DAMPING THE SPINNING SPACECRAFT VIA LOW LEVEL CONTROL

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The problem of angular velocity stabilization for the spinning spacecraft is considered. The spacecraft is assumed to be supplied a passive inertial energy dissipater in the form of a spring-mass-dashpot and small resistojets. The satellite is subjected to a combination of an excitational time varying torque and a control torque. The energy-based speed-gradient (SG) control law is proposed and numerical examination of the closed-loop system is provided. Numerical simulations have shown the effectiveness of SG control strategy and robustness properties with respect to excitation torque amplitude.

1. Introduction

The spinning spacecraft with a circumferential nutational damper is considered. The system consists of a rigid body rotating about some principal axis Z and an inertial energy dissipater in the form of a spring-mass-dashpot. A circumferential damper was chosen over an axial damper because of its effectiveness in operation over a wider range of nutation angles [1]. The small reaction-propulsion units can develop a control torque M_C about the Z-axis. The satellite is also subjected to an excitational time varying torque $M_E(t)$ assumed to be the periodically varying. Such a torque, in practice, may arise in the platform of a dual-spin spacecraft under malfunction of the control system causing rotor-driver fluctuations, or also during spin-up of an unbalanced rotor in a spacecraft [2,3]. The paper proposes the control method aimed to stabilize the satellite rotation rate near desired reference value without nutation or precession. An energy-based speed-gradient (SG) control technique [4–6] is applied to control law design. The corresponding Lyapunov function differs from that of [2,3].

2. System dynamic model and uncontrolled motion analysis

For the sake of simplicity, the 1-DOF model of the satellite angular motion is used below. The degrees of freedom of the system describe the damper mass displacement and rotation of the satellite. The damper is centered on the body fixed X-axis and has a point mass m. That mass moves along an axis perpendicular to X-axis at the some distance of the principal axis Z. Under these assumptions the system satellite-damper model can be written as follows [3]:

$$\begin{cases} (I + m(1-\mu)y^2)\dot{\omega} + 2m(1-\mu)y\dot{y}\omega - mb\ddot{y} = M(t), \\ m(1-\mu)\ddot{y} + c\dot{y} + (k-(1-\mu)\omega^2)y - b\dot{\omega} = 0, \end{cases} \tag{1}$$

where ω, y denote satellite angular velocity and damper mass displacement; I, m, k, c stand for the satellite moment of inertia about Z-axis, damper mass, spring constant and viscous resistance gain; $\mu = m/m_T$, where m_T denotes a total mass of the considered system. The external torque $M(t)$ is a sum of the excitational torque and the control torque, i.e. $M(t) = M_E(t) + M_C(t)$. It is assumed that $|M_C(t)| \le \overline{M}$, where $\overline{M}$ represents restriction on the control torque.

The system (1) examinations show that if $M(t) \equiv 0$ and initial conditions belong to some region, the system is dissipative and is attracted to the equilibrium state of constant angular velocity ω^* and no damper mass deflection. If these conditions are violated, the amplitude of $y(t)$ becomes inadmissible large and the system can perform chaotic jumps between two stable equilibrium points. To improve the system performance let us use, in addition, the active damping by means of the resistojets torque M_C.

3. Control law design

The control aim is to stabilize the desired state $[y, \dot{y}, \omega]^{\mathrm{T}} = [0, 0, \omega_{ref}]^{\mathrm{T}}$. This aim corresponds to the desired constant rotation rate $\omega(t) \equiv \omega_{\mathrm{ref}}$ and zero displacement of the damper mass $y(t) \equiv 0$. Following [5,6] let us use an energy-based approach and apply the speed-gradient (SG) method [4] for control law design.

The total energy H of the system (1) may be derived as

$$H(y, \dot{y}, \omega) = \frac{1}{2}\Big(\big(m(1-\mu) + k\big)y^2 + I\Big)\omega^2 - mb\dot{y}\omega - \frac{1}{2}m(1-\mu)\dot{y}^2. \tag{2}$$

Substitution of $y = \dot{y} = 0,\ \omega = \omega_{ref}$ to (2) gives the desired energy H_{ref} as $H_{\mathrm{ref}} = 0.5I\omega^2_{\mathrm{ref}}$. Let us introduce the *goal function* $Q = |H - H_{\mathrm{ref}}|^2$ and derive the SG control laws in the *finite form* [4]. It gives the "*proportional*" and *relay* algorithms as follows:

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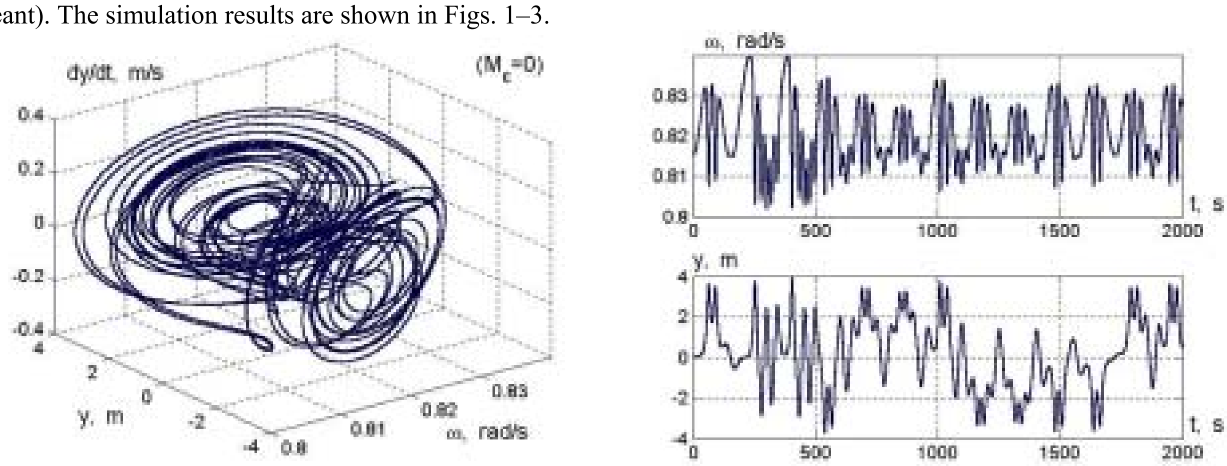
$$M_C\left(y,\dot{y},\omega,H_{ref}\right)=\gamma\left(H_{ref}-H(y,\dot{y},\omega)\right)\cdot\left(\omega+\dot{\tilde{y}}\left(\tilde{I}+\tilde{y}^2\text{-}1\right)^{-1}\right), \quad (3)$$

$$M_C\left(y,\dot{y},\omega,H_{ref}\right)=\gamma\,\mathrm{sign}\left(H_{ref}-H(y,\dot{y},\omega)\right)\cdot\mathrm{sign}\left(\omega+\dot{\tilde{y}}\left(\tilde{I}+\tilde{y}^2\text{-}1\right)^{-1}\right), \quad (4)$$

where $\tilde{y}=(1\text{-}\mu)b^{-1}y$, $\tilde{I}=(1-\mu)m^{-1}b^{-2}I$ are introduced. The control law (4) can be directly implemented by means of the on-off operating resistojets. In such a case the gain γ gives the control torque amplitude: $\overline{M}=\gamma$. The pulse-width modulation can be used for implementation of the "proportional" control law (3) by means of the on-off device.

4. Simulation results

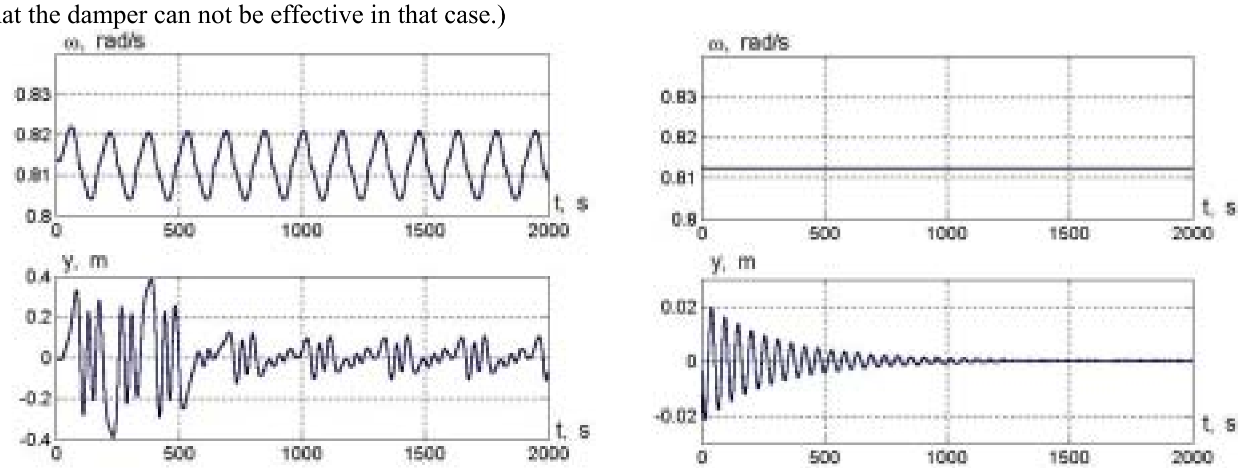
For numerical examination the parameters of the spinning spacecraft with circumferential nutational damper were chosen to be similar to that of Intelsat-II being m=0.3 kg, b=1 m, k=0.2 N/m, μ=0.01, I=100 kgm^2, c=0.002 Ns/m [2]. The harmonic disturbance torque M_E is taken, $M_E(t)=\overline{M}_E\sin\Omega t$. The excitation frequency Ω=0.04 s^{-1} and the amplitude $\overline{M}_E=0.05$ Nm. Following initial conditions are picked up for the simulations: ω(0)=0.815 s^{-1}, y(0)=0, $\dot{y}(0)=0$. Two cases of the control torque amplitude $\overline{M}$ are studied: a) $\overline{M}=0.0225$ Nm, $\overline{M}<\overline{M}_E$ and b) $\overline{M}=0.055$ Nm, $\overline{M}=1.1\overline{M}_E>\overline{M}_E$ (for example, the SSTL's water resistojets producing the thrust in the order 0.01÷0.10 N would be meant). The simulation results are shown in Figs. 1–3.



a) Phase plot   b) Time histories

Fig 1: Chaotic oscillations for the case of uncontrollabe motion

The simulation results for the case of active damping absence (M_C≡0) are plotted in Fig. 1. One sees that the chaotic motion with a large magnitude of $y(t)$ appears. (Note that in practice $y(t)$ is restricted due to travel limits, but it is seen that the damper can not be effective in that case.)

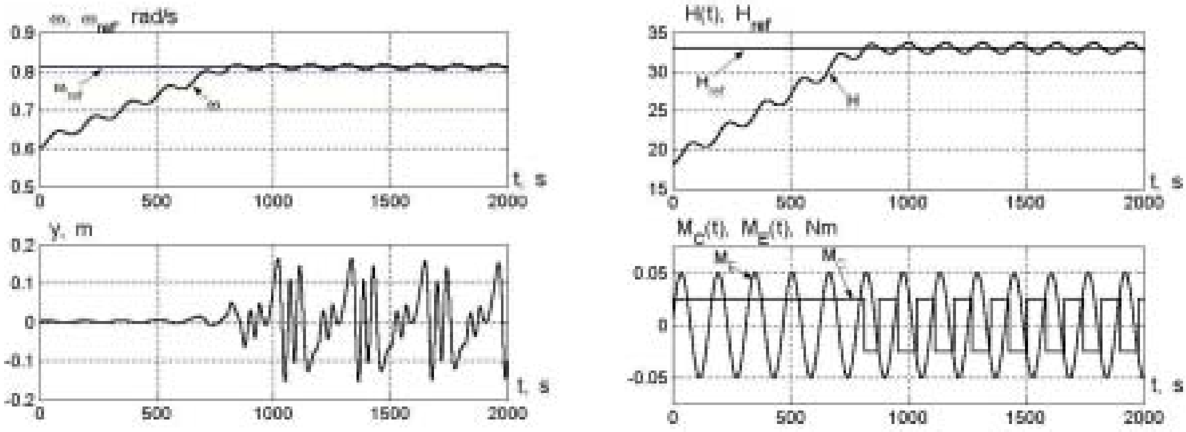


a) Time histories, $\overline{M}=0.0225$ Nm, $\overline{M}<\overline{M}_E$ b) Time histories, $\overline{M}=0.055$ Nm, $\overline{M}=1.1\cdot\overline{M}_E$

Fig 2: Active damping via control algorithm (4)

The effect of the feedback control via relay SG-law (4) is demonstrated in Fig. 2. It is taken H_{ref}=33 Nm, which corresponds to ω_{ref}=8.124 rad/s. It is seen that even in the case when the amplitude of control torque is less that one of the disturbance, $\overline{M}=0.5\cdot\overline{M}_E$ (Fig 2a), the system behaviour is improved in a great extent in comparison with the uncontrollable case. Perfect supression of oscillations is obtained for the case $\overline{M}=1.1\cdot\overline{M}_E$ (Fig. 2b). Note that in [2,3] the ratio $\overline{M}/\overline{M}_E$ is about 15. Therefore the proposed method is characterized as a low level control.

Speeding-up the satellite rotation from ω(0)=0.6 rad s^{-1} to given velocity ω_{ref} is demonstrated in Fig 3 for the case $\overline{M} = 0.5 \cdot \overline{M}_E$. In the case $\overline{M} = 1.1 \cdot \overline{M}_E$ the finite-time convergence of $\omega(t)$ to ω_{ref} takes place. The transient time is about 360 s. The sliding motion with exact holding the desired state arises after the transient is finished. (The similar processes are pictured in Fig. 2a.) The control algorithms with a dead-zone or pulse-width modulation can be used to reduce propellent consumption and working fluid discharge.



a) Time histories of $\omega(t)$ and $y(t)$ b) Time histories of $H(t)$, $M_C(t)$, $M_E(t)$.

Fig 3: Satellite speeding-up via the control law (4), $\overline{M} = 0.5 \cdot \overline{M}_E$.

5. Conclusions

The paper proposes the control method aimed to stabilize the satellite rotation rate ω close by desired reference value ω_{ref} without nutation or precession. The speed-gradient control technique is applied to control law design, ensuring achievement of the control goal for less value of $\overline{M}$ compared with other control methods. Numerical simulations have shown the effeciency of SG control strategy in eliminating chaotic instabilities in a spinning spacecraft and robustness properties with respect to excitation torque amplitude.

References

[1] *Cochran jr. J.E., Thompson J.A.* Nutation dampers vs precession dampers for asymmetric spacecraft. *J. Guid., Control Dyn.* 1980, 3, 22–28.

[2] *Meehan P.A., Asokanthan S.F.* Control of chaotic instabilities in a spinning spacecraft with dissipation using Lyapunov's method. *Chaos Solitons Fractals*, 2002, 13 (9), 1857–1869.

[3] *Meehan P.A., Asokanthan S.F.* Control of chaotic motion in a dual-spin spacecraft with nutational damping. *J. Guid., Control Dyn.* 2002, 25 (2) 209–214.

[4] *Fradkov A.L., Miroshnik I.V., Nikiforov V.O.* Nonlinear and adaptive control of complex systems. Kluwer Academic Publishers, 1999.

[5] *Fradkov A.L.* Swinging control of nonlinear oscillations. *Intern. J. Control*, 1996. 64 (6), 1189–1202.

[6] *Shiriaev A.S., Egeland O., Ludvigsen H., Fradkov A.L.* VSS-version of energy-based control for swinging up a pendulum. *Syst., Control Let*. 2001, 44 (1), 45–56.