Variable Parameter Nutation Damper for SAS-A

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This paper presents design objectives, functional description and in-flight performance of a variable parameter nutation damper for a dual-spin satellite. The damper consists of a torsion wire mounted pendulum which includes the capability of command changing the pendulum resonant frequency and damping constant in order to obtain optimum spin axis stabilization for both a dual-spin and single-spin spacecraft dynamical condition. State-of-the-art features of this damper include: 1) taut-band suspension, for a pendulous mass, which has no mechanical friction of hysteresis, 2) magnetic circuit for changing the torque constant of the taut-band thereby changing the damper natural frequency, 3) chargeable magnet system for varying the damping coefficient, and 4) 7-bit optical readout for telemetering the damper motion. The damper weights 2.7 lb and draws 20 mw power when functioning for dual-spin conditions. The minimum nutation damping time constant in this mode is 12 min with a predicted spin axis pointing accuracy of 1 min of arc. Stabilization to better than 2 min of arc has been achieved in orbit.

Nomenclature

B = magnetic flux density produced by parameter changing coil
B_g = magnetic flux density in gap of chargeable damping magnet
c = damping constant (600 dyne-cm-sec primary mode, 6700 dyne-cm-sec back-up mode)
H = angular momentum of rotor relative to spacecraft (2.41×10^7 g-cm^{2}rad/sec)
I = average transverse axis moment of inertia of satellite plus rotor (27.9×10^7 g-cm^2)
I_d = moment of inertia of damper about torsion wire axis (8.43×10^4 g-cm^2)
I_z = spin axis moment of inertia of satellite plus rotor (30.4×10^7 g-cm^2)
k = spring constant of torsion wire (580 dyne-cm primary mode, 25 dyne-cm back-up mode)
l = longitudinal distance between spacecraft mass center and damper plane (46.3 cm)
M = dipole moment of parameter changing magnet
r_0 = radial distance from spacecraft Z axis to torsion wire (1.9 cm)
r_1 = pendulum length (distance from torsion wire to pendulum center of mass, 17.4 cm)
α = damper angle off nominal equilibrium position
η = $(k/I_d + r_0\omega_z^2/r_1)^{1/2}$, natural frequency of nutation damper
ω_n = $(I_z\omega_z + H)/I$, space observed satellite nutation frequency
ω_z = angular rate of spacecraft about Z axis
Ω = $\omega_n - \omega_z$, mechanical excitation frequency of nutation damper
τ = nutation amplitude decay time constant as given by Eq. (2)

Introduction

THE small Astronomy Satellite-A (SAS-A), launched December, 1970, is the first in a series of scientific spacecraft designed to explore extraterrestrial sources radiating in the x-ray, gamma-ray, ultra-violet, visible and infrared regions of the spectrum. The SAS-A mission is to study the strength and time variation of x-ray sources and to locate these sources to within 1.5 min of arc relative to visible sources. The spacecraft (Fig. 1) weighed 291 lb (orbital weight) and was Scout launched from the San Marco platform, off the east coast of Kenya. The nominal orbit is circular, 300 naut miles alt, 2.9° inclination.

To accomplish the x-ray mission SAS-A is spin axis stabilized by a 1.78 ft-lb-sec momentum wheel. The main body rotates at $\frac{1}{12}$ rpm such that the side pointing x-ray experiment scans great circles on the celestial sphere. Specific reorientations of the spin axis by means of a magnetic control system allows for an eventual scan of the entire sphere. During the experimental phase, disturbances to spacecraft attitude include dynamic unbalance and gravity-gradient and aerodynamic torques, as well as transients following maneuvers of the spin axis. A nutation damper stabilizes the Z axis in the presence of these perturbations.

Nutation Damper Objectives

Because of spacecraft size and weight limitations there is only one nutation damper. This damper must provide spin axis stabilization for three spacecraft dynamical modes—acquisition, primary data taking mode, and a back-up mode. The acquisition mode follows payload separation from the

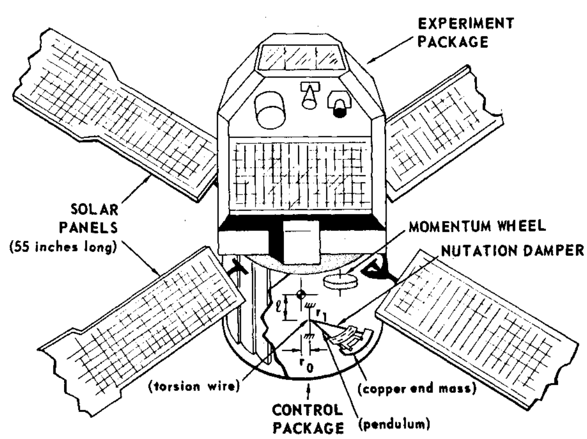

Fig. 1 SAS-A spacecraft and control system elements.

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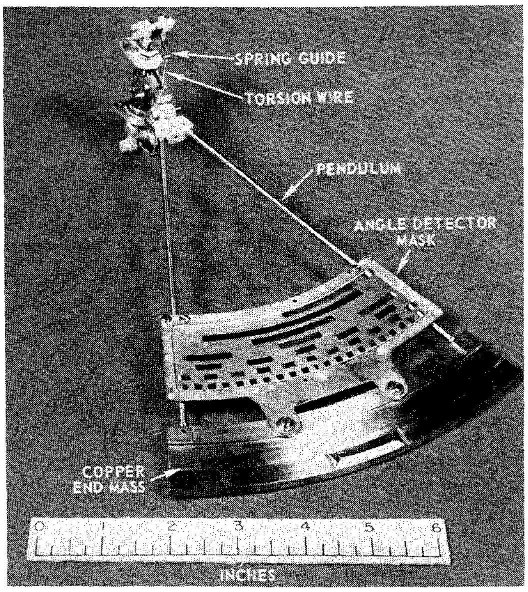

Fig. 2 SAS-A nutation damper.

launch vehicle where the spin rate is nominally 5 rpm with about $\frac{1}{4}$ rpm spin about a transverse axis. During acquisition, the momentum wheel is energized, the spin rate decreased to $\frac{1}{12}$ rpm and the spin axis precessed to an initial target. In the primary experiment mode, SAS-A spins at $\frac{1}{12}$ rpm with a 1.78 ft-lb-sec momentum wheel providing spin axis stabilization. The back-up experiment mode is used in the event that the momentum wheel fails. Angular momentum is provided by increasing the main body spin rate to $\frac{1}{4}$ rpm. It is noted that the ratio of spin to transverse moment of inertia is 1.09. For the back-up mode, somewhat reduced accuracy in x-ray source location is expected.

These three modes represent grossly different dynamical conditions for the design of a single mechanical damper. To be specific, for an axisymmetric dual-spin spacecraft the excitation frequency on the mechanical damper attached to the main body, is given by

$$\Omega = (I_z/I - 1)\omega_z + H/I \tag{1}$$

For SAS-A, the excitation frequencies (Ω) for the acquisition, primary and back-up modes, respectively, are 0.45 cpm to 0.83 cpm, 0.83 cpm and 0.022 cpm.

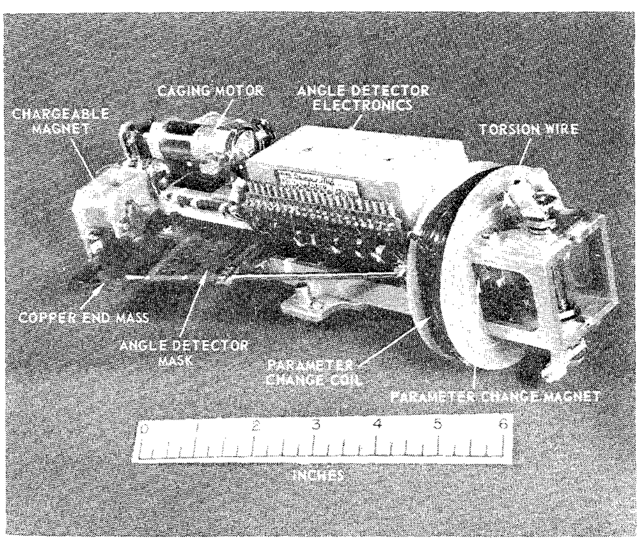

Fig. 3 Torsion wire and pendulum assembly.

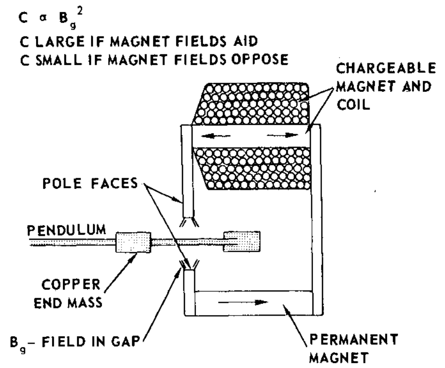

Fig. 4 Chargeable magnet system for variable coefficient.

A comparative evaluation of the various types of nutation dampers (ball-in-tube, fluid loop, pendulous, electromagnetic) established that a pendulous damper mounted on a zero threshold suspension was best suited for SAS-A. The pendulum would swing in a plane normal to the intended spin axis (Z axis) and this plane would be longitudinally displaced from the spacecraft mass center. It is noted that a pendulous damper is most effective when its resonance matches the excitation frequency and its damping coefficient selected to provide a minimum nutation amplitude decay time. For the SAS-A pendulous damper to respond to different excitation frequencies, it should, therefore, possess the capacity to vary its resonant frequency κ and damping coefficient c. Varying the pendulum resonance can be achieved by changing the spring constant k of its suspension.

The tradeoffs required between k and c to achieve a minimum time constant τ is provided by Eq. (2). This is an energy sink solution for the time constant of a SAS-A type pendulous damper.

$$\tau = 2r_1^2 I[(c\Omega/I_d)^2 + (\Omega^2 - \kappa^2)^2]/cl^2\omega_n^3\Omega \tag{2}$$

The derivation of Eq. (2) was carried out using techniques described, for example, by Likins,[1] Yu,[2] Spencer,[3] Alper,[4] and Taylor.[5] The time constants obtained, generally agreed with roots of the dynamical system characteristic equation and computer attitude simulations.[6]

For minimizing τ, it is noted that the bracketed expression is minimized if the damper is tuned, i.e. if its natural frequency κ matches the excitation frequency Ω. If tuning exists, τ can be further reduced by selecting lower values of c. If tuning cannot be achieved, then the term $(\Omega^2 - \kappa^2)^2$ generally predominates and τ is reduced by selecting higher values for c. It is also noted that excepting possible instabilities indicated in Ref. 6, smaller time constants are realized by increased values for l and ω_n. A minimum time constant, then, for each of the SAS-A dynamical modes is established in the primary mode by a lightly damped pendulum driven at resonance, i.e., relatively high k but low c; back-up mode by a heavily damped pendulum with a minimum natural frequency, i.e., low k and high c; and acquisition mode by a heavily damped high frequency pendulum, i.e., high k and high c.

Nutation Damper Design

The final configuration which met all design requirements and spacecraft constraints is the torsion wire mounted pendulous damper in Fig. 2. The device weighs 2.7 lb, dissipates 20 mw in the primary mode and 1.7 w in the back-up mode (1.5 w momentum wheel off). Minimum nutation damping time constants are 12 min for the primary mode and 2 hr for the back-up mode.

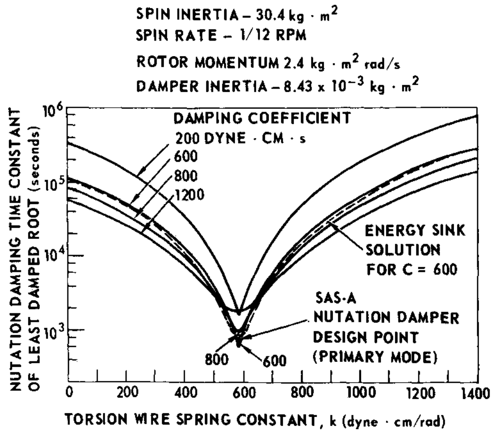

Fig. 5 Nutation damping time constant—primary mode.

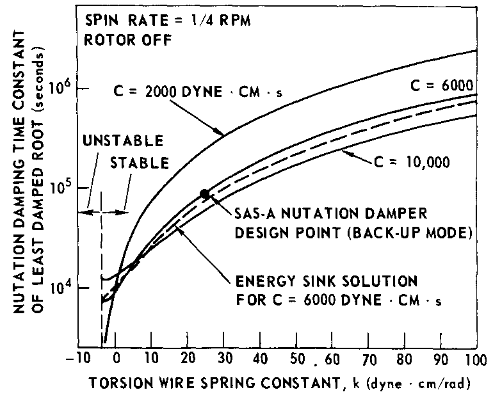

Fig. 6 Nutation damping time constant—back-up mode.

The torsion wire is parallel to the spacecraft Z axis (the intended spin axis) and causes the damper to swing in a plane normal to Z. This plane of motion is displaced from the spacecraft mass center so that the pendulum is sensitive to rotations about the X and Y axes (nutation). The assembled natural frequency of the pendulum and torsion wire matches the spacecraft nutation frequency in the primary mode (momentum wheel on). A parameter change system consisting of a magnet, coil and constant current source reduces the effective spring constant of the suspension for the low-frequency back-up mode.

Damping is achieved by eddy-currents induced in a copper vane as it swings between the pole faces of a chargeable "C" magnet circuit. In the primary mode the flux generated is low so as to effect light damping. In the back-up and acquisition modes the flux is increased so as to produce approximately 10 times as much damping.

Included in the nutation damper assembly is an angle detector which generates, in Gray code, the damper angle, plus a caging mechanism which locks the damper throughout launch and provides for its release in orbit.

Pendulum and Taut-Band Suspension

The pendulum assembly (Fig. 3), consists of a copper end mass, an optical mask, pendulum arms and torsion wire. The pendulum, excepting the parameter change magnet, is composed of nonmagnetic alloys so that magnetic forces will not effect damper motion. The end mass is high-purity copper and provides damper inertia and damping via magnetically induced eddy-currents. The angle detector mask is BeCu and the pendulum arms are thick walled BeCu tubing. The total pendulum mass is 245 g with a moment of inertia about its torsion wire axis of 8.43×10^4g-cm^2. The torsion wire is a 10% Ni/Pt ribbon of the type used in taut-band meter movements. The ribbon has a width to thickness ratio of 10:1 and affords high strength for the relatively weak torsional spring constants. The specific wire size for SAS-A is 0.016 in. $\times$ 0.0016 in. and each leg of the torsion wire is about 0.8-in.-long. BeCu springs position the torsion wire and provide a constant tension which restrains the pendulum from moving vertically or radially. The wire is attached to its tensioning brackets and pendulum pivot by epoxy. The inherent torsion wire torque constant is 580 dyne-cm/rad.

Caging Mechanism

The pendulum is caged throughout spacecraft testing, shipping and launch. The caging system clamps the copper end mass and at the same time pulls the pendulum pivot against solid restraints such that the torsion wire does not vibrate. In orbit, an uncage command supplies power to the d.c. motor which releases the damper. The motor supply voltage line is automatically opened when the caging mechanism has completely released the damper. During ground test an external test line can be energized in order to recage the damper. The in-flight damper release operation takes 30 sec. A cage-uncage telltale is provided for telemetering the state of caging of the nutation damper.

Angle Detector

The angle detection system consists of a BeCu encoded mask, attached to the damping vane, which swings between circuit boards containing phototransistors and light-emitting diodes. A seven bit Gray code provides angle magnitude and sense with $\frac{1}{2}°$ resolution over $\pm 20°$ swing. Current to the light emitting diodes is controlled by a power switch which is turned on by a TLM gate signal when the nutation damper angle is to be sampled. The turn-on time is 8 msec every 0.768 sec and the average power dissipation is 20 mw.

Variable Spring Constant Design

The mechanism for varying the effective torsion wire spring constant consists of a magnet, a coil and a constant current source. A permanent magnet is attached to the pendulum pivot which has a magnetic dipole moment M directed along the pendulum center line. A coil producing a fixed magnetic field is energized which produces a B field nominally opposing the permanent magnet. The net effect is that the torque on the pendulum is $k\alpha - MB \sin\alpha$. For small α the effective torque constant is $k - MB$. In the back-up mode, the MB product, using a 0.1% constant current source on the field coil, reduces the torsion wire torque constant to 25 dyne-cm/rad thereby producing a minimum natural frequency suspension. The coil uses aluminum wire, produces a magnetic field of 30 gauss and draws 1.7 w. The constant current source driving the coil is packaged within the damper electronics module and is automatically energized when power to the momentum wheel is off.

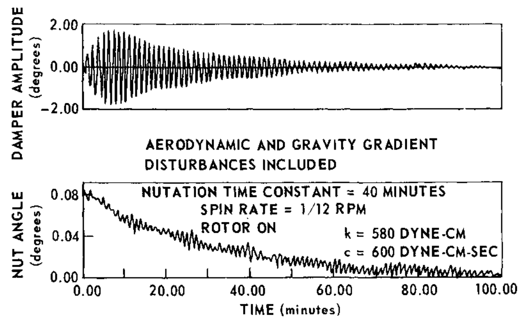

Fig. 7 Attitude performance—primary mode.

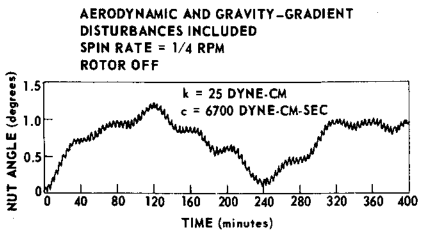

Fig. 8 Attitude performance—back-up mode.

Variable Damping Coefficient Design

The damping coefficient is varied by changing the magnetization within a chargeable magnet circuit as shown in Fig. 4. The chargeable magnet design uses a permanent magnet in the lower leg and a chargeable magnet in the upper. When the chargeable magnet is fully charged in the "aiding" sense its flux adds to the permanent magnet thus producing a large field in the "C" gap. When the chargeable magnet is fully charged in the "opposing" sense, its flux opposes the permanent magnet to the extent that the net flux in the gap is low. The low-flux state provides a damping constant of 600 dyne-cm-sec which is nearly optimal for the primary dynamical mode. The high-flux state provides 6700 dyne-cm-sec damping constant.

Theoretical Performance

Selection of final design parameters for the nutation damper was based on both the energy sink analytic solution and roots of the system characteristic equation. Verification of design parameters and expected flight performance was based on a digital computer simulation which included the rotor, nutation damper, satellite mass asymmetries and aerodynamic, magnetic and gravity-gradient torque perturbations

The energy sink analysis provided first estimates for nutation damping time constants and tradeoffs between time constant and damper shape, position, damping and spring constants. Analysis of the dynamical system characteristic equation provided stability criteria and exact time constants. Figures 5 and 6 plot nutation damping time constant for the primary and back-up modes as a function of k and c. The time constant is based on the least damped root of the system characteristic equation. A curve representing the energy sink analytic solution is included which indicates relatively good agreement with the least damped root.

The expected flight performance of SAS-A in the presence of aerodynamic, magnetic and gravity-gradient disturbance torques for the primary, back-up and acquisition modes is given by Figs. 7–9. Owing to a change in spacecraft moments of inertia at the final stages of assembly, the excitation frequency Ω no longer exactly matched the damper resonance and thus the nutation damping time constant increased from 12 to 40 min. Nevertheless, according to digital simulation, steady-state pointing accuracy was not degraded.

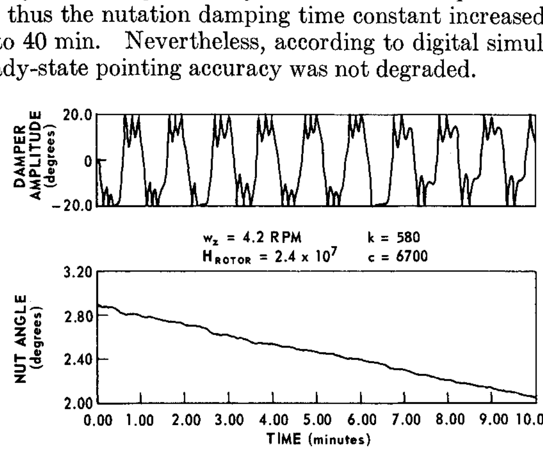

Fig. 9 Nutation damping performance—acquisition mode.

Postlaunch Performance

SAS-A was launched on December 12, 1970 into a near circular, 2.9° inclination orbit. On the first orbit a nutational half cone angle of 2.5° was observed, indicating that the transverse angular rate imparted to the spacecraft by the rocket and separation system were within expected limits.

At the first command opportunity, both the nutation damper and momentum wheel were uncaged and the wheel motor energized. Once uncaged, the damper oscillated at limiting amplitude (±20°). The damping constant and spring constant were at maximum value for the damper to be most effective at the 4 rpm spacecraft spin rate. On the second orbit, the damper oscillation had reduced to ±0.5° and no nutation could be observed on the real-time attitude detector (a 1° resolution device).

To reduce spacecraft spin to $\frac{1}{12}$ rpm as required for the x-ray mission, a magnetic torquing spin rate control system was energized. As the spin rate approached the desired level, the nutation damper's damping coefficient was reduced to 600 dyne-cm-sec to provide "optimum" stabilization. Star sensor analysis from the first several days indicated a nutation angle of about 0.5 degrees. To improve stabilization the damping constant was increased and nutation angles within 2 min of arc were subsequently achieved.

Conclusion

A variable parameter nutation damper is a highly desirable mechanism for achieving spin axis stabilization under varying spacecraft dynamical conditions. The SAS-A nutation damper, as an example, includes the capability of changing, by command, its mechanical resonant frequency and its damping coefficient. Its mechanical resonance can match a dual-spin nutation frequency of 0.83 cpm for the primary experiment mode and, if the spacecraft momentum wheel fails, to nearly match a single-spin nutational frequency of 0.022 cpm for a back-up capability. The damping coefficient of this damper can be varied from 600 dyne-cm-sec to 6700 dyne-cm-sec in order to achieve minimum nutation damping time constants for the primary, and back-up modes, as well as an acquisition mode. In the acquisition mode the spacecraft spin rate is gradually diminished from the value established by yo-yo despin of the Scout 4th stage, ~5 rpm, to the primary spin mode of $\frac{1}{12}$ rpm.

When operating in the primary mode for dual-spin conditions the minimum nutation damping time constant is 12 min. A change in spacecraft moment of inertia at final assembly altered the resonant condition and increased the nominal time constant to 40 min. This new condition, however, did not degrade steady-state pointing accuracy, which is observed to be roughly 1.0 to 5.0 min of arc. For the back-up mode pointing accuracies on the order of 1.2° are expected.

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