

## Effectiveness Of Large Booms As Nutation Dampers For Spin Stabilized Spacecraft

F. O. Eke\*

Department of Mechanical,  
Aeronautical and Materials Engineering  
University of California  
Davis, CA 95616

### ABSTRACT

This paper discusses the issue of using long slender booms as pendulous nutation damping device on spinning spacecraft. Motivation for this work comes from experience with the Galileo spacecraft, whose magnetometer boom also serves as passive nutation damper for the spacecraft. Performance analysis of a spacecraft system equipped with such a device indicates that the nutation time constant of such systems are relatively insensitive to changes in the damping constant of the device. However, the size and arrangement of such a damper raises important questions concerning spacecraft stability in general.

### INTRODUCTION

Most spin stabilized spacecraft are equipped with passive nutation damping devices that limit spacecraft nutation through on-board energy dissipation. The design of these devices is based on well established stability criteria for spinning bodies.<sup>1-4</sup> When disturbed slightly from its position of stable spin, a spacecraft with internal energy dissipation will recover faster than one without energy

---

\* Assistant Professor

dissipation. This has led to the design of several passive devices that are triggered into dissipating energy on board of a spacecraft anytime that the spacecraft attitude motion is disturbed. Such devices have included simple mass-spring-dashpot systems, damped compound pendulum, viscous fluid in ring-shaped tubes, etc... The Galileo spacecraft features a passive nutation damper that differs markedly from any that has been flown to date. As shown in Fig.1, this dual-spin spacecraft consists essentially of a rotor, carrying a high gain antenna and three long booms, and a stator section that houses a probe and carries the scan platform containing most of the imaging instruments. The rotor is connected to the stator through a spin bearing assembly that allows one degree of freedom of relative motion that is controlled by the "clock" control loop. The ratio of the rotor spin inertia to the vehicle transverse inertia is greater than one(1.4), so that the spacecraft spin axis is also its axis of maximum inertia. The spacecraft's longest boom - its science/magnetometer boom - is also utilized as a passive nutation damper by connecting it to the rotor bus through a one degree of freedom hinge and a torsional spring and damper system, as shown schematically in Fig.2. Although this damper is of the pendulous type, its length (8.6m) far exceeds that of any such damper used in past missions. Furthermore, the mass center of the boom is outboard of its pivot point. This, again, is unusual for pendulum dampers.

In the remaining part of this paper, the effectiveness of this design is explored and compared with that of traditional dampers. This is done essentially by examining the shape of the damper time constant versus damping constant curve as well as by studying the overall attitude dynamics of the spacecraft in the presence of such a large boom.

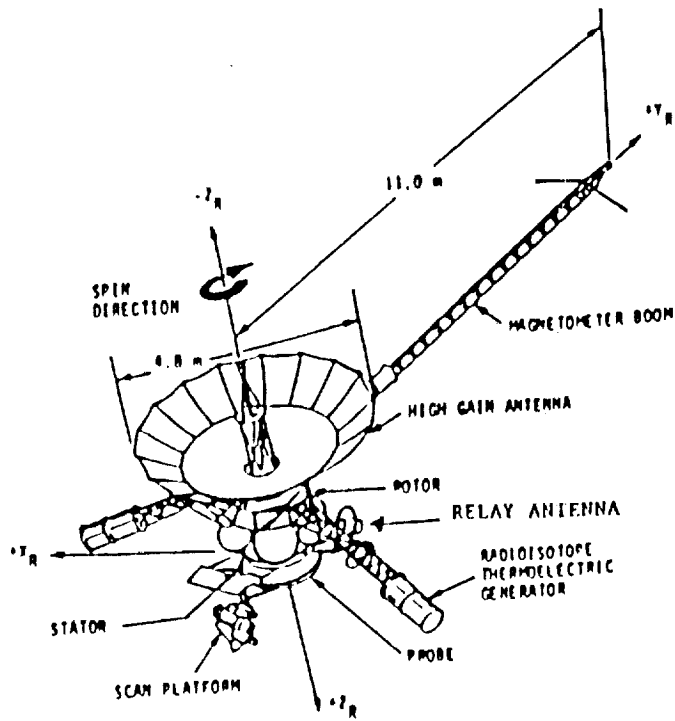


Fig. 1 Galileo Spacecraft

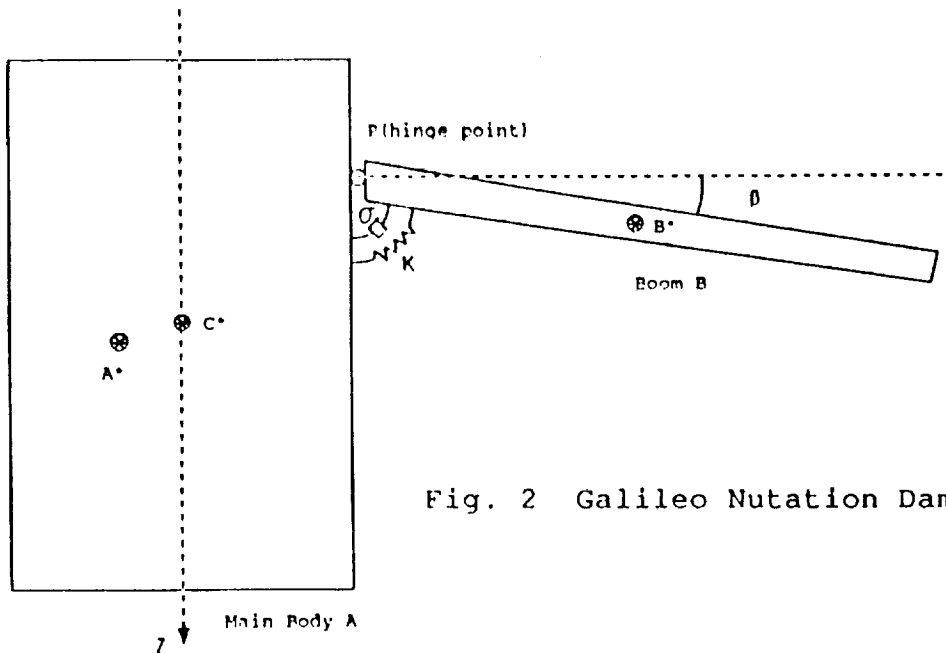


Fig. 2 Galileo Nutation Damper System

## EQUATIONS OF ATTITUDE MOTION

To derive the dynamical equations of attitude motion of the spacecraft, the model shown in Fig.3 is used. The dual-spin nature of the spacecraft is ignored, and the system is assumed to be made up of a main rigid body A and a boom B.  $A^*$  and  $B^*$  are mass centers of A and B respectively, and  $S^*$  is the mass center of the combined system. The following simplifications are also made:

- $S^*$  lies on the spin axis Z of the spacecraft and remains fixed in body A at all times;
- $A^*$ ,  $B^*$  and  $S^*$  all lie on a plane containing the Z axis;
- when  $\beta = 0$ , the central principal axes of the system for  $S^*$  are parallel to  $a_1, a_2$ , and  $a_3$ ;
- $b_1, b_2, b_3$  are parallel to central principal axes of B for  $B^*$ , and, for body B,  $I_1 = I_3$ , while  $I_2 = 0$ , where I indicates moment of inertia.

The equations of attitude motion of this system, as derived using AUTOLEV<sup>6,7</sup>, are:

$$\begin{aligned}
 & \left\{ [(L_B \sin \beta + z_0)^2 + (L_B \cos \beta + y_0)^2] m_B + (y_A^2 + z_A^2) m_A + (I_1^A + I^B) \right\} \ddot{u}_1 + \\
 & \left\{ [(L_B \sin \beta + z_0) L_B \sin \beta + (L_B \cos \beta + y_0) L_B \cos \beta] m_B + I^B \right\} \ddot{u}_4 - \\
 & \quad \left\{ [(u_1 + u_4) L_B \sin \beta + z_0 u_1] u_1 + \right. \\
 & (L_B u_2 \sin \beta - L_B u_3 \cos \beta + z_0 u_2 - y_0 u_3) u_2 + (u_1 + u_4) L_B \sin \beta u_4 \left. \right\} (L_B \cos \beta + y_0) m_B + \\
 & \quad \left\{ -[(u_1 + u_4) L_B \cos \beta + y_0 u_1] u_1 + [L_B (u_2 \sin \beta - u_3 \cos \beta) + z_0 u_2 - y_0 u_3] u_3 - \right. \\
 & \quad (u_1 + u_4) L_B \cos \beta u_4 \left. \right\} (L_B \sin \beta + z_0) m_B - \left\{ [(z_A u_2 - y_A u_3) u_3 - y_A u_1^2] z_A + \right. \\
 & \quad \left. [(z_A u_2 - y_A u_3) u_2 + z_A u_1^2] y_A \right\} m_A + (u_2 \cos \beta + u_3 \sin \beta) (u_3 \cos \beta - u_2 \sin \beta) I^B - \\
 & \quad (I_2^A u_2 + I_{23}^A u_3) u_3 + (I_{23}^A u_2 + I_3^A u_3) u_2 = 0
 \end{aligned} \tag{1}$$

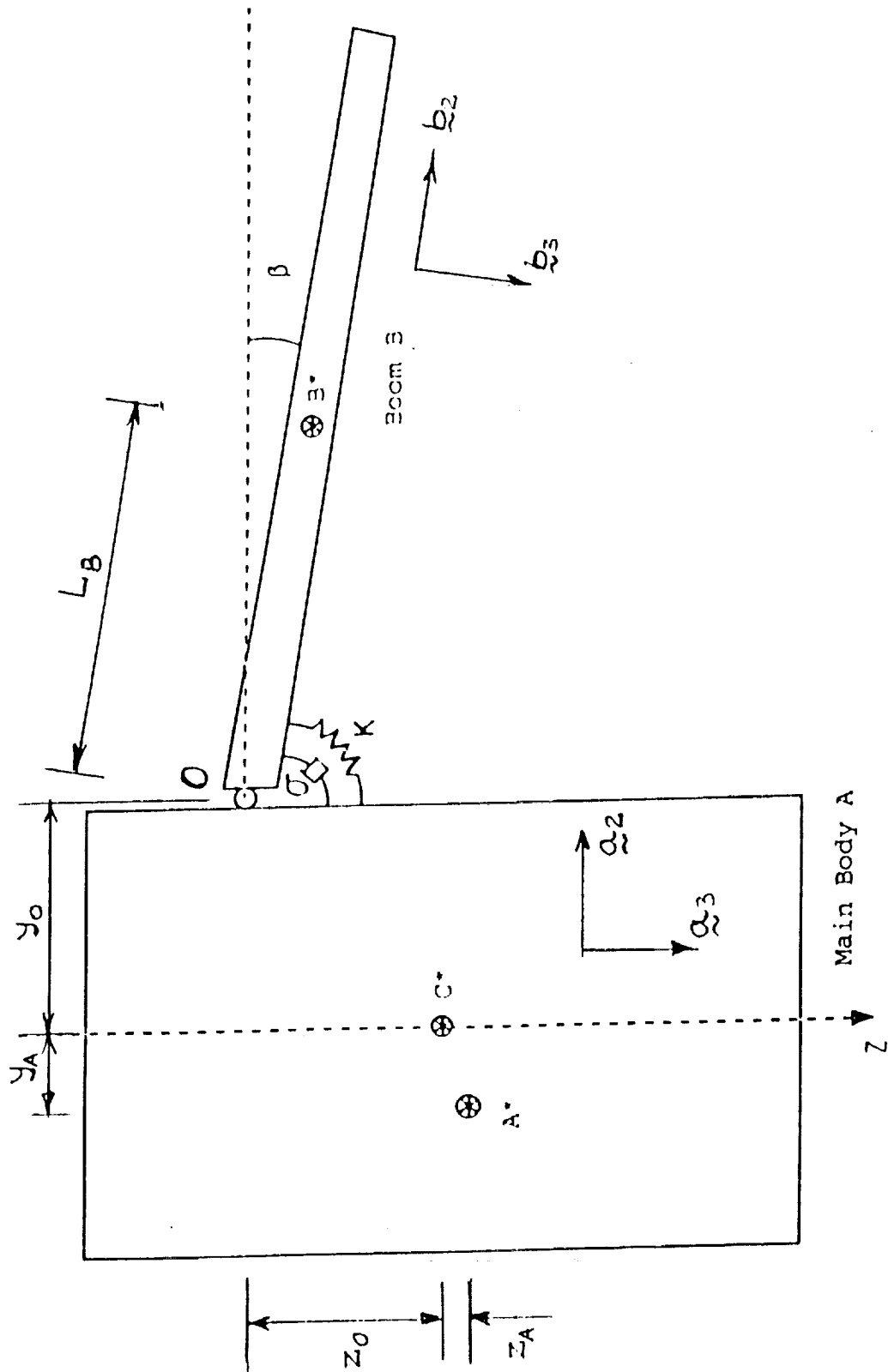


Fig. 3 Spacecraft Model

$$\begin{aligned}
& [(L_B \sin \beta + z_0)^2 m_B + (I_2^A + I^B \sin^2 \beta) + m_A z_A^2] \ddot{u}_2 - \\
& [(L_B \cos \beta + y_0)(L_B \sin \beta + z_0) m_B + I^B \sin \beta \cos \beta - I_{23}^A + m_A y_A z_A] \ddot{u}_3 + \\
& \{[(u_1 + u_4) L_B \cos \beta + y_0 u_1] u_2 + [(u_1 + u_4) L_B \sin \beta + z_0 u_1] u_3 + \\
& (u_2 \cos \beta + u_3 \sin \beta) L_B u_4\} (L_B \sin \beta + z_0) m_B + \{[(u_1 + u_4) u_3 - u_1 u_3] \sin \beta + \\
& [(u_1 + u_4) u_2 - u_1 u_2] \cos \beta\} I^B \sin \beta + (u_2 \cos \beta + u_3 \sin \beta) (u_1 + u_4) I^B \sin \beta - \\
& (I_{23}^A u_2 + I_3^A u_3) u_1 + (y_A u_1 u_2 + z_A u_1 u_3) m_A z_A + I_1^A u_1 u_3 = 0
\end{aligned} \tag{2}$$

$$\begin{aligned}
& [(L_B \cos \beta + y_0)(L_B \sin \beta + z_0) m_B + I^B \sin \beta \cos \beta - I_{23}^A + m_A y_A z_A] \ddot{u}_2 - \\
& [(L_B \cos \beta + y_0)^2 m_B + I^B \cos^2 \beta + I_3^A + m_A y_A^2] \ddot{u}_3 + \\
& \{[(u_1 + u_4) L_B \cos \beta + y_0 u_1] u_2 + [(u_1 + u_4) L_B \sin \beta + z_0 u_1] u_3 - \\
& L_B \cos \beta u_2 u_4 + L_B \sin \beta u_3 u_4\} (L_B \cos \beta + y_0) m_B + \{[(u_1 + u_4) u_3 - u_1 u_3] \cos \beta \sin \beta + \\
& [(u_1 + u_4) u_2 - u_1 u_2] \cos^2 \beta\} I^B + (u_2 \cos \beta + u_3 \sin \beta) (u_1 + u_4) I^B \cos \beta - \\
& (I_{23}^A u_3 + I_2^A u_2) u_1 + (y_A u_1 u_2 + z_A u_1 u_3) m_A y_A + I_1^A u_1 u_2 = 0
\end{aligned} \tag{3}$$

$$\begin{aligned}
& \{[(L_B \sin \beta + z_0) L_B \sin \beta + (L_B \cos \beta + y_0) L_B \cos \beta] m_B + I^B\} \dot{u}_1 + (I^B + m_B L_B^2) \dot{u}_4 - \\
& \{[(u_1 + u_4) L_B \sin \beta + z_0 u_1] u_1 + (L_B \sin \beta u_2 - L_B \cos \beta u_3 + z_0 u_2 - y_0 u_3) u_2 + \\
& (u_1 + u_4) L_B \sin \beta u_4\} L_B \cos \beta - \{[(u_1 + u_4) L_B \cos \beta + y_0 u_1] u_1 - \\
& (-L_B u_3 \cos \beta + L_B u_2 \sin \beta + z_0 u_2 - y_0 u_3) u_3 + \\
& (u_1 + u_4) L_B \cos \beta u_4\} L_B \sin \beta\} m_B + (u_2 \cos \beta + u_3 \sin \beta) (u_3 \cos \beta - u_2 \sin \beta) I^B + \\
& k \beta + \sigma u_4 = 0
\end{aligned} \tag{4}$$

where  $u_i$  ( $i = 1, 2, 3$ ) are the components of the angular velocity of A along  $\mathbf{a}_i$ ,  $u_4 = \beta$ ,  $m$  represents mass,  $I$  represents moment of inertia,  $k$  is spring stiffness,  $\sigma$  is damping constant, and the dimensions  $y_0, z_0, y_A, z_A, L_B$  are as shown in Fig. 3.

## NUTATION DAMPER TIME CONSTANT

A known equilibrium point of the system corresponds to the pure spin condition. That is the solution

$$u_1 = u_2 = 0, \quad u_3 = \Omega \text{ (const.)}, \quad u_4 = 0, \quad \text{and } \beta = 0.$$

This solution does satisfy Eqs.(1-4) provided that

$$I_{23}^A = m_A z_A y_A + m_B z_0 (L_B + y_0) \quad (5)$$

a condition that is indeed satisfied by the inertia related simplifying assumptions given earlier. When the full nonlinear dynamical equations given as Eqs(1-4) are linearized about the pure spin solution, the result is a set of first order differential equations that has the form

$$B \dot{x}^T = A x^T \quad (6)$$

where

$$x = [u_1 \quad u_2 \quad u_4 \quad \beta] \quad (7)$$

and A and B are 4 by 4 matrices with the following elements:

$$A_{11} = A_{13} = A_{22} = A_{23} = A_{24} = A_{31} = A_{41} = A_{42} = A_{44} = 0 \quad (8)$$

$$A_{12} = [m_B (L_B + y_0)^2 + m_A (y_A^2 - z_A^2) + I^B - I_2^A + I_3^A] \Omega \quad (9)$$

$$A_{14} = -[I^B + m_B L_B (L_B + y_0)] \Omega^2 \quad (10)$$

$$A_{21} = -[I_1^A - I_3^A m_A z_A^2 + m_B z_0^2] \Omega \quad (11)$$

$$A_{32} = -[I^B + m_B L_B (L_B + y_0)] \Omega \quad (12)$$

$$A_{33} = -\sigma, \quad A_{43} = 1 \quad (13)$$

$$A_{34} = -[m_B L_B (L_B + y_0) \Omega^2 + k] \quad (14)$$

$$B_{11} = \{I_1^A + I^B + m_A (y_A^2 + z_A^2) + m_B [(L_B + y_0)^2 + z_0^2]\} \quad (15)$$

$$B_{12} = B_{14} = B_{21} = B_{23} = B_{24} = B_{32} = B_{34} = B_{41} = B_{42} = B_{43} = 0 \quad (16)$$

$$B_{13} = [I^B + m_B L_B (L_B + y_0)] \quad (17)$$

$$B_{22} = [I_2^A + m_A z_A^2 + m_B z_0^2] \quad (18)$$

$$B_{31} = [I^B + m_B L_B (L_B + y_0)] \quad (19)$$

$$B_{33} = I^B + m_B L_B^2 \quad (20)$$

$$B_{44} = 1 \quad (21)$$

The eigenvalues of the matrices A and B are found to have negative real parts for inertia property values corresponding to all mission phases of the spacecraft. Hence, the pure spin solution is a stable solution. The nutation angle time constant is the negative reciprocal of the eigenvalue corresponding to  $u_1$  or  $u_2$ .

## RESULTS

Fig. 4 shows Galileo's nutation angle time constant plotted against the damping constant of the passive nutation damping device on board. The case shown corresponds to a damper spring stiffness of 335 N.m/rad, and spacecraft inertia property values near the beginning of the mission.

Two important facts emerge from this plot. First, there is an optimum damping constant corresponding to a given spring stiffness. The most remarkable thing about the curve shown is the fact that it is so flat; especially near the



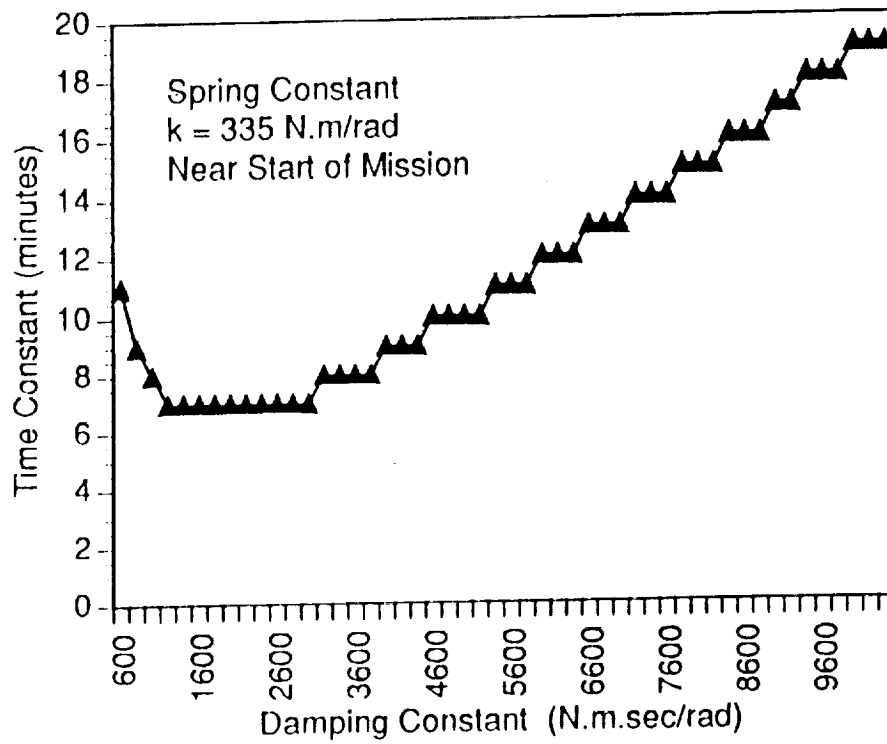


Fig. 4 Time Constant Vs. Damping Constant

minimum time constant value. This means that there is a wide range of values of  $\sigma$  for which the time constant changes very little. This result is in great contrast with what obtains for traditional passive dampers, where such plots are not flat at all, and "tuning" of the damper is almost always a necessity if one desires reasonably small time constants. This relative insensitivity of the time constant to  $\sigma$  is particularly appropriate for interplanetary missions. This is because the viscosity of damper fluids is generally very sensitive to temperature, and, therefore, the damping constant can be expected to vary widely during a long interplanetary flight that takes a spacecraft through varied environments. It is thus advantageous to have a damper, whose performance will not be degraded by the inevitable fluctuations in damper fluid viscosity.

#### CONCLUSION

As exemplified by the design and performance analysis of the Galileo passive damper system, the use of long booms as nutation damper for spin stabilized spacecraft introduces a new and important advantage over traditional damping devices. It renders the system nutation angle time constant practically insensitive to the device damping constant, thereby drastically reducing the need for "tuning" of such dampers. The main disadvantage of such a large device is that it becomes an important factor in spacecraft stability. Furthermore, because of the small relative damper displacements that are to be expected from this design, factors such as stiction become important in the evaluation of the damper's performance, and may impose thresholds on the amount of nutation that can be damped out.

## REFERENCES

1. Likins, P. W., "Attitude Stability Criteria for Dual-Spin Spacecraft," J. Spacecraft and Rockets, 4 (No. 12), (1967).
2. Mingori, D. L., "Effects of Energy Dissipation on the Attitude Stability of Dual-Spin Satellites," AIAA J., 7 (no. 1), (1969).
3. Auelmann, R. R., and Lane, P. T., "Design and Analysis of Ball-in-Tube Nutation Dampers," Proc. of the Symposium on Attitude Stabilization and Control of Dual-Spin Spacecraft, 1968..
4. Bainum, P. M., Fuechsel, P. G., and Mackison, D. L., "Motion and Stability of a Dual-Spin Satellite with Nutation Damping," J. Spacecraft and Rockets, 7 (No. 6), (1970).
5. Yeates, C. M. and Clarke, T. C., "The Galileo Mission to Jupiter," Astronomy, 10 (No. 1), 1982.
6. Schaechter, D. B. and Levinson, D. A., "Interactive Computerized Symbolic Dynamics for the Dynamicist," J. of the Astronautical Sciences, 36 (No. 4), 1988.
7. Levinson, D. A. and Kane, T. R., "AUTOLEV - A New Approach to Multibody Dynamics," Multibody Systems Handbook, Springer Verlag, Berlin, 1990.

