Attitude Motion of a Nutationally Damped Dual-Spin Spacecraft in the Presence of Near-Earth Environment

P. G. Fuechsel*
The Johns Hopkins University, Silver Spring, Md.

P. M. Bainum†
Howard University, Washington, D. C.

AND

P. J. Grunberger‡
The Johns Hopkins University, Silver Spring, Md.

Theme

THE effect of both gravity-gradient torques and the near-Earth environment on the attitude motion of a dual-spin spacecraft with nutation damper is predicted by digital simulation. The program employs a geometrical modeling technique to determine the total unshadowed spacecraft surface area required for the computation of aerodynamic torques. In addition, the deliberate steering of the satellite spin axis with magnetically induced torques is described.

Content

The dual-spin Small Astronomy Satellite (SAS-A) scans the entire celestial sphere to determine the location of X-ray sources relative to the fixed position of the stars. A digital computer program was developed to predict the attitude motion and was based upon the following dual-spin flight configuration (Fig. 1): a slowly rotating ($\frac{1}{12}$ rpm) main body including four extensible solar panels, a high-speed rotor whose spin axis is parallel to the main spacecraft figure axis (Z), and a pendulous-type nutation damper constrained to move in a plane perpendicular to Z and supported by a torsion wire pivot that also provides a restoring torque.

The attitude dynamics and stability of this satellite in a torque-free environment were treated previously.[1] The nonlinear equations of motion were derived using the quasi-Lagrangian formulation.[1] The present paper describes the method of simulation and the predicted continuous effect of: the generalized gravity-gradient torques, magnetic torques created by the reaction of generated dipole moments along the three axes of the main body with the Earth's magnetic field, and aerodynamic torques.

For a near-Earth satellite the largest perturbation is attributed to aerodynamic forces and torques, which are dependent on the atmospheric density, the relative velocity between the satellite and the earth's atmosphere, and the angle of incidence between the impinging molecules and the nonshadowed (exposed) surface area of the spacecraft. The effective (nonshadowed) projected area is a function both of the particular surface area determined by the velocity vector and the local

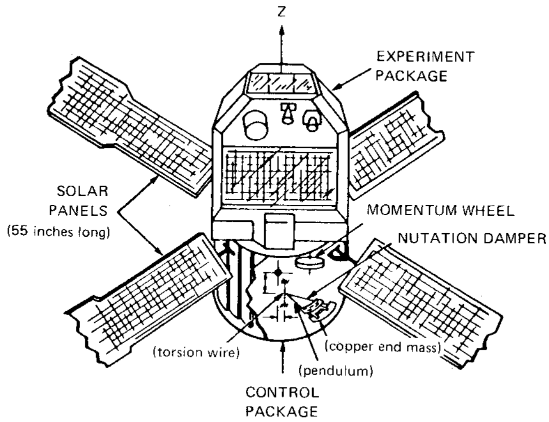

Fig. 1 SAS-A flight configuration.

surface normal, and of the shadowing of this surface by other parts of the spacecraft structure.

The aerodynamic force calculations were greatly simplified by assuming the force to be caused by the collision of free flow air molecules with flat surfaces. Secondary collisions of molecules with other elemental surfaces were ignored, and the air density was assumed to be a constant around the orbit. Then, by employing a geometrical modeling technique similar to that developed by Skladany,[2] the total unshadowed spacecraft surface area could be determined. Each surface ele-

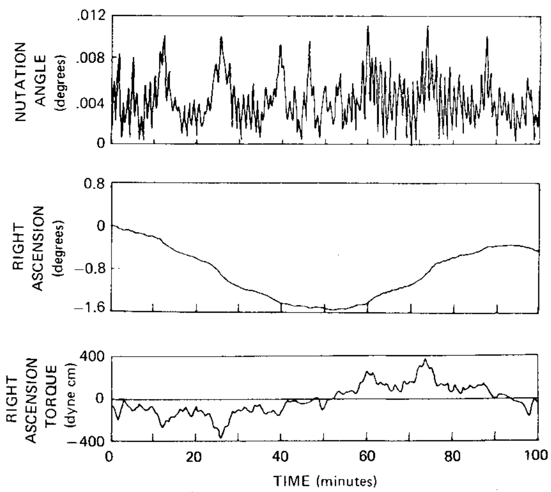

Fig. 2 Steady-state attitude motion, rotor on, with gravity gradient and aerodynamic torques.

Presented as Paper 71-90 at AIAA Ninth Aerospace Sciences Meeting, New York, N.Y., January 25–27, 1971; submitted February 9, 1971; synoptic received May 28, 1971. Full paper is available from AIAA. Price: AIAA members, $1.50; nonmembers, $2.00. Microfiche, $1.00. **Order must be accompanied by remittance.**

Index category: Spacecraft Attitude Dynamics and Control.

* Associate Engineer. Member AIAA.

† Associate Professor of Aerospace Engineering; also Consulting Engineer. Member AIAA.

‡ Associate Engineer.

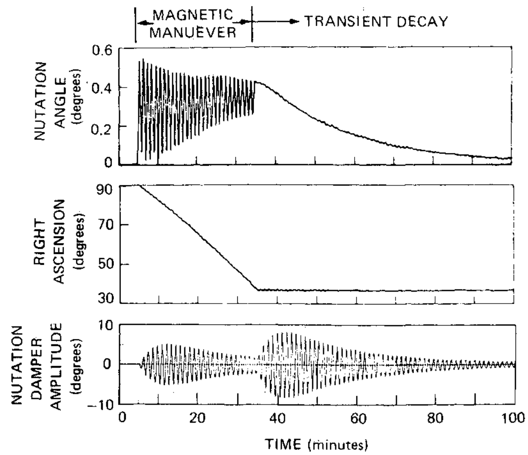

Fig. 3 Magnetic steering maneuver with rotor on.

ment of the satellite is divided into a number of equivalent flat plate surfaces, each having a normal vector that can be expressed in the spacecraft body axes system. For a given spacecraft figure axis orientation, the following quantities are computed for each panel: the incident angle between the relative velocity vector and the surface normal, the projected exposed surface area, and the center of pressure relative to the center of gravity of the satellite system. The resultant torque acting on the spacecraft is obtained by summing the torque contribution of all surfaces. The aerodynamic torques are precomputed for systematic changes in spacecraft orientation and stored in a table. A table look-up technique with linear interpolation is used by the simulation to obtain torque components for the computed satellite attitude at each integration time step.

Numerical runs were made assuming a balanced spacecraft in a 300 naut-mile circular equatorial orbit. The steady-state motion is characterized by a $\frac{1}{12}$ rpm spin rate of the main body (momentum = 1.75 slug-ft^2-rpm) the momentum wheel rotating at 2000 rpm (16.9 slug-ft^2-rpm) and the damper uncaged. Figure 2 is representative of the attitude motion when the spacecraft is perturbed by both gravity-gradient and aerodynamic torques and the damper uncaged. It can be seen that the maximum nutation buildup is 0.011° resulting from torques having a peak value of 400 dyne-cm. The nutation angle is defined as the angle between the Z axis and the total angular momentum vector. When the figure axis drift is linearly projected over 24 hr, the precession is $\sim$5.7° in right ascension and 0° in declination, for an initial spin axis declination of 60°. This precession exceeds the mission requirements of a maximum allowable figure axis precession rate of 5 deg/day. It was expected that this projected drift rate represented a conservative upper bound for the following reasons: 1) The value of density used (4×10^{-15} gm/cm^3) was twice as great as the maximum expected value corresponding to the highest solar activity.[3] 2) Preliminary simulation results indicated that declination angles near 60° result in the largest values for aerodynamic torques when averaged over the entire orbit. Satellite flight data have shown average daily drift rates of 5° or less.

Since the celestial sphere is to be scanned for X-ray emitting sources, it will be necessary to slue the spin axis to new orientations in inertial space. The maneuvering torque is generated by the interaction of the Earth's magnetic field and a commandable dipole (50,000 pole-cm) aligned with the Z axis (Z dipole).

The nutation angle response (Fig. 3) is characterized by two distinct phases. The first, during the maneuver, shows the initial amplification and decay of nutational motion under the presence of magnetic (precessional) torques and the second illustrates the transient decay of the nutation angle resulting from the terminal conditions of the magnetic maneuver. For the second phase the nutation angle plot shows a damping time constant τ of 25 min. This compares with the time constant of 21 min for the least damped mode from the linearized analysis of the torque-free system.[1]

The precession in figure-axis right ascension as a result of the magnetic maneuver should be noted. It is also apparent that without the action of the nutation damper, sufficient reduction in the residual nutation angle resulting from the terminal conditions of the magnetic maneuver would not occur.

In the event of rotor failure, the satellite's spin rate is increased from $\frac{1}{12}$ rpm to $\frac{1}{4}$ rpm with the magnetic spin control system to increase the angular momentum of the main body from 1.75 slug-ft^2-rpm to 5.25 slug-ft^2-rpm. The nutation damper spring constant is reduced from 610 dyne-cm/rad to 25 dyne-cm/rad, and the damping coefficient is increased to 6700 dyne-cm/rad/sec to optimize damping performance.[1]

The steady-state nutation angle is predicted to be no larger than 1.20°. This is well within the 45° maximum allowable nutation angle for the case of rotor failure.

A magnetic maneuver was simulated for the rotor-off case with the Z dipole turned on for 30 min. During that interval, the nutational angle increased from 1.6° to 8.8° with the spin axis slueing from 90° to 45° in right ascension under a maximum torque of 16,000 dyne-cm. After the Z dipole is turned off, the projected decay in nutation angle results in a time constant of 13 hr. The nutational motion was large enough during and after the maneuver to force the damper to hit the ±20° mechanical stops.

References

[1] Bainum, P. M., Fuechsel, P. G., and Mackison, D. L., "On the Motion and Stability of a Dual-Spin Satellite System with Nutation Damping," *Journal of Spacecraft and Rockets*, Vol. 7, No. 6, June 1970, pp. 690–696.

[2] Skladany, J. T. and Rochkind, A. B., "Determination of Net Thermal Energy Incident on a Satellite," ASME-AICHE Heat Transfer Conference and Exhibit, Seattle, Wash., August 6–9, 1967.

[3] *Proceedings of the International Space Sciences Symposium*, Committee on Space Research (COSPAR) International Reference Atmosphere, 1965, p. 103.