Spacecraft Attitude Dynamics for Undergraduates

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Abstract

Teaching spacecraft attitude dynamics to undergraduate students is a challenging proposition. The subject has a hefty mathematical base that poses a significant challenge to many aerospace engineering undergraduate students. The challenge for the instructor is to provide a course where students can begin to build their intuition and give them tools to predict how spacecraft behave in space, without the force of gravity. Building this intuition is difficult since the gravity environment is the one we are all most familiar with. In addition, the three dimensional nature of spacecraft adds an additional challenge, as working with matrices and matrix equations are a must.

At Embry-Riddle, the students taking this class have had some introduction to spacecraft attitude dynamics in a brief way in a spacecraft systems course. The course on spacecraft attitude dynamics is meant to give the students depth in attitude dynamics and control that they don't get in the introductory material given in other courses. The students use what they learn in this course in their spacecraft design course, which is taken simultaneously.

This paper outlines both the tools used in the classroom to help the students visualize the dynamics and the scope of subject matter that help make the course accessible to the undergraduate student. Matlab™ is used extensively in the course to make the computations less of an obstacle and to enable visualization.

I. Introduction

Few schools teach spacecraft attitude dynamics and control (sometimes called spacecraft attitude determination and control) at the undergraduate level, while many teach it at the graduate level. Even fewer require it as part of the aerospace engineering curriculum. It is taught at the undergraduate level at Virginia Tech[1], University of Southern California[2], Purdue University[3], and the United States Air Force Academy[4]. At Embry-Riddle Aeronautical University, the course is taught as a required course for the astronautics option within aerospace engineering. Approximately 40 students per year take the course. It is a required co-requisite to the first capstone design course in the sequence.

Approaches to teaching this course that are found in the literature include the introduction of spacecraft anomalies, resulting from problems with the attitude control system[5], and the use of simulation with animation of spacecraft behavior[6].

There are challenges in teaching spacecraft attitude dynamics at the undergraduate level. One of the features of the material is that it requires the ability to work comfortably with matrix algebra and a coupled system of differential equations. It is recognized that the mathematics required for the subject matter make the course difficult to translate into a physical interpretation of the spacecraft behavior[6]. Another feature that makes the course challenging is that it teaches three-dimensional dynamics. While students learn two-dimensional dynamics in their sophomore level dynamics course (which is usually challenge enough), three-dimensional dynamics becomes much more challenging. The third challenge in this course is that students do not have any real experience with dynamics without gravity and typical forces we see and use on earth. In addition to the difficulty of zero gravity and no atmosphere, spacecraft typically employ spinning components to maintain and control their attitude. The use of momentum to manage pointing is seldom used in earth-based applications. This makes it hard to sanity-check the results, since typically, our sense of whether or not an answer makes sense is based on our experience.

In contrast, a flight mechanics course has the advantage that many students have experience with the forces of gravity and aerodynamics, or at least have spent more time studying these effects, prior to taking a flight mechanics course. In fact, many of our students are pilots and have direct, hands-on experience with aerodynamic behavior. Because of this lack of familiarity with spacecraft behavior, we need to employ other tools to help students build their intuition about how spacecraft will behave in space. This intuition, in turn, will enable the student to "sanity-check" their analyses to determine if the "answer" makes any sense at all.

In the following sections, approaches to addressing the above concerns are presented. These include a an approach to the mathematics, application of simulation aides and use of three-dimensional models.

II. Approach to Mathematics

In early iterations of teaching the spacecraft attitude dynamics course, it appeared that the students were unfamiliar with the basics of matrix methods that are often taught in high school. I have used a diagnostic quiz for several semesters now that indicates that a review of basic matrix arithmetic and algebra are needed. This includes basic matrix addition, subtraction, multiplication, inverses and eigenvalues/eigenvectors.

While tensors are frequently used in teaching spacecraft attitude dynamics[7], I have chosen to keep the mathematics as simple as possible by using only vector and matrix notation, with sub and super-scripts to denote the appropriate reference frame. This is mostly consistent with the notation used in reference 8.

III. 3-D Visualization Aids

Understanding the spacecraft attitude of a rigid body requires a keen understanding of three-dimensional dynamics. Often, two-dimensional dynamics are challenging enough for the student in his/her sophomore year. Understanding the spacecraft attitude requires an understanding of kinetics and kinematics. Some of the three-dimensional visual aids I have used are coordinate frames made from Kinex™ toys, spacecraft models used in class with movable solar panels and antennas that need to point at earth, a mechanized demonstration of spacecraft spin, nutation and orbit – relating all three motions, a spinning wheel to demonstrate torque generated by moving the momentum vector, and a spinning wheel inside a box to demonstrate how change of wheel momentum gives rise to box rotation. All of these have some relevance to helping the student learn how spacecraft attitude behaves and how it can be controlled.

Kinetics requires the student to learn how the spacecraft coordinate frame is moving relative to the inertial frame (or some other relevant reference frame). Translational kinetics are fairly easy to understand because there are no rotations involved. For three-dimensional rigid body kinetics, rotations are important. Two-dimensional rotations are taught in a typical dynamics course, but there is only one axis that the rigid body can rotate about. Adding two additional axes of rotation complicates things considerably. To help students visualize the angular motions, particularly Euler Angles, I provide the students with a set of two coordinate frames made from Kinex™ toys. These prove very useful in the classroom during my lectures when I am teaching about Euler Angles and the students are encouraged to use the coordinate frames on exams as well. Using the physical coordinate frames, the student can take the frame through a series of rotations and sanity-check their analytical result with the result obtained by physically rotating their coordinate frame.

A model showing the geometry of the earth/satellite/sun system enables the student to see the different elements on a spacecraft that require precise pointing. In class, I use a three-dimensional spacecraft model with movable solar panels and antennas that should face earth. This helps students understand how the spacecraft attitude will remain fixed if nothing is done. It also shows how the solar panels must rotate in order to track the sun for a nadir pointed satellite. Students usually assume that the spacecraft will track the earth naturally. It makes it clear that the spacecraft rate must equal the orbit rate for the spacecraft to maintain its attitude fixed on the earth. Having the student hold and move this model spacecraft around its orbit helps the student understand that the attitude will remain fixed unless you do something to change it. This model is also useful in illustrating roll/yaw coupling as well as illustrating how solar pressure can result in a cyclical torque.

Because of the different coordinate frames, it is hard for students to visualize orbital motion, spacecraft spin, and spacecraft nutation (coning), all happening simultaneously. To enable students to see this better, a group of students designed and built a model that illustrates all three motions (nutation, spin and orbital motion). This model consists of a spacecraft model, spinning about a given axis, attached to a protractor that allows the student to set the “nutation” angle. The spin axis is motorized and the protractor apparatus is motorized and spins at a different rate than the spin, to illustrate nutation. Axis attached to the spacecraft model show how an antenna attached to the spacecraft will cone and an earth model at the center illustrates how this coning affects the antenna pattern seen on Earth. The tilted spacecraft (and its motors) is attached to an arm that can be cranked around the model of the Earth, illustrating the orbital motion.

Spacecraft often use momentum management to reorient the spacecraft or to stiffen it against external torques[9]. Since this method is not often used in Earth-based applications, it is typically an un-familiar concept. A spinning wheel (for example, those used in physics classes as a demonstration) is one device that can indicate how a spinning spacecraft is more difficult to rotate under the influence of external torque. The use of the spinning wheel is also interactive – the student can feel the torque him/herself as they try to re-orient the wheel while it is spinning. The spinning wheel is a very simple demonstration that helps illustrate how moving the momentum vector correlates to a torque and how having a spinning wheel makes the spacecraft less sensitive to torque acting perpendicular to the spin axis of the spacecraft.

The last visual aid I would like to discuss is another student-build demonstration. This is pictured below. The change of wheel speed is often used in spacecraft to provide a rate to the spacecraft or to absorb an external torque that the spacecraft is experiencing. The device that illustrates this concept is a casing (on a bearing) with a spinning wheel inside. Two demonstrations are possible, illustrating both points above. In one demonstration, the wheel speed is changed such that the change in momentum is transferred to the external casing of the wheel, and the student can observe the casing start to spin in the opposite direction. This shows how changing the wheel speed can provide a rate to the spacecraft through conservation of momentum. The second demonstration has the student control the wheel speed while another student provides a torque to the external casing, simulating an external torque on the spacecraft, controlled by an internal momentum wheel. The operator, whose objective is to keep the spacecraft casing oriented towards a target, controls the wheel speed. In this demonstration, the student controlling the wheel speed is acting as the "controller" that would typically be programmed in the spacecraft's computer.

III. Simulation Aids

The spacecraft dynamics are difficult to visualize in three dimensions, as stated above.

Simulation is another tool that can illustrate the spacecraft behavior. It can do this in several ways. One way can show the actual motion of the spacecraft body; another way is that the simulation can show spacecraft motion as seen through spacecraft telemetry (e.g., angular rates as transmitted by on-board gyroscopes). The tool that I have used to do this is Matlab. I have used a simulation that shows how the coordinate axes change as a result of applying a set of Euler Angles. I use Matlab simulations of tri-inertial spacecraft behavior and have used this to compare to the approximate behavior derived in class. I have used simulations to illustrate rigid body instability; show the effect of a sinusoidal torque, simulate a nutation damping maneuver, simulate reorientation maneuvers, simulate the effect of an applied constant torque, and simulate the attitude dynamics using quaternions. In addition to simulation of specified attitude dynamics, the students can learn by backing out the spacecraft behavior from the "gyro traces" – simulating telemetry.

I have used these simulations as demonstration tools in the classroom. I have also made the Matlab files available to students and have required the students to modify the simulations to perform various homework assignments.

The use of Matlab simulations on homework has resulted in mixed success since students have a varying degree of competency with Matlab. This should be somewhat remedied in the future since our current freshmen are learning Matlab and should be using it throughout the curriculum.

Future simulations that would be useful in teaching the spacecraft attitude course are: simulated sensors on the spacecraft with attitude determination processing of the sensor data, simulated gravity gradient torque on a rigid spacecraft to illustrate regions of instability and stability, simulated solar torque, nutation growth due to energy dissipation, and effects of flexibility (fuel slosh or flexible appendages) on the angular rates and the spacecraft attitude.

IV. Making the Course Accessible to Undergraduates

In order to make the material more accessible to all undergraduates pursuing the astronautics option, minimizing the amount of new mathematics and notation helps to keep the student from getting lost in the mathematics and unable to see the physical interpretation of the spacecraft dynamics. Since a course in controls is not a pre-requisite to the course, I have chosen to concentrate on single rigid body dynamics and covering this subject in some detail. With the study of rigid body dynamics, the students can learn about the spin-stabilized spacecraft behavior under a variety of conditions and can understand how to plan any maneuver required, such as nutation damping, reorientation maneuvers, apogee or perigee boost maneuvers and spin change maneuvers. In addition, stability conditions for rigid body and gravity gradient stabilization are covered. Some introduction to spacecraft with a spinning wheel is given and environmental torques such as aerodynamic drag, magnetic torque, gravity gradient torque and solar torque are covered. Three-axis stabilization is not covered since the students don't have adequate preparation in control systems at this point in the curriculum and because there is not sufficient time with the choices made above. These topics provide a fair amount of depth in spin dynamics and environmental torques and introduce the student to some of the other methods of spacecraft attitude control.

V. Summary

Spacecraft attitude dynamics can be made accessible to all undergrad AE students (without self-selection by students with aptitude). The use of computer simulation, model spacecraft and physical reference frames enables the students' learning. Minimizing new notation and mathematics also helps to make this course accessible to undergraduate students. Depth in single rigid body dynamics allows the students to fully understand spin-stabilized spacecraft.

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