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Passive Nutation Control of Spinning Spacecraft Through the Use of Multiple Booms

F. O. Eke*
University of California, Davis, California 95616
A. Harvey†
Toyo Tanso USA, Inc., Troutdale, Oregon 97060
and
E. M. Eke‡
California State University, Sacramento, California 95819

Introduction

SEVERAL of the spacecraft in use today are spin-stabilized and are thus equipped with some form of nutation control system. Spacecraft nutation control devices can be active or passive. Passive nutation damping systems limit spacecraft nutation through onboard energy dissipation, and the design of such systems is based, for the most part, on well-established attitude stability criteria for spinning bodies.[1,2] When disturbed slightly from its position of stable spin, a spacecraft with internal energy dissipation will, in general, regain its original orientation faster than one without energy dissipation. This fact has led to the design of several passive devices that are triggered into dissipating energy onboard of a spacecraft anytime that the spacecraft attitude motion is disturbed. Such devices have included simple mass-spring-dashpot systems, damped physical pendulum, viscous fluid in ring-shaped tubes, etc.[3–5]

Spacecraft systems often include several rod-like appendages or booms attached to the main spacecraft bus, which serve various purposes during the vehicle's mission. In this study it is proposed to use two such booms on a given spacecraft for nutation control purposes. The idea is to replace the usual rigid attachment of such booms to the bus, with a one-degree-of-freedom hinge, together with a torsional spring and damper system. This effectively converts each boom into a pendulous damper for the spacecraft. Such arrangement differs markedly from the usual design of pendulous dampers in that the mass center of each boom would be outboard of the pivot point and the length would substantially exceed that of traditional pendulum dampers.

Motivation for this work comes from experience with the Galileo spacecraft,[6,7] where one such boom—its magnetometer boom—was used successfully as pendulous damper[8] to control spacecraft nutation. One area of concern for Galileo's single-boom damper design is stiction because of the small boom motions that are to be expected from such a damper design. Another is the possible deleterious effect of the dynamic imbalance that can result from the combination of spacecraft spin motions and boom deflection during thrusting, a phenomenon often referred to in the literature as wobble amplification.[9] In the case of Galileo, requirements on stiction were met without difficulty; however, wobble amplification was thought to pose enough danger to warrant the inclusion of a wobble control algorithm[7] in the attitude and articulation control subsystem.

The objective of this work is to explore the possibility of using more than one long pendulous boom as nutation damping device for spinning spacecraft. Specifically, we wish to study the effectiveness of using two identical pendulous booms arranged symmetrically with respect to the spacecraft's main bus as shown schematically in Fig. 1. There are two main potentially advantageous features of the proposed design. First, the symmetry of the arrangement eliminates, or at least drastically reduces, the imbalance or wobble amplification problem. The design also introduces some degree of redundancy in the nutation control system.

Equations of Attitude Motion

The physical system of interest is shown schematically in a general configuration in Fig. 1. A is the spacecraft's main bus, and B and C are booms that are connected to A through one-degree-of-freedom hinges. Stiffness and damping at the hinges are represented by the torsional spring and damper systems shown. Assuming that 1) A, B, and C are all rigid bodies; 2) A is uniform, homogeneous, and axisymmetric, with mass center at A^*; 3) B and C are identical, uniform, and homogeneous, with mass centers at B^* and C^*, respectively; the equations of attitude motion of the system are derived using the symbol manipulator software AUTOLEV.[10] The same software is also used to linearize these equations about the solution of pure spin, that is, a motion in which A spins about the zz' axis, and $\beta = \theta = 0$. The resulting equations are

$$\begin{aligned}&\left\{I_A + 2I + 4m_A P^2 Z^2 + 2m[(L+Y)^2 + Z^2(2P-1)^2]\right\}\dot u_1\\&\quad + [I + mL(L+Y)](\dot u_4 + \dot u_5) = \Omega\left\{I_A + 2J + 4m_A P^2 Z^2\right.\\&\quad \left. - 2I - J_A - 2m[(L+Y)^2 - Z^2(2P-1)^2]\right\}u_2\\&\quad + \Omega^2[J - I - mL(L+Y)](\beta + \theta) \qquad (1)\end{aligned}$$

$$\begin{aligned}&\left[I_A + 2J + 4m_A P^2 Z^2 + 2mZ^2(2P-1)^2\right]\dot u_2\\&\quad = -\Omega\left[I_A - J_A + 4m_A P^2 Z^2 + 2mZ^2(2P-1)^2\right]u_1\\&\quad - J\Omega(u_4 + u_5) \qquad (2)\end{aligned}$$

$$\begin{aligned}&[I + mL(L+Y)]\dot u_1 + \left[I - m_A L^2 P^2 + mL^2(1-2P^2)\right]\dot u_4\\&\quad + mL^2 P \dot u_5 = \Omega[J - I - mL(L+Y)]u_2 - \sigma u_4\\&\quad -\{K + \Omega^2[I - J + mL(L+Y)]\}\beta \qquad (3)\end{aligned}$$

$$\begin{aligned}&[I + mL(L+Y)]\dot u_1 + mL^2 P \dot u_4 + \left[I - m_A L^2 P^2\right.\\&\quad \left. + mL^2(1-2P^2)\right]\dot u_5 = \Omega[J - I - mL(L+Y)]u_2\\&\quad - \sigma u_5 - \{K + \Omega^2[I - J - mL(L+Y)]\}\theta \qquad (4)\end{aligned}$$

and

$$\dot u_3 = 0 \qquad \text{or} \qquad u_3 = \Omega = \text{const} \qquad (5)$$

where, in addition to the quantities shown in Fig. 1, I_A and J_A are, respectively, the transverse and spin central moments of inertia of A; I, and J are the corresponding inertia scalars for B or C; m_A is the mass of A; m is the mass of B or C; Ω is the constant spin rate of A under pure spin condition; and

$$P = m/(m_A + 2m) \qquad (6)$$

Furthermore, the generalized speeds u_i ($i = 1, 2, 3$) are the $\boldsymbol{a}_1, \boldsymbol{a}_2, \boldsymbol{a}_3$ scalar components of the inertial angular velocity of A, and u_4 and u_5 represent the respective angular speeds of B and C relative to the main body A. The preceding linearized dynamical equations can be supplemented with the kinematical differential equations

$$\dot\beta = u_4, \qquad \dot\theta = u_5 \qquad (7)$$

The stability of the pure spin solution can be studied through eigenvalue analysis and leads straightforwardly to the determination of the time constant of the damper system.

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*Associate Professor, Department of Mechanical and Aeronautical Engineering.
†Development Engineer, Engineering Department–Development Section, 2575 N.W. Graham Circle.
‡Professor, Department of Mechanical Engineering.

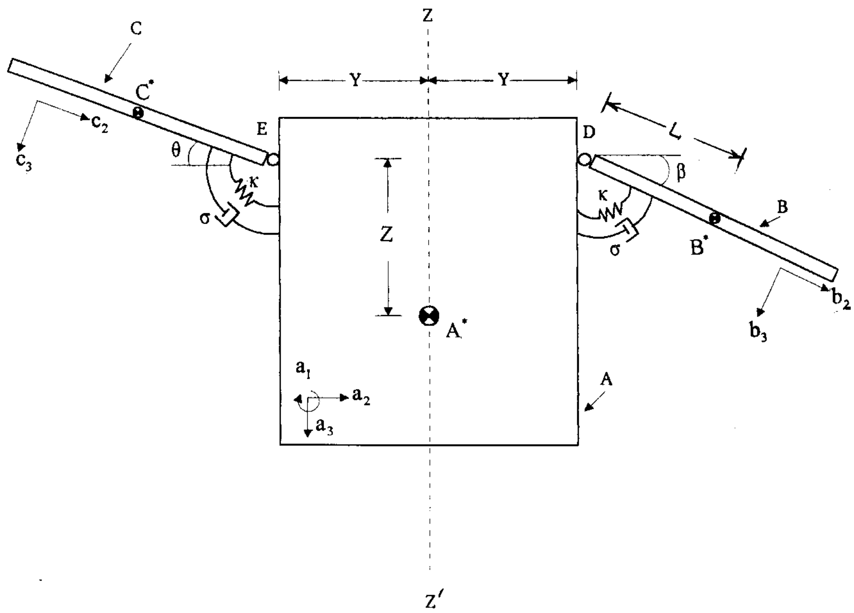

Fig. 1 Dual-pendulum damper system.

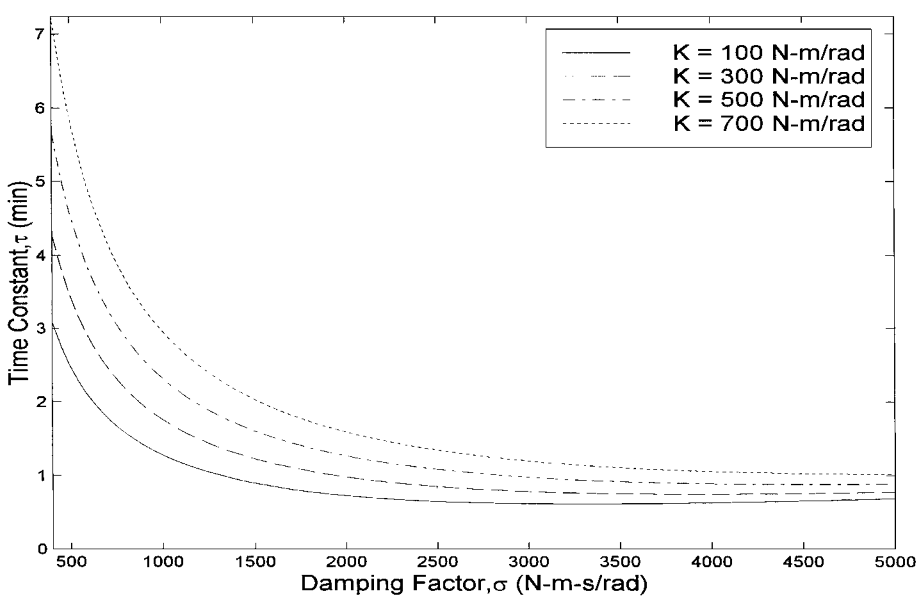

Fig. 2 Time constant vs damping factor; $\Omega = 1.0$ rad/s.

Results

To evaluate the performance of the passive nutation damper system under study, damper time constant values for system parameters that are representative of spacecraft of the Galileo class were determined. Two sets of parameter values were used for most of the study; one represents the beginning phase of a typical mission, when propellant tanks are full and the spacecraft is heavy, and the other is representative of a light spacecraft that is close to the end of its mission, with the propellant nearly depleted.

First, we examined how changes in damping factor at the boom hinges affect the rate at which the system would damp out nutation. Figure 2 shows plots of the nutation damper time constant as function of damping factor σ for four values of the torsional spring stiffness K and heavy spacecraft spinning at the rate of 1 rad/s. Similar results were obtained for the same spacecraft at 0.3 rad/s and the light spacecraft at 0.3 and 1 rad/s. We observe, as has been observed with other passive nutation damping devices, that there appears to exist an optimum value of damping factor for a given spring stiffness. We also notice the remarkable fact that the time constant is relatively insensitive to parameter changes. This result is in great contrast with what one obtains for traditional passive dampers where "tuning" of the damper is almost always a necessity if one desires reasonably small time constants. The proposed design would be particularly appropriate for long interplanetary flights that usually take a spacecraft through varied environments where damper parameters can vary widely.

Next, the effect of the ratio of the mass of the booms to that of the spacecraft on damper performance was explored. This was done by varying the boom to system mass ratio ρ while keeping the length of each boom constant and maintaining the spring stiffness at the same value throughout. The assumption was that the change in boom mass could be accomplished in practice by using different types of material, either heavy or light material. In this case we found that as the ratio ρ was increased from 0.05 to 0.3 time constant values decreased, at first, for all values of the damping factor. But this trend only held for as long as the mass ratio remained below some limiting value ρ_L. As ρ was increased beyond ρ_L, the trend reversed, and higher values of ρ led to a degradation in damper performance. It turned out that the value ρ_L at which trend reversal occurred decreased with spin rate. We conclude that increasing the mass of the booms as compared to that of the whole spacecraft is beneficial up to a point, but can substantially degrade performance if a certain limit is exceeded. The effect of boom inertia change that is not a result of change in mass was also studied. The mass of each boom was kept constant at some value, and the length of the boom was varied, thus resulting in an inertia change. The results obtained here were similar to those observed for boom mass change. Damper performance can be greatly enhanced by using very long booms, but there is a limit to admissible boom length both from the practical point of view as well as the point of view of system performance. We also found that changes in boom length had a much more dramatic impact on damper performance than changes in boom mass.

Finally, we assessed the ability of one of the booms to reduce nutation in the event of a malfunction of the other. As expected, one boom was not as effective as the two-boom system in damping out nutation. Nutation damper time constant values increased for each given spring stiffness and for all values of the damping factor. However, the performance still remained quite reasonable. For example, assuming a spring stiffness of 300 N-m/rad and a damping factor of 2500 N-m-s/rad (values close to those used on the Galileo spacecraft), the time constant only increased to about 3 min when only one damper was functional. It is thus apparent that spacecraft nutation can still be kept under control even if one of the boom dampers should malfunction.

Conclusion

This study is motivated by the fact that many spacecraft carry rod-like attachments, which are usually rigidly connected to the spacecraft's main bus and which are used as antennas or for various other purposes during the spacecraft's mission. The study investigates the idea of converting any two of such rod-like elements into pendulous dampers for the purpose of controlling nutation for spinning spacecraft. The study is restricted to the case where the two booms that are converted to dampers are identical and placed symmetrically with respect to the spacecraft's main body and where the rigid inner body is a major axis spinner. The results obtained demonstrate that the proposed arrangement has great merit for several reasons. The rate at which nutation is damped by the proposed dual-damper system is found to be relatively insensitive to such system parameters as the device's damping factor. This is a major advantage over traditional dampers, for which tuning is normally a necessity. From a practical point of view, the fact that the damping factor can vary widely without much degradation in performance can lead to a much simpler physical device for the system's dashpot. For example, there will be no need to include elaborate temperature control systems that would ordinarily be needed to keep the temperature (and thus the damping factor) of the damper fluid within a tight band.

This study also shows that the performance of the damper system is influenced by the length of the booms, as well as by the ratio of the mass of the booms to that of the whole spacecraft. Each of these has a limiting value, below which an increase in the parameter improves performance and above which the reverse is the case. These limiting values depend on the spin rate of the spacecraft; they are lowered by increasing the spin rate. In general, changes in boom length have a more dramatic influence on damper effectiveness than changes in boom mass. Finally, the proposed arrangement naturally introduces redundancy into the nutation control scheme. Failure of one of the boom dampers does not constitute a crisis because the second damper can continue with the nutation damping process at a reasonable rate.

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Frequency-Domain Recursive Robust Identification

Xu Feng* and Ching-Fang Lin†
American GNC Corporation, Chatsworth, California 91311
and
Norman P. Coleman‡
Army Armament Research, Development and Engineering Center, Picatinny Arsenal, New Jersey 07806

I. Introduction

CONVENTIONAL system identification theory is mainly focused on how to obtain a single accurate model of the plant and how to ensure that the obtained model approaches the real model of the plant. It is assumed that the best an identification algorithm can provide is a good model that is sufficiently close to the real model. For controller design purposes, this assumption implies that a controller, which is designed for a good model, will exhibit good performance when it is applied to the real plant. Such an assumption has been widely used in control practice.[1]

Recently, alternative approaches to system identification for controller design have been proposed.[2–5] One of the alternatives is to derive a family of models instead of a single model to ensure that the true dynamics of the plant are included in the model family. Obviously, this is a more practical approach than conventional ones, especially for those plants with highly complex dynamics, such as aerospace systems.

In this Note, a frequency-domain recursive robust identification algorithm is proposed for a system with unmodeled dynamics. The algorithm yields estimates of the system transfer function at N frequency points on the unit circle, as well as the error bounds of these estimates. Such estimation results provide potential data for the so-called H_∞ identification approaches, which in turn provide possible models for the robust (H_∞) controller design.[5]

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*Senior Research Scientist, 9131 Mason Avenue; xfeng@americangnc.com.

†President, 9131 Mason Avenue; cflin@americangnc.com. Associate Fellow AIAA.

‡Chief, Automation and Robotics Laboratory, AMSTA-AR-FSF-R; ncoleman@pica.army.mil.