Chapter 1

Introduction

Imagine lacking the ability to control your direction; it would be difficult to accomplish much of anything. The first US satellite, Explorer 1, suffered from this problem: due to flexible antenna on the craft, it began rotating orthogonal to its designed spin. The orientation, or attitude, control of a satellite can be difficult. However, satellite attitude control is crucial for satellite use in general; measurement, communication, propulsion, and much more are directly related to the satellite attitude. For these reasons, as satellites progressed beyond Explorer 1, so did attitude control methods. Early methods were passive: spin stabilization (spin about one axis fast enough so minor torques are negligible, much like a top), gravity gradient (aligns with the earth nadir direction due to differential gravity acting on the body), or passive magnetic attitude control, the subject of this dissertation.

Passive magnetic attitude control (PMAC) has been in use since the early 1960's. However, this does not mean it has outlived its usefulness. Far from it; PMAC remains a useful tool available to the spacecraft designer. As spacecraft decrease in size so does available power from the solar cells; the attitude control design space shrinks. Thus, many nanosatellite developers choose PMAC systems for the following reasons: the simplicity of installation (no processor running control laws is needed), low mass (often less than 5% of the satellite mass), zero power use, and alignment with the local magnetic field. However, PMAC is often little understood by many developers, especially student teams. This lack of understanding has led to poor design and inadequate performance prediction. This research grew from the desire to understand this control method to avoid design pitfalls and allow for improved performance estimation.

Passive magnetic attitude control is the use of a magnet to torque the spacecraft towards earth's local magnetic field in conjunction with a dampening method. The dampening method most often used are hysteresis rods: soft magnetic material which is easily magnetized by the earth's local field. Because of satellite rotation, the direction of the local magnetic field relative to the hysteresis rod changes over time. This change in the direction of the local magnetic field changes the magnetization the rod, which decelerates the satellite angular velocity as rotational energy is converted to heat between the magnetic domains of the rod.

Research of the mechanics and simulation of Passive Magnetic Attitude Control is presented. A simulation of the rotational response of a satellite using a PMAC system is developed. This simulation is intended to predict the response of a PMAC system and thus is useful in design of future missions. Good PMAC system design can avoid negative consequences such as pointing offset error (a constant angular offset from the local magnetic field) or increased settling time (the time duration from initial orbit insertion to closely tracking the local magnetic field). The settling time is an important factor for small satellites which typically have a total mission lifetime of a few months; the success of such missions will be greatly hampered if they need to wait months or even years for attitude alignment.

Because an understanding of rotational motion and magnetic theory is crucial to an understanding of PMAC, these concepts are presented in Chapter 2. The difference between magnetizing field $\mathbf{H}$ and magnetic flux density $\mathbf{B}$ is described and applied to hysteresis rods to determine the relation between the hysteresis loop and the rod-based magnetic moment $\mathbf{m}_{\text{hyst}}$, which is crucial for the determination of hysteresis rod magnetic torque vs. the applied field. Although most small satellite developers to date have used material reference hysteresis loops, a vastly more realistic loop is based on empirical measurement of the flight hysteresis rods; this argument is developed throughout this research.

Chapter 3 presents an overview of PMAC history. A timeline of select missions is presented in an effort to understand which mission types are best for a PMAC system. The analytical models which have been developed for some of these missions are shown, along with any assumptions which the models have used. The same treatment is given to the numerical models which have been used in the past. Finally, an overview of previous hysteresis rod measurement is presented.

Chapter 4 describes the Colorado Student Space Weather Experiment (CSSWE), a 3kg nanosatellite funded by the National Science Foundation (NSF) for space weather investigation. This CubeSat used a PMAC system for attitude control and serves as a concrete satellite example throughout this dissertation.

Chapter 5 presents the design of a PMAC system for the CSSWE CubeSat. The sizing and distribution of the bar magnet and hysteresis rods are discussed. Although applied to a CubeSat, design rules from this chapter are useful for any small satellite using a PMAC system.

Chapter 6 discusses a Multiplicative Extended Kalman Filter (MEKF) developed for attitude determination of a PMAC satellite. After the filter is defined, both simulation- and empirical-based tuning is performed using the CSSWE CubeSat. The on-orbit attitude performance of the CSSWE CubeSat is shown. The MEKF output is then verified by independently-measured telemetry.

Chapter 7 outlines the design of a Helmholtz cage and describes a variety of magnetic measurements applicable to a PMAC system. The cage is built such that a 3U CubeSat will experience a 99% uniform field across its length. After manufacturing, the Helmholtz cage setup is used to measure the magnetic moment of the CSSWE flight bar magnet. The Helmholtz cage setup is then used to measure CSSWE hysteresis rods. The hysteresis loops fitted to these empirical data are used as inputs to the dynamics simulation.

Chapter 8 presents a simulation developed to predict the attitude response of a satellite using a PMAC system. The components of the simulation are presented in detail such that mission teams may recreate the full simulation. This chapter also covers attitude dynamics which apply to a PMAC satellite; understanding these effects are helpful in interpreting the simulation output. A simplified simulation is developed to investigate the limitations and expected performance of the full simulation. The simplified simulation is also useful in selecting a numeric integrator and time step which achieve acceptable accuracy at a realistic computational cost. The results of the full simulation are shown and compared to simulation output generated using a higher-order integrator. The full simulation results are also compared to the on-orbit attitude data filter output.