Hysteresis Nutation Damper for Spin Satellite

Hamed Shahmohamadi Ousaloo*

Space Science Research Institute (SSRI), Tehran, Iran

Abstract: Hysteresis dampers are commonly used in Passive magnetic Attitude Control System (PACS). In PACS these rods produce a damping torque and reduce the satellite angular momentum and angular velocity. In this paper, a spin satellite was investigated which utilizes a passive magnetic damper consisting of magnetic hysteresis rods aligned with principal axis or spin axis of satellite and de-tumbling of the satellite, and the pure spin was achieved.

An analytical model was presented to analyze hysteresis damper and a numerical simulation was performed to obtain dynamic properties of the spin attitude. In addition, assuming a dynamic imbalance, attitude behavior and damper effect on the spin rate of satellite were analyzed. The behavior of this passive magnetic stabilized satellite was simulated from the initial post separation phase.

Keywords: Hysteresis dampers, nutation damper, spin stabilization, dynamic imbalance, passive magnetic attitude control system.

INTRODUCTION

Spin stabilization is a current method to stabilize the attitude of a satellite in space. With spin stabilization, the satellite gains a gyroscopic stiffness which makes its accurate control possible. Unwanted oscillations of the satellite must be damped out. Therefore, satellites are usually equipped with one or more nutation damping equipments. Nutation or damping unwanted angular rate can be achieved by active or passive attitude control. The active way is performed by counteracting the attitude determination using the respective sensors. This feedback system increases the power consumption, complexity, and risk of an active attitude determination and control system. But in the passive way, no external energy and additional sensors and actuators are required. However, a dynamic analysis of the satellite attitude with damper is required to obtain mass properties and arrangement of the damper inside the satellite without any damage.

Passive angular rate damping of the satellite using dampers was first performed in 1963 by Miles [1]. Many types of nutation dampers have been designed for spin-stabilized spacecrafts ranging in size from small to large satellites. Nutation dampers dissipate the kinetic energy of periodic rotations of a satellite in a specific direction. When energy is dissipated, the principal axis of the angular momentum vector becomes aligned with the largest moment of inertia. There are a variety of these including viscous ring dampers [2], ball in tube dampers [3], pendulum dampers [4], wheel dampers [5] and spring-mass-dampers [6].

The purpose of the present paper is to investigate the results of using hysteresis dampers as nutation dampers in spin satellite to dissipate kinetic energy. One way to acquire passive angular rate damping is simply adding magnetic hysteresis material. Passive magnetic stabilization is very attractive. It’s often used in small and light satellites to gain basic pointing or merely to avoid random and unpredictable tumble. Magnetic hysteresis rods are used to create passive de-tumble torques on the satellite. With this system, the rotation is damped about two un-spin axes. The main advantages of these dampers are their cost and reliability. But they are not programmable and their capability for attitude stabilization is limited.

DESIGN OF HYSTERESIS DAMPER FOR SPIN SATELLITE

To investigate hysteresis damper, a mathematical simulation of the hysteresis phenomenon and the satellite spin is required. Hysteresis dampers are currently used in passive magnetic attitude control system (PACS) [7-9]. PACS has two main components. One plays as permanent magnets which aligns the satellite with the earth magnetic field when it moves on its orbit. These permanent magnets are made of hard ferromagnetic materials and exchange the angular momentum of the satellite. The other component of PACS is a set of hysteresis rods. These rods produce a damping torque to enhance the energy dissipation property of soft ferromagnetic materials and reduce the satellite angular momentum by converting a part of the angular motion kinetic energy to heat; consequently, the angular velocity decreases. Hysteresis magnetic materials are much like permanent magnets in their function, except that their permeability is significantly higher. The most popular and current hysteresis magnetic material is hysteresis damper represented by an elongated rod made of soft-magnetic materials with heat treatment. Hysteresis materials have...
magnetic domains with random distribution resulting in a zero magnetic dipole. When subjected to an external field, the domains orient themselves. After removing the external field, the residual magnetization remains. In fact, depending on the material magnetic properties, it retains a magnetic dipole of some strength when the external magnetic field is removed.

The damping torque provided by the hysteresis rods in a magnetic field is obtained from:

\[ T = m \times B^e \]  

(1)

where \( B^e = [B_x, B_y, B_z] \) is the earth magnetic flux expressed in body-fixed frame relative to inertial frame, \( m \) is the magnetic moment of the hysteresis rod given by:

\[
m = \begin{bmatrix} m_h & 0 & 0 \end{bmatrix}
\]

\[
m_h = \frac{B_h V_h}{\mu_0}
\]

(2)

where \( m_h \) is the magnetic moment of hysteresis rod aligned with spin axis or \( \text{X} \) axis (Fig. 1), \( B_h \) is the magnetic flux induced in the rod, \( V_h \) is the volume of the rod, and \( \mu_0 \) is the permeability of free space.

![Spin Axis](image1.png)

Fig. (1). Hysteresis materials in spin satellite aligned with spin axis.

In this paper, hysteresis damper was investigated with two hysteresis rods aligned with the satellite spin axis (Fig. 1). In this configuration, the un-spin angular rate is damped passively and the nutation angle is dissipated.

The hysteresis rods produce variable magnetic dipoles (\( m_h \)) proportional to the earth magnetic field component along with the satellite spin axis. Hysteresis magnetic materials have significantly higher permeability than permanent magnets. Hence, affecting by a variable magnetic field, the hysteresis materials tend to show a dynamic realignment of micro-magnetic dipoles and a variation in magnetic domain boundaries. These changes cause frictional dissipation of energy at the molecular level. This phenomenon is known as hysteresis dissipation [13].

**MODEL OF MAGNETIC HYSTERESIS DAMPING**

The B-H curve of Fig. (2) represents a hysteresis loop at saturation state. This loop is generally defined by three magnetic hysteresis parameters. The material can be characterized by the maximum magnetization (saturation induction (\( B_s \))), the remaining magnetization after removal of the external field (remanence (\( B_r \))), and the magnetic field required to nullify the magnetization (coercive force (\( H_c \))). The way by which soft magnetic materials are magnetized depending on the external field can be displayed in a B-H curve.

This curve was shown in Fig. (2).

![Hysteresis Loop](image2.png)

Fig. (2). Hysteresis loop diagram.

Various mathematical models were presented for hysteresis rods in the literature [10, 11]. One of them was proposed by Kumar [11] based on an induced flux density developed by Flately [10] as:

\[
\gamma = \frac{1}{H_c} \tan\left(\frac{\pi B}{2B_s}\right)
\]

\[
B_h = \frac{2}{\pi} \tan^{-1}[\gamma(H \pm H_c)]
\]

(3)

where \( \gamma \) is a constant value and \( H \) is the component of magnetic field strength aligned with the hysteresis rod. A positive value for \( \text{Hc} \) is used if \( dH/dt < 0 \) and a negative value of \( -\text{Hc} \) is used if \( dH/dt > 0 \).

The magnetic material PERMENORM 5000 H2 is used in all hysteresis rod dampers because it produces high hysteresis losses and is unaffected by pace environment over long periods of time. Some properties of this material are:

\[
H_c[A/m]=5, B_s[T]= 1.55, B_r[T]= 0.755, \rho [g/cm^3]= 8.25
\]

**HYSTERESIS DAMPER AND SPIN DYNAMIC CONDITIONS**

Consider the rotational properties of a rigid satellite equipped with hysteresis dampers. First, we assume that the satellite is dynamically balanced and the body-fixed coordinates are selected to be coincident with the spacecraft principal axes. The dynamic properties of spacecraft are given by:

\[
dL / dt = N_p - \omega_m \times L_p
\]

(4a)
A quaternion satisfied the constraint
\[ q^T q = 1 \]
where \( q = (\varepsilon_1, \varepsilon_2, \varepsilon_3, \eta_4) \) for attitude representation can be derived from the Euler axis, \( e \), and principal rotation angle, \( \theta \), as follows:
\[
\begin{align*}
\varepsilon_1 &= e_1 \sin(\theta/2) \\
\varepsilon_2 &= e_2 \sin(\theta/2) \\
\varepsilon_3 &= e_3 \sin(\theta/2) \\
\eta_4 &= \cos(\theta/2)
\end{align*}
\]

A quaternion satisfied the constraint \( q^T q = 1 \):
\[ \eta_4^2 + \varepsilon_1^2 + \varepsilon_2^2 + \varepsilon_3^2 = 1 \]

Hysteresis dampers utilize the magnetic rate damping to establish a desired spin rate about the spin axis or X axis and remove transverse rates about the Y and Z axes. A Lyapunov function can be used in the form:
\[ V = \frac{1}{2} (\omega - \omega_s)^T l (\omega - \omega_s) \]

where \( \omega_s = [\Omega \ 0 \ 0] \)

where \( \omega \) is the rate vector, \( \omega_s \) is the desired rate vector about X axis, and \( \Omega \) is the acquisition spin rate. It can be shown that if the magnetic hysteresis is selected based on Eq. (2), the time variation rate of \( V \) is negative for an axisymmetric inertia matrix of the form \( l = \text{diag}(I_1, I_1, I_1) \). It was observed in Fig. (3) that the time rating of Lyapunov function is negative throughout the system damping via hysteresis rods.
Consequently, for the nutation angle, we have:

\[ \theta = \tan^{-1}\left(\frac{\sqrt{\chi^2 + \chi_1^2}}{\chi_2}\right) = \tan^{-1}\left(\frac{\sqrt{(I_{xx}\omega_x - I_{xy}\omega_y - I_{xz}\omega_z)^2 + (I_{yy}\omega_y - I_{yz}\omega_z - I_{yx}\omega_x)^2}}}{I_{xx}\omega_x - I_{xy}\omega_y - I_{xz}\omega_z}\right) \]

where \( \chi = [\chi_x, \chi_y, \chi_z] \) is the angular momentum expressed in body-fixed frame relative to inertial frame.

SIMULATION RESULTS

An effective attitude dynamic design begins with an analysis of external torques by the satellite. The satellite experiences these torques at the height of 500 kilometers. The simulation was for an oblate spin satellite with the following mass properties: bus mass \( m_b = 40 \text{ kg} \), with principal moments of inertia (kg.m\(^2\)) of \( I_{xx} = 0.750 \), \( I_{yy} = 0.735 \), \( I_{zz} = 0.725 \). Under dynamically unbalanced situation, the product of inertia is \( I_{xy} = I_{xz} = I_{yz} = 0.01 \); these amounts are zero for balanced satellite. The IGRF model for the earth magnetic field is incorporated into the computation of the magnetic torques due to the hysteresis rods. Two hysteresis rods were assumed to be identical, with volume \( V_h = 8.75 \times 10^{-7} \text{ m}^3 \) and hysteresis constants as stated earlier. The initial angular velocity at post separation phase was \( \omega(0) = [30, 30, 30] \text{ deg/sec} \).

A complete simulation of the satellite during the first 16 orbits after separation was illustrated in Figs. (4-8), including plots of the body angular rates (\( \omega_x, \omega_y, \omega_z \)) for dynamically balanced satellite (Figs. 4-6) and unbalanced satellite (Figs. 7, 8). According to Figs. (4-6), when the satellite is principally spinning around its long axis or x axis, damping of un-spin angular velocity is performed exactly and the spin rate is remained constant (Fig. 5). But in unbalanced satellite not only un-spin angular velocities are damping, but also spin rate is decreased (Figs. 7, 8).

CONCLUSION

This paper presented a hysteresis nutation damper for the dynamically balanced and unbalanced spinning satellites. The spin and hysteresis rods dynamic conditions were modeled. This model is a passive solution to nutation damping in spin satellites while the hysteresis rods are aligned with the satellite spin axis. Therefore, as a result of
Fig. (8). All angular velocities damping in the dynamically unbalanced spin satellite (Spin rate is dissipated).

these simulations, hysteresis damper is not appropriate for dynamically unbalanced spin satellite because the spin axis is not aligned with satellite angular momentum. Consequently, in order to use hysteresis rods as nutation damper, it’s necessary to dynamically balance the satellite during the ground tests.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

ACKNOWLEDGEMENTS

Declared none.

REFERENCES