the x-axis and gyro output on the y-axis. Convert units on the gyro data to rad/s. Fit a line to the data to determine the gyro bias [rad/s] and the adjusted scale factor (unitless [(rad/s)/(rad/s)]. Make a table of the bias and sensitivity measured in each run for the gyro. Using the results from multiple trials, compute the mean and standard deviation of your computed bias and scale factor.

With this calibration complete (i.e. using the bias and adjusted scale factor found above), compute the measured angular rate and angular position based on the rate gyro measurements. Plot the angular position as a function of time.

2) REACTION WHEEL MEASUREMENTS

A reaction wheel is an actuator used to stabilize a platform or to counteract/absorb the effects of externally applied torques. To use the wheel for this purpose you need to know its moment of inertia (MOI). The MOI can be found by applying a known torque to the wheel and measuring the resulting angular velocity. We use the reaction wheel motor on the spacecraft mockup to produce a constant torque on the wheel and then read out the angular speed of the wheel with the hall-effect sensors onboard the reaction wheel brushless motor.

a) Draw a block diagram of the experimental setup

The diagram should be hand drawn or drawn on a computer. Identify each of the key elements (reaction wheel, power, signal conditioning unit, etc.) of the system, the input and outputs (use arrows), and connections. Describe in one or two sentences the function of each.

b) Measure the change in velocity due to a fixed applied torque

Use the LabVIEW VI (see instructions at the end of the lab handout) to apply a constant torque to the wheel and record the angular velocity data as the wheel accelerates. (Hold onto the spacecraft to keep it stationary and from interacting with the wheel.) Save the output to an appropriately named file. Repeat at least four more times with different driving torques, saving files each time. To convert from the column of motor current in amps to torque refer to the datasheet for the motor that you are using, i.e. the reaction wheel motor to get the torque constant in Nm/Amp.

c) Data Analysis

Import the data into MATLAB and plot the angular velocity as a function of time. Find the average angular acceleration by fitting a line to the data; then compute an estimate of the moment of inertia of the wheel in [kg m^2]. Using the multiple trials compute the mean and standard deviation of your estimate.

3) PHYSICAL RATE GYRO

The physical rate gyro provides a hands-on experience to observe how a single-axis gyro is used to measure an input angular rate.

a) Obtain a physical rate gyro and two AA batteries, then insert the batteries into the battery compartment and turn the switch on. The motor inside should begin to accelerate a disc and reach a constant angular velocity. Experiment with rotating the rate gyro about each axis.

- Observe how the spinning disk inside the gyro assembly moves as you rotate the gyro about different axes. What consistent patterns do you observe?
- Describe the torques you feel from the rate gyro as you rotate about different axes.

b) Based on your observations, rotate the physical gyro by hand about the axis that causes precession. By observing the resulting tilt direction, determine the rotational direction of the disc. (Is it rotating with positive or negative spin with respect to the positive y-axis?)

4) CONTROL MOMENT GYROS (CMG)

Unlike a reaction wheel, control moment gyros nominally spin very fast at a constant rate and are mounted in a gimbal. The gimbal can be rotated using a torquer motor, thus changing the orientation of the spinning gyro. This change in the direction of the angular moment of the CMG causes a precession or reorientation of the spacecraft. In this part of the lab, a bicycle wheel will serve as the CMG and *you* will be the spacecraft. This part of the lab will be physically experienced and qualitative.

a) Stand on the swivel board. Hold the bicycle wheel in front of you with arms straight and wheel axle horizontal. Have another group member spin up the wheel using the hand held electric spin-up motor. Experiment with tilting the wheel spin axis. Try to obtain reaction torques that cause you to rotate about the vertical axis.

b) Use the wheel to point a horizontal body axis (e.g. the axis described by our outstretched arms) to track a moving reference point (e.g. a walking group member). Try this with more than 1 group member and note any differences in performance.

ANALYSIS

1. **RATE GYRO ANALYSIS** - How precisely were you able to determine the sensitivity of the MEMS gyro? Over what range of rates would you consider it to be useful? Based on the manual experiment, how does the gyro perform when given abrupt changes in spin rate? How repeatable is the gyro bias and is this important? How did the angular position estimates based on the MEMS gyros in Part C compare with the known angular position of the spacecraft, and what do you think is going on?

2. **REACTION WHEEL MEASUREMENTS** - Using the data obtained in the procedure part 2), calculate how long the reaction wheel could resist an aerodynamic torque of 10^{-4} Nm before the wheel speed exceeds the limit of 4000 rpm. What is the angular momentum capacity of this wheel in [N m/s]?

3. **PHYSICAL GYRO** - Draw a diagram of the physical rate gyro and a coordinate frame setup where the gyro wheel rotates about the y-axis, the gyro tilts about the x-axis and the rotation of the box by hand is about the vertical z-axis. Label each axis on your diagram. Using Euler's rotational equations of motion, explain what is happening when the physical rate gyro is rotating about the z-axis. Assume a constant spin for both the rotor and your rotation about the z-axis.

4. **CONTROL MOMENT GYROS** - Explain qualitatively how you were able to obtain pointing torque using the bicycle wheel as a control moment gyro. Draw a diagram showing the momentum vector and its vector rate of change, as well as the resulting moment vector.

REPORT OUTLINE & GRADING

Title Page (2 pts) – Lab, Course Number, Group Members, Date

Abstract (5pts) – short summary of objectives, experiment, results, and analysis

Introduction (5pts) – brief introduction to this lab, what you plan to investigate, how this could be applied to spacecraft attitude control

Preliminary Questions (15pts) – answer the preliminary questions associated with the lab

A. MEMS Rate Gyro Characterization (15 pts)

- Experiment –equipment list, block diagram with explanations, description of procedures
- Theory (short) – explain briefly, with equations, how the measurements made in the experiment are used to compute the sensitivity. Describe how angular position is computed from the gyro output.
- Results – plots of results, key results in a table including a measure of the errors, observations made during the experiment
- Analysis – Describe the experimental results compared with your expectations. What conclusions can you draw from your manual experiments? What are the possible sources of error? Answer any questions given in the analysis part of the assignment

B. Reaction Wheel Characterization (15 pts)

- Experiment –equipment list, block diagram with explanations, description of procedures
- Theory (short) – explain briefly, with equations, how the measurements made in the experiment are used to compute the moment of inertia of the wheel and the capacity of the wheel
- Results – plots of results, key results in a table including a measure of the errors, observations made during the experiment
- Analysis – Describe the experimental results compared with your expectations. What are the possible sources of error? Answer any questions given in the analysis part of the assignment

C. Control Moment Gyro Experiment (10 pts)

- Experiment – equipment list, description of procedures
- Results & Analysis – Describe the qualitative results of your experiment and explain your findings

D. Physical Rate Gyro (10 pts)

- Experiment – Observations on the physical rate gyro when it rotates
- Analysis – Diagram w/ coordinate frame, explanation, with Euler's equations of motion, of the dynamics
- within the physical rate gyro

Conclusions and Recommendations (5 pts)

- What did you learn from this experiment?
- What would you recommend to improve the experiment or to extend it beyond the given objectives?

Team Member Participation Table (2 pts)
Acknowledgements (1 pt) List who did what in the group and what outside assistance you received

References
[Style & Clarity 15 pts]

- Organization (3) – clear flow, follows required outline, numbered pages
- Figures (4) – clear figures, appropriate axes, informative titles, clearly labeled units
- Tables (4) – clear tables, significant figures, headings, informative titles, clearly labeled units
- Spelling & Grammar (4)

Lab Acknowledgments
The original spacecraft modules were developed by Prof. Dale Lawrence and Walter Lund, Matt Rhode (manufacturing), Brad Dunkin (LabVIEW) with lab updates by Trudy Schwartz, Gabe LoDolce, Prof. Penina Axelrad, Prof. Hanspeter Schaub and others.

The updated spacecraft modules were developed by grad students Lewis Gillis, Devon Campbell, Joshua White and others along with Bobby Hodgkinson and Trudy Schwartz.