The Spinning Rocket Simulator: An Experimental Design Project for Teaching and Research

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Abstract

An experimental apparatus is being developed to simulate the dynamics and control of spinning, thrusting bodies with internal mass motion. An interdisciplinary team of undergraduate engineering students is executing the first phase of development as a senior design project at Oral Roberts University under the direction of faculty advisors. The apparatus will enhance instruction in dynamics and control systems by providing demonstrations of fundamental dynamical principles and experimentation with spacecraft attitude control concepts. In addition, the apparatus will be used to conduct research in the dynamics and stability of spinning rockets with internal mass motion, and the passive and active control of such vehicles.

Introduction

Undergraduate engineering students need learning opportunities that more closely resemble the challenges they will face in industry and graduate school. Successful teamwork and communication in engineering design, especially between the engineering disciplines, are essential skills that should be practiced at the undergraduate level. This approach is facilitated in the Oral Roberts University Engineering and Physics Department since students work closely with those of other disciplines. The ABET accredited undergraduate degree in general engineering allows for mechanical or electrical emphasis, Undergraduate degrees in computer engineering, bioengineering, and engineering physics are also conferred within the same department. The two-semester senior design project experience typically involves a team of students from several of these areas with an engineering design problem requiring work in multiple disciplines. This paper describes the initial phase of one such project and the benefits derived for both the students and the university.

The long term goal of the project is to develop an experimental apparatus to accurately model the dynamics and control of nonrigid, spinning bodies under thrust. An initial concept for such an apparatus has been proposed by Meyer[1]. The first phase consists of the development of three interdependent and essential elements: a general spacecraft model with variable inertias, a hemi-spherical air bearing to support the model, and the sensor systems necessary to track the orientation of the model during test. This last element is required for future phases to allow accurate modeling of the thrust force. Completion of the first phase allows laboratory simulation of the rotational dynamics of a rigid body in space over a wide range of inertia properties. In addition, the motion is sensed and recorded for analysis. At this stage, the apparatus is useful for demonstrating fundamental concepts of three dimensional rigid body dynamics that are typically difficult for students to visualize, and hence grasp. The completion of future phases will provide a vehicle for laboratory experimentation and research in the dynamics and control of nonrigid, spinning bodies under thrust, validating and extending the work of Halsmer and Mingori[2].

General Spacecraft Model

In order to investigate the general principles which govern the motion of an arbitrarily shaped spinning spacecraft under thrust, it is advantageous to design a spacecraft model which can be easily modified to reflect a wide range of inertia characteristics. The current design is based on the principle that the inertias of any arbitrarily shaped body can be duplicated by the appropriate placement of eight specified corner masses of a rectangular parallelepipeds.

Figure 1 illustrates this concept, and shows that these masses are held fixed in the body by a system of

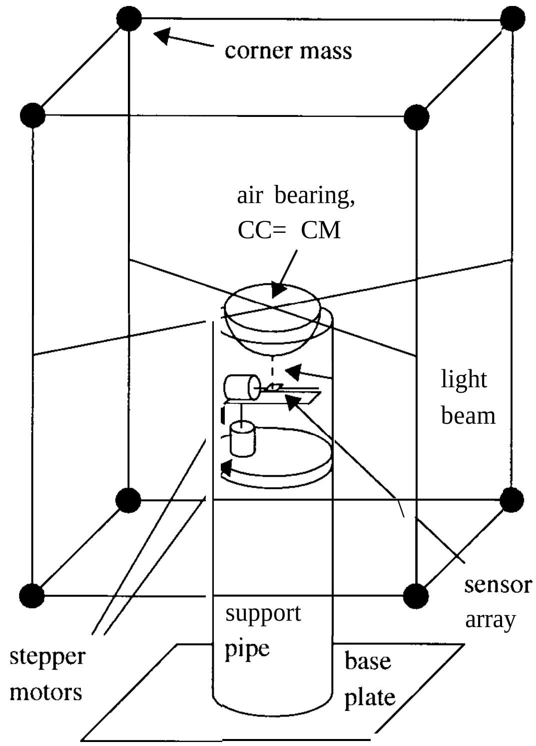

Figure 1. Phase 1: Model, Bearing, and Sensor

horizontal and vertical members. The effective lengths of these members are variable to allow for testing of prolate, oblate, and asymmetric configurations. The two crossing horizontal members support the model via attachment to the upper surface of the convex (moveable) part of the air bearing. Placing the center of curvature (CC) of the air bearing coincident with the center of mass (CM) of the model allows for virtually torque-free motion of the model about its CM. The nominal spin axis is a vertical axis through the center of the model. Spin, precession, and nutation (of up to 17.5°) are sensed and recorded for the analysis of notational (coning) stability.

The current design is capable of inertia ratios (I_{spin} / $I_{transverse}$) in the range of 0.33-1.67. The average length of one side of the model is approximately one meter and the model has a mass of approximately 25 kilograms. Software is being developed to compute the inertias for a given configuration, and also to simulate the motion of the model prior to test.

Initial tests consist of spinning the model up to a starting speed and then measuring the growth/attenuation rate of coning. The decrease in spin speed due to friction in the bearing and aerodynamic drag on the model are small enough to be considered negligible with regard to coning motion. Drag calculations are conducted to predict the spin deceleration rate. Not shown in Figure 1 is an annular plate around the air bearing that can be positioned to facilitate spin up. It also serves as a stop if the cone angle reaches a predetermined maximum value.

Hemi-spherical Air Bearing

The heart of the apparatus is the air bearing which provides essentially frictionless, hydrostatic support for the model while drawing from a supply at 100 psi. Twelve evenly spaced air holes in the concave surface provide an extremely thin (0.03-0.1 mm) cushion of air. Both the concave and convex spherical surfaces are machined from brass to the necessary tolerances using a specially developed radius cutter on a lathe. The radius of curvature is 6.35 cm. The concave piece is rigidly mounted to the top of a vertically oriented, 15 cm support pipe. The pipe is 1 meter in length and rigidly attached to a fixed base plate at its bottom.

The air bearing is specially designed and outfitted to provide a means for detecting the instantaneous orientation of the model throughout a test. Embedded in the convex part of the bearing is a battery powered light source emitting a beam which is aligned with the nominal spin axis of the model. The light beam passes through a circular opening in the concave part of the bearing in order to impinge on a photo-electric sensor array. This sensor is positioned to maintain the light beam in the center of the array as described in the following section.

Attitude Sensor Systems

In future phases of this project, it is planned to simulate the effect of a thrust, or follower force aligned with the nominal spin axis of the model. This will be accomplished by eccentrically mounting the base plate on a turntable, and continuously adjusting the eccentricity and turntable speed such that the resultant of centrifugal and gravity forces on the model always remains aligned with the nominal spin axis of the model. It should now be obvious why the instantaneous orientation of the model must be accurately tracked. How else would it be possible to adjust the eccentricity and turntable speed in order to maintain correct alignment of the simulated thrust force? Closed loop control systems will be developed for this purpose, however, the details are omitted since this work is not part of the initial phase.

The two stepper motors and sensor array for tracking model attitude are shown in Figure 1. These systems are mounted within the support pipe a few centimeters below the air bearing. The vertically oriented motor provides rotational motion of a horizontal track. The horizontally oriented motor provides translational motion of the sensor array along the track through a screw drive. The array consists of 7 photo-sensitive elements arranged in a hexagonal pattern with one in the center. The illumination of the outside elements actuates the stepper motors rapidly enough to maintain illumination of the center element. The signals sent to the motors are also recorded in a computer, The motion of the model is derived from this information and compared to computer simulation.

The accuracy of the sensor systems is verified by rate gyros mounted directly to the model. These gyros sense model angular rates and transmit the information via RF to the computer. Again, the model motion is derived from these rates and compared with the other data.

Design Team Organization

The design team for this project consists of five senior engineering students under the direction of a faculty member and a retired faculty member. The spacecraft model subsystem is being engineered by a student with a mechanical emphasis. The engineering of the air bearing subsystem is being shared by two students, each with a mechanical emphasis. The sensor subsystems are being engineered by two students, one with an electrical emphasis, and one with a double emphasis in electrical and computer engineering.

The entire team meets weekly to submit informal progress reports, and exchange information. Formal project proposals, progress reports, and final reports in both oral and written forms are conducted at appropriate times throughout the senior year. Team members within each subsystem work closely together, and with members of the other subsystems when engineering decisions require such interaction. This benefits the students by requiring them to consider how their designs effect the system as a whole. In addition, they are afforded the opportunity to work out their designs with input from those with a different perspective (emphasis). Valuable team working skills are also developed in the process. Project management and communication skills are developed as well as engineering skills in the particular application that is being pursued.

Educational and Research Benefits

Besides the educational benefits obtained by the students participating in the engineering development work, many more students will benefit from demonstrations and experimentation with the completed apparatus. The concepts of precession and nutation of a body spinning freely in space are typically difficult for students to grasp because of the inability to illustrate these concepts effectively using conventional methods. Computer simulation can help but even this approach is inherently two dimensional. An apparatus which reproduces the motion in the classroom or laboratory greatly facilitates understanding of the dynamics involved.

Understanding is further enhanced by allowing the students to conduct experimentation. The spin deceleration rate may be measured and compared to that derived from aerodynamic drag considerations. The coning growth/attenuation rate may be measured and compared to that derived from the dynamical equations and inertia values. Experimentation should confirm that spin about an axis of maximum inertia is stable resulting in an attenuation of the cone angle from an initial value. Spin about an axis of minimum inertia is unstable for any real body, and the coning growth rate depends on the extent to which the body is nonrigid. Spin about an intermediate axis of inertia is also unstable, and is characterized by large coning growth rates.

Experimentation may also be conducted to investigate the control performance of the primary attitude sensor. Students may design and implement various control schemes for keeping the sensor array illuminated, and compare the resulting accuracy with the on-board sensors. They may be challenged to suggest other approaches that would improve the attitude tracking performance. The tracking accuracy will determine how accurately the thrust force will be modeled when investigating its effects in future phases of this project.

The spin dynamics and stability of a body in torque-free motion are well understood. The motion and stability characteristics of nonrigid, spinning bodies under thrust have only recently been investigated, and are not as well understood. An apparatus that simulates this motion in the laboratory will be a valuable asset to a research program with goals of describing the dynamical behavior of such bodies. Theoretical and computer results will be validated, and novel schemes for controlling the coning of spinning thrusting vehicles will be investigated. Both passive and active moving mass controllers will be developed and tested on board a modified spacecraft model. Passive controllers will consist of various mass-spring-damper designs located and tuned to attenuate coning motion. Active devices will consist of a closed loop, computer controlled, moving mass system to accomplish the same purpose.

The effects of various forms of spacecraft flexibility (such as fuel slosh) will also be investigated. In addition, appropriate modification of the model will allow its inertias to be varied during testing. The inclusion of remote controlled screw drives within appropriate model members will allow simulation of time varying mass properties. This research would provide insight into the coning problems experienced by recent spin-stabilized transfer orbit boost vehicles. It would also further our understanding of spinning body dynamics in general. Support is currently being sought to fund the future phases of this project.

Conclusions

Educational and research goals can be accomplished simultaneously by utilizing teams of undergraduate engineering students from multiple disciplines to conduct "real-world" engineering research and development projects under the direction of faculty advisors. The development of an experimental apparatus to simulate the dynamics and control of spinning rockets at the Oral Roberts University Engineering and Physics Department is an example of such a project.

Subsystem engineering of the spacecraft model, spherical air bearing, and attitude tracking systems are synthesized to complete the first phase of development. At this stage, students gain enhanced understanding of the torque free motion of a body in space through demonstrations and experimentation. In future phases, both educational and research programs will be pursued with the additional capability of simulating the effects of a body fixed thrust force. Such experimentation will significantly enhance the quality of engineering instruction, and further our understanding of the dynamics and control of spinning bodies.

References

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DOMINIC M. HALSMER

Dominic Halsmer received his Ph.D. degree in Mechanical Engineering from UCLA in 1992. From 1985 to 1992, he worked as a dynamics and controls engineer for Hughes Aircraft Company. He joined the faculty of Oral Roberts University in August 1992, where he is currently an assistant professor and Director of Engineering Programs. His current research interests are in the dynamics, stability, and control of spinning bodies.

WILLARD E. BAIR

Willard Bair received his D.Eng. degree in Mechanical Engineering from Yale in 1956. From 1983 to 1992, he served on the engineering faculty at Oral Roberts University from which he is now retired. He continues to contribute to the department by lending his engineering experience and expertise to current students and faculty.

PEY-CHII (PEGGY) NG

Peggy Ng anticipates her B.S. degree in Engineering with a mechanical emphasis from Oral Roberts University in December of 1996. She designed and constructed the spacecraft model for the spinning rocket simulator, and developed the software for computing the mass properties and simulating the vehicle dynamics. She plans to attend graduate school in either Aerospace or Mechanical Engineering.