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# A hybrid attitude controller consisting of electromagnetic torque rods and an active fluid ring

Nona A. Nobari *, Arun K. Misra [1]

*Department of Mechanical Engineering, McGill University, 817 Sherbrooke St. W., Montreal, QC, Canada H3A 0C3*

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ABSTRACT

In this paper, a novel hybrid actuation system for satellite attitude stabilization is proposed along with its feasibility analysis. The system considered consists of two magnetic torque rods and one fluid ring to produce the control torque required in the direction in which magnetic torque rods cannot produce torque. A mathematical model of the system dynamics is derived first. Then a controller is developed to stabilize the attitude angles of a satellite equipped with the abovementioned set of actuators. The effect of failure of the fluid ring or a magnetic torque rod is examined as well. It is noted that the case of failure of the magnetic torque rod whose torque is along the pitch axis is the most critical, since the coupling between the roll or yaw motion and the pitch motion is quite weak. The simulation results show that the control system proposed is quite fault tolerant.



## 1. Introduction

The selection of an attitude control actuator for a satellite depends on its size. In this regard, small satellites, like micro-satellites, which require small torques for stabilization, are constrained by their weight and power budget. For this type of satellites, one option is to use magnetic actuators as they are quite light and easy to implement. However, there are some drawbacks associated with magnetic torque rods stemming from the fact that no torque can be generated about an axis parallel to the Earth's geomagnetic field vector. Moreover, since the magnitude of this vector cannot be estimated accurately, the accuracy of stabilization is also affected. Nevertheless, a satellite can be completely stabilized, although slowly, by using only two magnetic coils due to the strong coupling between the roll and yaw motions. Some research work has been reported in the literature on combining magnetic torquers with other types of control actuators or with passive methods of stabilization. For instance, Guerman et al. [1], Ovchinnikov et al. [2] and de Ruiter [3] studied a spinning satellite equipped with three magnetic torque rods which can produce torque along the three axes of roll, pitch, and yaw. Recently, Wang et al. [4] used aerodynamic drag as a passive stabilizer method. To use this force, these authors chose the center of pressure and the centroid of the satellite as its design parameters. By selecting the proper positions of these centers, the attitude motions of a satellite can be kept bounded. They then proposed to utilize electromagnetic torque rods for asymptotic stabilization of the attitude angles of the system. Sofyali and Jafarov [5] and Chen et al. [6] added a reaction wheel to the actuation system composed of three magnetic torque rods for attitude stabilization. Forbes and Damaren [7] also considered magnetic torque rods and reaction wheels as control actuators. They proposed a method to obtain the part of the missing control torque to be produced by one, two, or three reaction wheels.

A fluidic type of actuator has been proposed in the literature that can be added to a system of magnetic torque rods. The literature on fluidic actuation is limited,

* Corresponding author. Tel.: +1 514 398 3098; fax: +1 514 398 7348.
*E-mail addresses:* nona.abolfathinobari@mail.mcgill.ca (N.A. Nobari), arun.misra@mcgill.ca (A.K. Misra).
[1] Tel.: +1 514 398 6288; fax: +1 514 398 7365.

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since the very early work reported by Maynard [8] in 1988. He proposed such an actuator to neutralize the disturbance torques exerted on spacecraft, ocean ships and all other suspended systems. This research was expanded and improved for spacecraft attitude control by Lurie and Schier [9] and Lurie et al. [10], who studied a more detailed system including different components, such as pumps, hydraulic actuators and valves. They indicated that fluid loops, which are a kind of fluidic actuators, can have any shape so as to fit into the available space in a satellite. Laughlin et al. [11] proposed a dual function system to measure the attitude and generate torque. This system consists of a permanent magnet and a fluid loop filled with a conductive fluid. The satellite attitude motion causes the fluid to rotate in the loop. However, since the fluid is conductive and subject to the magnetic field, the induced voltage can be used to determine the satellite attitude angles. On the other hand, a voltage is applied to the fluid, an electric field is produced whose interaction with the permanent magnetic field leads to a torque. This can be exploited to stabilize the satellite attitude angles. The common feature of the aforementioned studies is the idea of using a fluid–based controller; however, no feasibility analysis has been reported yet. Kelly et al. [12] tested the performance of a fluidic momentum controller (FMC) in an experimental set-up with two fluid loops whose axes of symmetry have the same direction. In this set-up two pumps were used in each loop to generate dual-direction of the flow. Kumar [13] examined a three-axis attitude controller using three orthogonal fluid loops. He studied the attitude motion of satellites equipped with three fluid rings in elliptic orbits. However, the dynamics model developed does not include all reaction moments transferred between the satellite and the fluid rings. Recently, Nobari and Misra [14] improved Kumar's model by developing a complete version. They developed a fault tolerant system using four fluid rings in a pyramidal configuration. The authors found that the voltage required for regulating the fluid is quite high. Hence, they suggested using fluid rings in small satellites.

The functionality of fluid rings is similar to that of reaction wheels; however, the former, in principle, can produce a larger torque compared with a reaction wheel of the same mass. The reason behind this is that the distribution of the mass of a fluid ring is close to its radius, while in a reaction wheel, the mass is sort of uniformly distributed over its whole area. Therefore, the moment of inertia of a fluid ring is larger than that of a reaction wheel with the same mass; hence, with identical angular accelerations, a fluid ring can produce larger torque compared with a reaction wheel. This promotes the idea of combining fluid ring actuators instead of reaction wheels with a system of magnetic torque rods.

In this paper, two magnetic torque rods and one fluid ring are considered as the system of actuation. First, the dynamical model of this system is derived. Then, a PID controller is designed to stabilize the attitude motion. Using the reconfiguration of effective matrices, the control torque is decomposed to determine the torque required to be produced by each actuator. Finally, to study the behaviour of the actuators in presence of failures, this case is examined for each actuator.

## 2. Dynamical modeling

To find the dynamical model, a micro-satellite consisting of two magnetic coils which produce torque along the roll and pitch axes and a fluid ring whose axis of symmetry is in the yaw direction is considered (Fig. 1). The center of mass of the set of the two coils and the fluid ring is assumed to coincide with that of the satellite. A reference frame located at the center of mass of the micro-satellite is defined as follows: $Y_0$ is perpendicular to the orbital plane, $Z_0$ is directed towards the center of the Earth, and $X_0$ is determined so as to obtain a right hand coordinate system. In the equilibrium configuration, the principal axes of the satellite are aligned with the reference frame. The orientation of the satellite at an arbitrary instant is described by three rotation angles $\theta_1$, $\theta_2$, and $\theta_3$ about $X$, $Y$, and $Z$ axes of the body frame, respectively. It should be pointed out that in this paper, vectors are denoted by small boldface letters, while matrices are denoted by boldface capital letters.

The equations of motion of the satellite and the fluid ring can be written as:

$$\mathbf{I_s}\dot{\boldsymbol{\omega}} + \boldsymbol{\omega} \times \mathbf{I_s}\boldsymbol{\omega} = \boldsymbol{\tau}_{\mathbf{gg}} + \boldsymbol{\tau}^{\mathbf{c}} + \boldsymbol{\tau}_{\mathbf{r}} \tag{1}$$

$$\mathbf{I_f}\left(\dot{\boldsymbol{\omega}} + \ddot{\boldsymbol{\beta}} + \boldsymbol{\omega} \times \dot{\boldsymbol{\beta}}\right) + \boldsymbol{\omega} \times \mathbf{I_f}\left(\boldsymbol{\omega} + \dot{\boldsymbol{\beta}}\right) = \boldsymbol{\tau}_{\mathbf{gg_f}} - \boldsymbol{\tau}_{\mathbf{r}} - \boldsymbol{\tau}_{\mathbf{p}} \tag{2}$$

where $I_s$, $I_f$ are the inertia matrix of the satellite and the fluid ring, respectively, $\omega$ is the satellite angular velocity, $\dot{\boldsymbol{\beta}} = [0 \quad 0 \quad \dot{\beta}]^T$ with $\dot{\beta}$ being the fluid angular velocity. Further, $\tau_{gg}$ and $\boldsymbol{\tau}_{\mathbf{gg_f}}$, are the gravity gradient torques exerted on the satellite and the fluid ring, respectively, while $\boldsymbol{\tau}^{\mathbf{c}}$ denotes the control torque. In the equation above $\boldsymbol{\tau}_{\mathbf{r}} = [m_1 \quad m_2 \quad \tau_f]^T$ is the reaction torque, where $m_1$ and $m_2$ are the reaction moments exerted by the fluid ring on the satellite, and $\tau_f$ is the fluid friction torque caused by the fluid shear stress. To find this torque, the shear stress should be integrated over the inner area of the ring that results in the fluid friction force. The control torque can then be calculated from this force.

The model adopted for the shear stress is:

$$\sigma = \frac{1}{8} f \rho r^2 \dot{\beta}^2 \tag{3}$$

where $r$ is the ring radius (shown in Fig. 1(b)), $\rho$ is the fluid density, and $f$ is the friction coefficient. For laminar

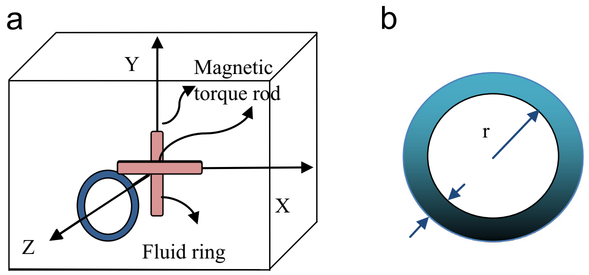


**Fig. 1.** (a) A satellite with the two magnetic coils and one fluid ring; (b) fluid ring.