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Attitude Maneuver of Service Vehicle with Spinning Spent Satellite

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Orbit transfer of Earth-orbiting, spinning, spent satellites via a service vehicle will constitute an important part of space infrastructure in the very near future. In the orbit transfer process, after grappling a spinning spent satellite with a hinge mechanism equipped on top of a long arm, the service vehicle must maneuver in such a way as to avoid a collision with the spent satellite. This paper describes the complex spinning dynamics of the service vehicle combined with the spent satellite, and the new control law for its attitude maneuver. The whole equation of motion is derived by Kane's method and its three-dimensional motion is numerically simulated to confirm the effects of the control law. The control torque is an internal torque generated at the hinges using the feedback of the hinge angular velocity and the hinge angle, taking advantage of the energy dissipation during conservation of angular momentum. It is shown that the control law with a change of feedback coefficient based on the hinge angular velocity is more effective than that with a change of feedback coefficient based on the hinge angle.

Introduction

RECENTLY the number of spent satellites in geostationary orbit has increased rapdily. A method of eliminating these satellites has become an important problem. Among several methods previously proposed, tumble orbit transfer technique using a service vehicle is one of the most promising methods.[1,2] This is done by an independent service vehicle equipped with a long arm and a grapple mechanism on its top. After grappling the spinning spent satellite, the service vehicle combined with the spent satellite orients its axis perpendicular to an orbit plane. Then a thruster is activated to provide an impulse to the service vehicle, which simultaneously causes a velocity change and a tumbling of the combined system. The separation at apogee brings the service vehicle and the spent satellite into different orbits; the spent satellite into one orbit with a higher energy and the service vehicle into another orbit with a lower energy. The total impulse required for the orbit transfer is reduced to half of that required in an ordinary orbit transfer. In this process, the attitude maneuver of the combined vehicle from the instant of grappling the spent satellite to the flat spin should be carefully controlled to avoid a collision between the service vehicle and the spent satellite.

In a previous report,[1] a plane motion without spin was analyzed, and it was shown that the deviation of angle at the grapple point was kept below 0.4 rad, assuming zero rotational stiffness at the grappling point. However, in case of a spinning spent satellite, the deviation of angle at the grappling point cannot necessarily be kept low enough to avoid a collision. Generally, a spinning body with an energy dissipation mechanism, free of applied torques and active control, is stable only when rotating about its axis of maximum moment of ineritia.[3] This phenomenon has been widely used for passive attitude control,[4,5] and also holds true for the attitude maneuver of the combined vehicle. However, those passive attitude controls were applied to only one rigid spinning body, not to the combined spinning vehicle. This type of the combined vehicle system during attitude maneuver has never been discussed. In addition, its three-dimensional spinning motions are so complex that they remain to be simulated.

Primary objectives of this study are to investigate the dynamic behavior of the combined vehicle for realistic satellite configurations and the control law for reducing its hinge angle deviation. The dynamic equation of motion of the combined system is derived by using Kane's method. Then, control laws based on energy dissipation are investigated by using a computer simulation of the derived dynamic equations.

Tumble Orbit Maneuver Procedure

In an orbit transfer maneuver, the service vehicle captures the spent satellite, using a long arm, at any one point, as shown in Fig. 1a. When the spent satellite is spinning, the capture maneuver is not easy. The easiest way is to spin the service vehicle also in such a way that the spin axis is aligned to that of the spent satellite. When the spin rate of the service vehicle approaches that of the spent satellite, the relative motion of the two vehicles disappears. The capture becomes feasible if the spent satellite possesses a hard point in the vicinity of the spin axis. The service vehicle combined with the spent satellite is stable only about its axis of maximum moment of inertia while maintaining the direction of its angular momentum vector in an inertial space. Because the service vehicle usually has energy absorbers, such as a nutation damper wheel and a hinge mechanism, immediately after grappling the spent satellite, the whole system of the service vehicle starts to transfer its spin axis to a stable flat spin, as shown in Fig. 1b, which is a spin within an orbital plane. The instant the arm axis is aligned perpendicular to the velocity vector of the orbit, a thrust is applied to the service vehicle, also perpendicular to the arm axis. Thereby, the velocity increment of the combined system is activated along with a rotational motion around the mass-center added. The velocity increment puts the whole system into an intermediate transfer orbit. Viewed from the center of attraction, the angular momenta of both masses are exchanged periodically. The separation at the apogee puts the spent satellite into a higher circular orbit and the service vehicle into an orbit closer to the original orbit when the angular momentum of the spent satellite is maximum, which means that the angular momentum of the service vehicle is minimum. The amount of propellant required is half of that required in an ordinary orbit transfer maneuver.[2] Taking into account that many spent geostationary satellites have their spin axes perpendicular to the orbital plane, the tumble orbit transfer technique mentioned above is attractive. Therefore, the control method of the attitude maneuver during the transfer of the spin axis becomes very critical.

System Description

The service vehicle used to capture a spent satellite is modeled as a system with three rigid bodies connected by two hinges, as shown in Fig. 2. The service vehicle is divided into two parts. One is the main body of the service vehicle itself, which is modeled as rigid body A. The other is a long arm that captures the spent satellite,

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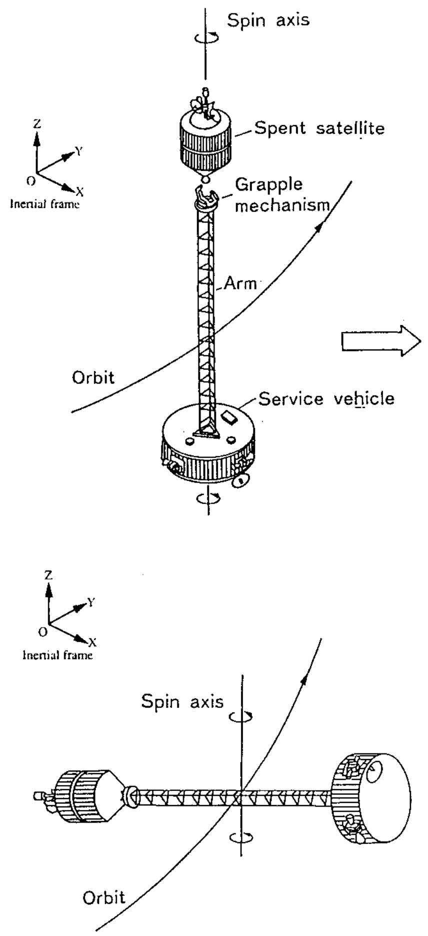

Fig. 1 Attitude maneuver of service vehicle with spent satellite: a) acquisition and b) completion of transfer of spin axis.

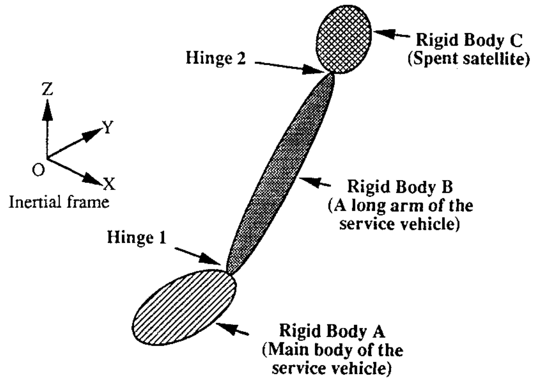

Fig. 2 Three-rigid-body model of the whole system.

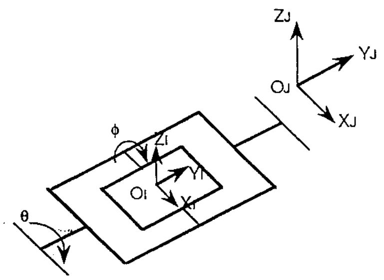

Fig. 3 Two-axis gimbal hinge.

which is modeled as rigid body B. The spent satellite is modeled as rigid body C. Two hinges are used to connect the rigid bodies. Each hinge is realized by using the two-axis gimbal system, shown in Fig. 3. The rotation at the hinge from body I fixed frame to body J fixed frame is expressed by two Euler angles, ϕ and θ. One damper wheel is located on the main body of the service vehicle (i.e., body A) as an energy absorber to cause the transfer of the spin axis in case of no torque at the hinges, and its axis is aligned with the z axis in body A.

The whole equation of motion is derived by using Kane's method.[6] Using the associated generalized inertia force and the associated generalized active force, we arrive at 11 dynamical equations, 3 equations of the translational motion, and 3 equations of the rotational motion of the combined vehicle with respect to the inertial space, 2 equations of the rotational motion of hinge 1, 2 equations of the rotational motion of hinge 2, and 1 equation of the rotational motion of damper wheel.

Control Law

An isolated physical system, undergoing motion, which gives rise to relative motion of its parts and consequent dissipation of mechanical energy, approaches in time the motion of minimum mechanical energy consistent with conservation of angular momentum. For a rigid body, the minimum energy state for a given angular moment of inertia is spin about the principal axis of the maximum moment of inertia.

The combined vehicle, as shown Fig. 1a, in which is shown the service vehicle, the long arm, and the spent satellite all aligned with the same axis, is spinning in a state of maximum mechanical energy. It is assumed that the combined vehicle's angular momentum is preserved during the maneuver because small external torques applied to it can be neglected. Therefore, in time it changes its axis from about the principal axis of minimum moment of inertia to about the principal axis of maximum moment of inertia, as shown in Fig. 1b; that is, the axis of maximum moment of inertia is oriented in the angular momentum direction.

During the maneuver, the hinge angles are expected to fluctuate. As a matter of fact, it is desirable that the deviation of the hinge angle be within the range that prevents the service vehicle, the long arm, and the spent satellite from colliding with each other, and that the transfer of the spin axis be completed in an adequate amount of time.

The spin axis transfer is a function of the energy dissipation rate,[3] and its behavior is an unstable phenomenon caused by a complicated nonlinear term in dynamical equations derived. Keeping the hinge angle within a specified value and causing the spin axis transfer contradict each other. Therefore, the linear control theory cannot be applied to the maneuver. The control law that causes the transfer of spin axis and allows a certain amount of hinge angle deviation is difficult to find. An internal torque at each hinge is adopted as a practical control torque to the combined vehicle under conservation of angular momentum. Focusing on both energy dissipation and hinge angle deviation, the torque is generated based on feedback of the hinge angular velocity and hinge angle. Feedback of the hinge angular velocity causes energy dissipation. Feedback of the hinge angle fundamentally curbs the rotational motion of the hinge angle, thereby preventing a collision between the service vehicle, the long arm, and the spent satellite.

On the other hand, a large energy dissipation rate causes a rapid transfer of the spin axis and consequently causes a collision. A large control torque at the hinges achieved by the large feedback quantity of the hinge angle prevents the rotational motion of the hinges and consequently makes it hard to dissipate mechanical energy there. It takes much more time to complete the transfer of the spin axis.

Therefore, the feedback quantity of the hinge angle and hinge angular velocity and the completion time of the attitude maneuver should be a trade-off. In this study, the completion time is chosen to be between 10 and 30 min.

Based on the aforementioned control law, three kinds of control laws are investigated. One is the feedback law itself. Two of them are the feedback laws with a nonlinear element. In control law 2, the feedback quantity based on the hinge angle is stepwise amplified for a hinge angle that exceeds a specified value. This directly prevents the hinge motion and tries to keep the hinge angle small. In control

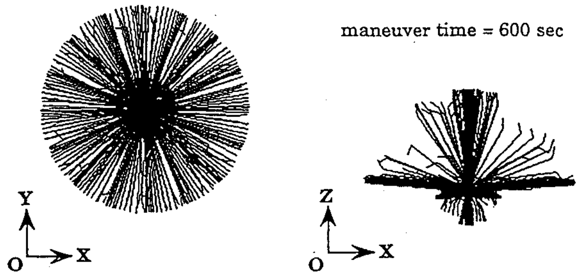

Fig. 4 Simulation of attitude maneuver (control law 1).

law 3, the feedback quantity based on the hinge angle is stepwise amplified for a hinge angular velocity that exceeds a specified value. This regulates energy dissipation rate and indirectly tries to keep the hinge angle small. These control laws are described as follows:

Control Law 1:

$$T_c = -k_1\dot{\theta} - k_2\theta \tag{1}$$

Control Law 2:

$$T_c = -k_1\dot{\theta} - k_2\theta \begin{pmatrix} k_2 = K(\text{if } |\theta| \leq \beta) \\ k_2 = \alpha K, \alpha > 1 \ (\text{if } |\theta| \leq \beta) \end{pmatrix} \tag{2}$$

Control Law 3:

$$T_c = -k_1\dot{\theta} - k_2\theta \begin{pmatrix} k_2 = K(\text{if } |\dot{\theta}| \leq \gamma) \\ k_2 = \alpha K, \alpha > 1 \ (\text{if } |\dot{\theta}| \leq \gamma) \end{pmatrix} \tag{3}$$

The same control law is applied for two gimbals at the associated hinge point.

Computer Simulations

A computational algorithm based on the derived equations has been developed and was used to simulate the three-dimensional, spinning free-flying motion of a service vehicle combined by two hinges with a spent satellite and to confirm the effect of the control laws already described.

The service vehicle with a 10-m-long arm was modeled after a 1-ton class satellite, and the spent satellite was modeled after the Japanese Communication Satellites two and three (CS-2,3). The initial spin rate of the combined vehicle was set at about 6 rad/s (i.e., 1 rps). To induce an energy dissipation in the simulation in a limited period of time, a small external torque with 1 Nm magnitude and 1 s duration was applied around the X axis at the start of the simulation.

First, the computer simulation was carried out for the combined system with a damper wheel as a single energy dissipator and no internal control torque at the hinges. In this simulation, the hinge angle exceeded 180 deg. This means that the main body of the service vehicle and the 10-m-long arm or the 10-m-long arm and the spent satellite collided.

A second computer simulation was carried out for the same system with both a damper wheel and the internal torque generated by the control laws as energy dissipators. The parameters of each control law and the hinge angle deviation as a result of the simulations are shown in Table 1, corresponding to case 1 simulation.

First, parameters k_1 and k_2 of control law 1 were determined by trial and error using a number of simulations to the point where the deviation of the hinge angle at both hinge points was less than 90 deg, and the completion time of the transfer of the spin axis was less than 30 min.

One typical simulation result, based on control law 1, is shown in Fig. 4. This figure shows the motion of the combined vehicle with respect to inertial frame N and corresponds to case 1 in Table 1, in which the hinge angle was minimum in the simulations conducted. The trace of its motion is plotted by a step of 1 s. Only the lines that connect the center of mass for each body and two hinges are expressed by the solid line. The right side of the figure is a trace of its motion in a x–z plane of inertial frame N. The left side of the figure is a trace of its motion in a x–y plane of inertial frame N. Profiles of one of the hinge angle deviations and its energy dissipation rate are depicted in Fig. 5. A large energy dissipation rate occurs during a short period of time.

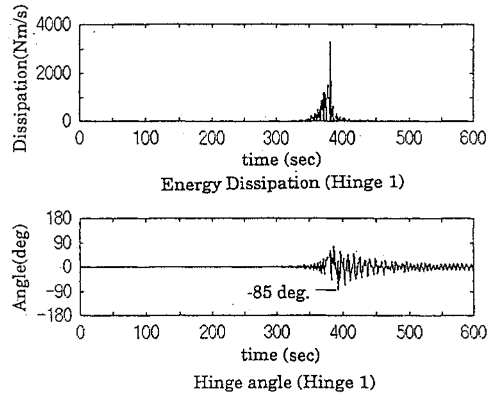

Fig. 5 Angle and dissipation profile at hinge 1 (control law 1).

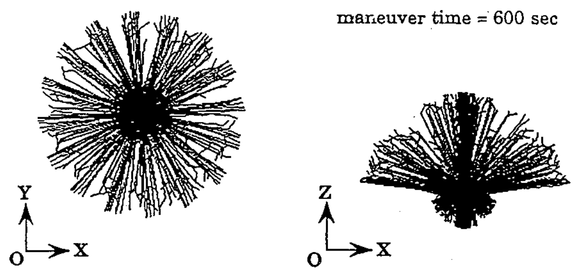

Fig. 6 Simulation of attitude maneuver (control law 2).

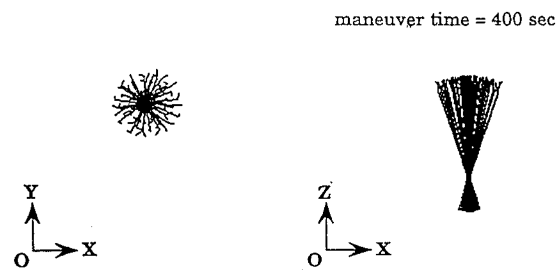

Fig. 7 Simulation of attitude maneuver (control law 3).

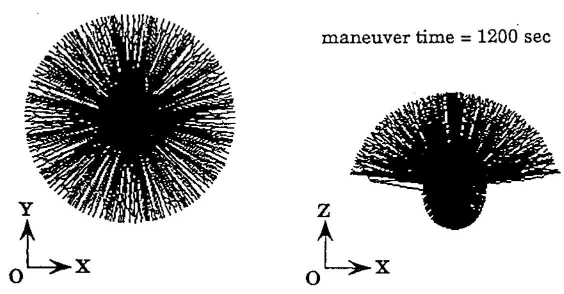

Fig. 8 Simulation of attitude maneuver (control law 3).

A feature of the attitude maneuver based on control law 1 is that the deviation of the principal axis of minimum moment of inertia from the spin axis is very small for a considerable period of time. However, it suddenly diverges in several seconds, at this time the hinge angle deviation becomes maximum, and then the combined vehicle gradually enters into a flat spin around the principal axis of maximum moment of inertia.

Next, by using the same parameters as those used in control law 1, a computer simulation based on control law 2 (case 2) was carried out, and its result is shown in Fig. 6. In this case, the maximum hinge angle deviation $\theta_{\max}$ is kept less than 71 deg at hinge 1 and 86 deg at hinge 2. However, the combined vehicle maneuvers as rapidly as that in Fig. 5 (case 1) and takes twice as much time as that in case 1 to complete the transfer of the spin axis.

Table 1 **Parameter of control laws and hinge angles**

		Hinge 1, $k_1 = 75$ Nms, $K = 1400$ Nm/rad				Hinge 2, $k_1 = 50$ Nms, $K = 1100$ Nm/rad			
	Control law	α	β, rad/s	γ, rad	θ_{max}, deg	α	β, rad/s	γ, rad	θ_{max}, deg
Case 1	1	—	—	—	85	—	—	—	118
Case 2	2	10	—	1	71	10	—	1	86
Case 3	3	10	1	—	61	10	1	—	77

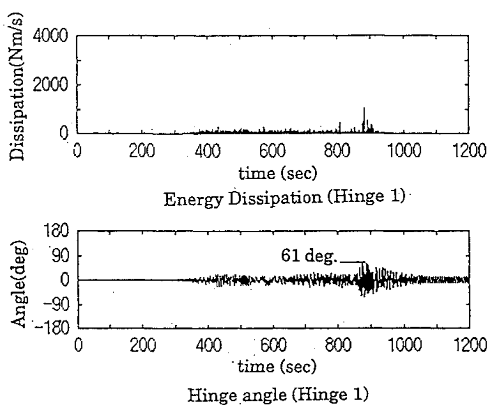

Fig. 9 Angle and dissipation profile at hinge 1 (control law 3).

Finally, by using the same parameters as those used in control law 1, a simulation based on control law 3 (case 3) was carried out, and its results are shown in Figs. 7 and 8. The combined vehicle constantly maneuvers without rapid transfer of the spin axis, compared with the maneuvers in Figs. 4 and 5 for case 1 and Fig. 6 for case 2. In this maneuver, the energy dissipation rate as shown in Fig. 9 is almost constant compared with that in Fig. 4 (case 1). This means that the hinge angular velocity is also almost constant. The maximum hinge angle deviation θ_{max} is kept to less than 61 deg at hinge 1 and 77 deg at hinge 2. Therefore, it maintains a relative angle between each body of more than 119 deg and 103 deg at hinges 1 and 2, respectively, and a collision among bodies is prevented.

As a result of the control laws considered here, control law 3 is the most suitable for a transfer of the spin axis with the hinge angle deviation reduced. The reason is that a transfer of spin axis is mainly a function of the energy dissipation rate; to constrain the motion of the hinge at the instant when the hinge angular velocity exceeds a specified value would bring a no time-of-delay direct energy dissipation regulation, and therefore would cause a calm attitude maneuver. On the other hand, to constrain the motion of the hinge at the instant when the hinge angle exceeds a specified value certainly tries to prevent the motion of the hinge; however, the hinge angular velocity at that instance is so small that the energy dissipation can be scarcely regulated.

Conclusion

The three-dimensional motion of the spinning service vehicle combined with the spent satellite is simulated to investigate the control law that prevents a collision between the service vehicle and the spent satellite. Three control laws at the hinges are considered in reducing the hinge angle deviation. Among those control laws, the control law with a change of feedback coefficient based on the hinge angular velocity is confirmed to be capable of reducing the hinge angle deviation and avoiding a collision between them. The law can keep the hinge angular velocity within a specified value, thereby controlling the energy dissipation rate of the combined system and bringing a calm attitude maneuver along with a small hinge angle deviation.

References

[1]Yasaka, T., "Low Cost Transfer of Inoperative Satellite by a Service Vehicle," *Proceedings of the 41st Congress of the International Astronautical Federation* (Dresden, Germany), AIAA, Washington, DC, 1990 (IAF-90-168).

[2]Yasaka, T., "Tumble Orbit Transfer of Spent Satellites," *Journal of Spacecraft and Rockets*, Vol. 27, No. 3, 1990, pp. 348–350.

[3]Likins, P. W., "Effect of Energy Dissipation on the Free Body Motions of Spacecraft," NASA TR 32-860, July 1966.

[4]Kaplan, M. H., and Beck, N. M., Jr., "Attitude Dynamics and Control of an Apogee Motor Assembly with Paired Satellites," *Journal of Spacecraft and Rockets*, Vol. 9, No. 6, 1972, pp. 410–415.

[5]Hubert, C., "Spacecraft Attitude Acquisition from an Arbitrary Spinning or Tumbling State," *Journal of Guidance and Control,* Vol. 4, No. 2, 1981, pp. 164–170.

[6]Kane, T. R., Likins, P. W., and Levinson, D. A., *Spacecraft Dynamics,* McGraw-Hill, New York.