Effect of Void Gas Lying between Fluid Slugs in Nutation Dampers

By

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Summary: Nutation dampers of a partially filled annular type have been often installed in satellites to remove their coning motion, if any. It is expected that during the cruising of a satellite the fluid slug in its damper tends to be separated into several owing to the existence of temperature gradient, and this results in the deterioration of its damping characteristics. Under such conditions it is better to mount the damper with offset in the satellite. The increase in kinematic viscosity ν of working fluid is also advantageous, but there is little merit in having a large size of inner radius r. Anyway once this phenomenon has occurred, the drastic increase in the damping time is inevitable, so it is most important for the whole damper to be kept uniform in temperature.

1. Introduction

Halley's Comet explorers, 'SUISEI' and 'SAKIGAKE' are both spin stabilized ones. They are equipped with annular nutation dampers which are intended to remove the nutational or coning motions caused during controlling the attitudes and/or trajectories of the satellites. As for 'SAKIGAKE', the damping characteristics of its damper were degenerated in two weeks after launch. We can ascribe this phenomenon to the separation of damper fluid into several slugs [1]. The damper is equipped with heaters and is heated during coasting, and there exists temperature gradient along the annulus. Then the fluid partially filled in the damper (in this case, silicon oil is used) is vaporized at both ends of the initial slug. This vapor is condensed again into drops and they adhere to the wall at the unstable equilibrium point of the damper, namely at the opposite side to the stable point. This process goes on till there generates another slug. The voids between these slugs are filled with the saturated vapor and other gases remaining in the procedure of seal. Therefore the pressure of these gases acts on the slugs as a spring and prevents them from running through the annular damper.

Based upon these considerations, an investigation of a model for two slugs has been conducted to explain the increase in the damping time of 'SAKIGAKE' satisfactorily. For the present, an analysis is conducted on a model for N slugs generally and an investigation is made on the parameters governing the damping characteristics.

2. Analysis of Motion of Fluid Slugs

2.1 Basic Equations Governing Motion of Fluid Slugs

The 'SAKIGAKE' and its nutation damper are shown in Fig. 1. Its damper is mounted in an equatorial plane with offset from spin axis. The coning angle θ_0 caused by burning of RCS (Reaction Control System) thrusters is obtained from the sun-spin axis angle θ_s measured by a solar sensor. Fig. 2 shows the results of change of θ_s. Case (a) is the result at the early stage of coasting. The damping time is about 7 minutes. Case (b) is that acquired on 17 days after launch. From these figures, we can see immediately that there is obvious difference between damping amplitude in case (a) and (b). Fig. 3 shows a schematic view of a nutation damper in a satellite and notations used in the following analysis. As shown in Fig. 4 the slugs in the damper are regarded to move in an equatorial plane if the coning angle θ_0 is small enough.

When the fluid in the annular damper is divided into N slugs, the governing equation of the ith slug is expressed as follows;

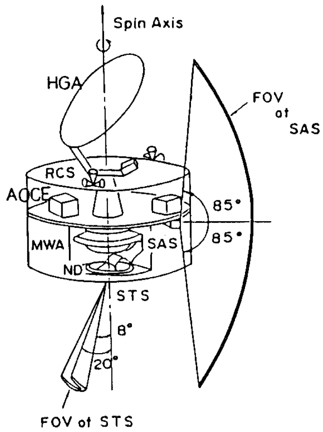

Fig. 1. "SAKIGAKE" and its nutation damper.

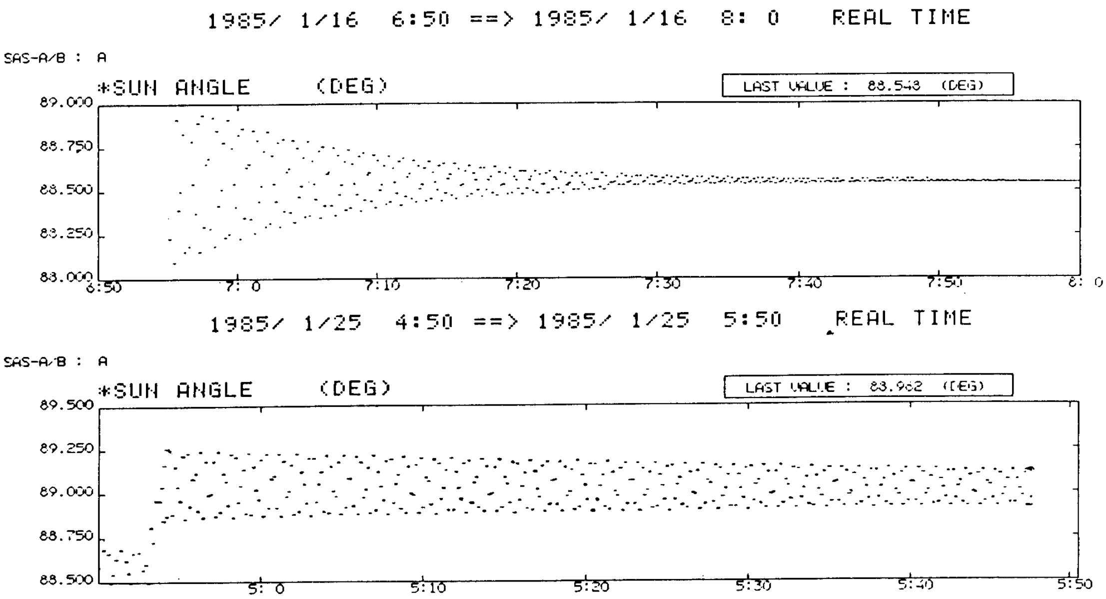

Fig. 2. Examples of damping motion of nutation.

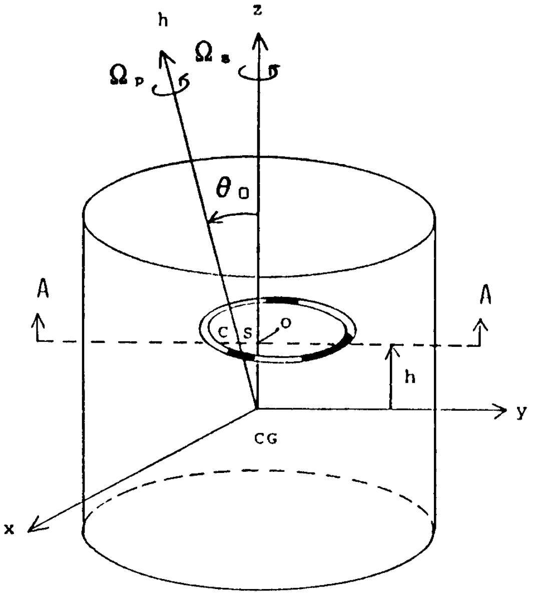

Fig. 3. Satellite and partially filled nutation damper.

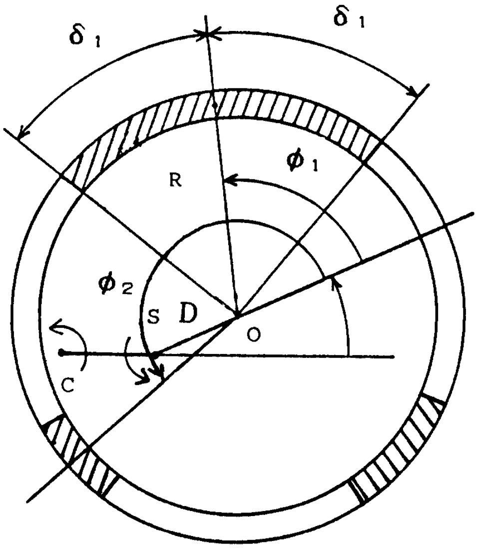

Fig. 4. Schematic view of fluid slugs in nutation damper (cross section A-A).

$$\begin{aligned} m_i R\ddot{\phi}_i = & -h_i\theta_0\Omega_p^2 m_i \sin(\Omega_s t+\phi_i) - D_i\omega_0^2 m_i \sin\phi_i \\ & -m_i CR\dot{\phi}_i + \pi r^2(P_{i-1,i} - P_{i,i+1}) \end{aligned} \tag{1}$$

where

$$h_i = h\cdot \sin\delta_i/\delta_i \tag{2}$$

$$D_i = D\cdot \sin\delta_i/\delta_i \tag{3}$$

$$C = 8\nu/r^2 = 8\omega_0/R_e \tag{4}$$

m_i is the mass of the ith slug and $P_{i-1,i}$ means the pressure in the void between the $(i-1)$th and ith slugs. The first term in the right side of Eq. (1) represents the inertial force due to the coning motion, the second is that due to offset, the third is the friction drag and the fourth term means the void pressure. Here we can assume Poiseuille flow approximation for a small number of N, and although it is inadequate for a larger number of N, we can see soon after that there is no necessity of taking such a model into account for a certain reason. (We should use C_f of a laminar boundary layer as a value of drag coefficient if N is large.) Further, there exists another force acting on the surface of each end, namely the surface tension, but we neglect this term for simplicity. (Silicon oil is so-called the wetting liquid and has a small surface tension [2].)

2.2 Analytical Solution of these Equations

There are two typical modes of the motion of fluid slugs, 'spin synchronous mode' and 'nutation synchronous mode' [3]. Here we consider the former mode and the slugs are oscillating with small amplitude around their equilibrium centers.

$$\phi_i=\phi_{i0}+\tilde{\phi}_i, \qquad \phi_{i0}\gg\tilde{\phi}_i \tag{5}$$

Thus;

$$\sin(\Omega_s t+\phi_i)\doteqdot\sin(\Omega_s t+\phi_{i0}) \tag{6}$$

$$\sin\phi_i\doteqdot\cos\phi_{i0}\cdot\tilde{\phi}_i+\sin\phi_{i0} \tag{7}$$

Assume;

$$P_{i-1,i}=P_0, \qquad \text{when } \phi_i=\phi_{i0} \tag{8}$$

then the pressure $P_{i-1,i}$ with the motion of slugs is expressed as;

$$P_{i-1,i}=\left[\frac{\phi_{i0}-\phi_{(i-1)0}-(\delta_i+\delta_{i-1})}{\phi_{i0}-\phi_{(i-1)0}-(\delta_i+\delta_{i-1})+\tilde{\phi}_i-\tilde{\phi}_{i-1}}\right]P_0 \tag{9}$$

or

$$P_{i-1,i}=\left[1-\frac{\tilde{\phi}_i-\tilde{\phi}_{i-1}}{\phi_{i0}-\phi_{(i-1)0}-(\delta_i+\delta_{i-1})}\right]P_0 \tag{10}$$

Using Eqs. (6), (7) and (10), we can linearize Eq. (1) to obtain;

$$\begin{aligned} m_iR\ddot{\tilde{\phi}}_i= & -h_i\theta_0\Omega_r^2m_i\sin(\Omega_s t+\phi_{i0})-D_i\omega_0^2m_i(\cos\tilde{\phi}_{i0}\cdot\phi_i+\sin\phi_{i0})-m_iCR\dot{\tilde{\phi}}_i \\ & +\pi r^2P_0\left[\frac{\tilde{\phi}_{i+1}-\tilde{\phi}_i}{\phi_{(i+1)0}-\phi_{i0}-(\delta_{i+1}+\delta_i)}-\frac{\tilde{\phi}_i-\tilde{\phi}_{i-1}}{\phi_{i0}-\phi_{(i-1)0}-(\delta_i+\delta_{i-1})}\right] \end{aligned} \tag{11}$$

Rewrite Eq. (11);

$$\begin{aligned} \ddot{\tilde{\phi}}_i= & -(h_i\theta_0\Omega_p^2/R)\sin(\Omega_s t+\phi_{i0})-(\omega_0^2D_i/R)(\cos\phi_{i0}\cdot\tilde{\phi}_i+\sin\phi_{i0}) \\ & -C\dot{\tilde{\phi}}_i+Ku_i(\tilde{\phi}_{i+1}-\tilde{\phi}_i)-Kv_i(\tilde{\phi}_i-\tilde{\phi}_{i-1}) \end{aligned} \tag{12}$$

where

$$K=\frac{P_0}{2R^2\rho_0} \tag{13}$$

$$u_i=\frac{1}{\delta_i}\times\frac{1}{\{(\phi_{(i+1)0}-\phi_{i0})-(\delta_{i+1}+\delta_i)\}} \tag{14}$$

$$v_i=\frac{1}{\delta_i}\times\frac{1}{\{(\phi_{i0}-\phi_{(i-1)0})-(\delta_i+\delta_{i-1})\}} \tag{15}$$

and ρ_0 is the density of the fluid. Further transformation of Eq. (12) leads to;

$$\ddot{\tilde{\phi}}_i = -A_i\,[\exp\{i(\Omega_s t+\phi_{i0})\} - \exp\{-i(\Omega_s t+\phi_{i0})\}] - B_i\,(\cos\phi_{i0}\cdot\tilde{\phi}_i + \sin\phi_{i0}) \\ -C\dot{\tilde{\phi}}_i + E_i\tilde{\phi}_{i+1} + F_i\tilde{\phi}_i + G_i\tilde{\phi}_{i-1} \tag{16}$$

where

$$A_i = h_i\theta_0\Omega_p^2/(2Ri) \tag{17}$$

$$B_i = \omega_0^2 D_i/R \tag{18}$$

$$E_i = Ku_i \tag{19}$$

$$F_i = -K(u_i+v_i) \tag{20}$$

$$G_i = Kv_i \tag{21}$$

Assume the forced oscillating solution of Eq. (16) as follows;

$$\tilde{\phi}_i = R_i + P_i\exp(i\Omega_s t) + Q_i\exp(-i\Omega_s t) \tag{22}$$

Substituting Eq. (22) into Eq. (16), we can obtain the vectors R, P, and Q as follows;

$$R = \{R_i\} = A^{-1}(E,\ F-b_c,\ G)\cdot b_s \tag{23}$$

$$P = \{P_i\} = A^{-1}(E,\ F-b_c+(\Omega_s^2 - i\Omega_s C)\Delta,\ G)\cdot a_+ \tag{24}$$

$$Q = \{Q_i\} = -A^{-1}(E,\ F-b_c+(\Omega_s^2 + i\Omega_s C)\Delta,\ G)\cdot a_- \tag{25}$$

where

$$A(E,\ F,\ G) = \begin{bmatrix} F_1 E_1\, 0\cdots\cdots 0 & G_1 \\ G_2 F_2 E_2 \cdots\cdots\cdots & 0 \\ \vdots & \vdots \\ 0\cdots\cdots G_{N-1} & E_{N-1} F_{N-1} \\ E_N 0\cdots 0 \quad G_N & F_N \end{bmatrix} \tag{26}$$

$$a_+ = \begin{bmatrix} A_1\ \exp(i\phi_{10}) \\ \vdots \\ A_N\ \exp(i\phi_{N0}) \end{bmatrix} \tag{27}$$

$$a_- = \begin{bmatrix} A_1\ \exp(-i\phi_{10}) \\ \vdots \\ A_N\ \exp(-i\phi_{N0}) \end{bmatrix} \tag{28}$$

$$b_s = \begin{bmatrix} B_1\ \sin\phi_{10} \\ \vdots \\ B_N\ \sin\phi_{N0} \end{bmatrix} \tag{29}$$

$$b_c = \begin{bmatrix} B_1 \cos\phi_{10} \\ \vdots \\ B_N \cos\phi_{N0} \end{bmatrix} \tag{30}$$

$$\Delta = \begin{bmatrix} 1 \\ \vdots \\ 1 \end{bmatrix}$$

2.3 Damping Time Constant

The dissipation rate $\dot{E}_{\text{fluid}}$ of the coning energy E_c by the oscillations of the fluid slugs is expressed as;

$$\dot{E}_{\text{fluid}} = \sum_{i=1}^{N} \langle m_i R^2 C \dot{\tilde{\phi}}_i^2 \rangle \tag{31}$$

Here < > means the time averaged value. On the other hand, the coning energy of the satellite E_c is given by;

$$E_c = -1/2 \cdot \sigma I_3 \omega_0^2 \theta_0^2 \tag{32}$$

where

$$\sigma = 1 - 1/\gamma = 1 - I_3/I_1 \tag{33}$$

I_3 and I_1 are respective moments of inertia about spin and transverse axes. The damping time τ is defined by;

$$\tau = 2E_c/\dot{E}_{\text{fluid}} \tag{34}$$

2.4 Nondimensional Parameters

Replacing time derivative $\partial/\partial t$ in Eq. (16) by $\partial/\partial t^*$ ($t^* = \omega_0 t$), we can non-dimensionalize the simultaneous equations as follows;

$$\begin{aligned} \partial^2\tilde{\phi}_i/\partial t^{*2} = & -A_i^* [\exp\{i(\sigma t^* + \phi_{i0})\} - \exp\{-i(\sigma t^* + \phi_{i0})\}] \\ & - B_i^* (\cos\phi_{i0} \cdot \tilde{\phi}_i + \sin\phi_{10}) - C^* \partial\tilde{\phi}_i/\partial t^* \\ & + E_i^* \tilde{\phi}_{i+1} + F_i^* \tilde{\phi}_i + G_i^* \tilde{\phi}_{i-1} \end{aligned} \tag{35}$$

where A_i^*, B_i^*, C^*, E_i^*, F_i^*, *and* G_i^* are nondimensional parameters. Assume that each fluid slug is of the same size and all the intervals between the adjacent oscillation centers are the same as well, then we can easily show the parameters as follows;

$$A_i^* = h_i \theta_0/(2R\gamma^2 i) \tag{36}$$

$$B_i^* = D_i/R \tag{37}$$

$$C^* = 8\nu/r^2\omega_0 = 8/R_e \tag{38}$$

$$E_i^* = G_i^* = \pi^2/4 \cdot P_0 N^2 / \{R^2 \omega_0^2 \rho_0 \eta (1-\eta)\} \tag{39}$$

$$F_i^* = -2E_i^* \tag{40}$$

η is the fill ratio of the fluid. The solution $\tilde{\phi}_i^*$ is proportional to A_i^*, therefore;

$$\dot{\tilde{\phi}}_i = \omega_0 \dot{\tilde{\phi}}_i^* = \omega_0 A_i^* \cdot \text{func}(N, R_e, D_i/R, P_0/\{R^2\omega_0^2\rho_0\eta(1-\eta)\}) \tag{41}$$

Using Eqs. (34) and (41), the nondimensional damping time τ^* is given as a function of four parameters, N, R_e, P_D, P_P, and a proportional term P_r.

$$\tau^* = \tau/(2\pi/\omega_0) = \tau/T = P_r \cdot \text{func}(N, R_e, P_D, P_P) \tag{42}$$

where

$$P_r = \frac{\sigma}{(1-\sigma)^4} \cdot \frac{I_3 R_e}{m_i h_i^2} = \frac{\sigma}{(1-\sigma)^4} \cdot \frac{I_3 \omega_0}{\rho_0 R \eta h_i^2 \nu} \tag{43}$$

$$P_D = D_i/R \tag{44}$$

$$P_P = P_0/\{R^2\omega_0^2\rho_0\eta(1-\eta)\} \tag{45}$$

P_r includes the ratio of moment of inertia of the satellite to that of the damper fluid.

3. Effects of the Parameters on Damping Characteristics

The data of the spacecraft 'SAKIGAKE' and of its nutation damper are given below;

$I_1 = 2.0\times10^8\ \text{g}\cdot\text{cm}^2$, $I_3 = 3.0\times10^8\ \text{g}\cdot\text{cm}^2$, $\gamma = I_1/I_3 = 0.67$, $h = 44$ cm,
$\Omega_s = -0.325$ rad/s, $\Omega_p = 0.975$ rad/s, $\omega_0 = 0.65$ rad/s, $R = 19.0$ cm,
$r = 1.0$ cm, $D = 2.0$ cm, $\eta = 0.37$, $\nu = 1.5\times10^{-2}\ \text{cm}^2/\text{s}$, $\rho_0 = 0.85\ \text{g/cm}^3$,
$R_e = 43.3$, $P_D = 0.103$

The increase in the damping time τ^* according to the number of separated slugs N is seen in Fig. 5. Here all slugs are of the same size and $\phi_{i0} = (2/N)\cdot(i-1)$ for each i. The damping time τ^* is expected to be asymptotic when $N\to\infty$. The initial void pressure P_0 is a function of temperature T_e (°C) and is given as a sum of the saturated gas pressure P_S and the remaining gas pressure P_R, where;

$$P_S = 10^{(7.64\log(83.+T_e)-15.8)}\ \text{mmHg} \tag{46}$$

$$P_R = 0.020\times(273.+Te)/273.\ \text{mmHg} \tag{47}$$

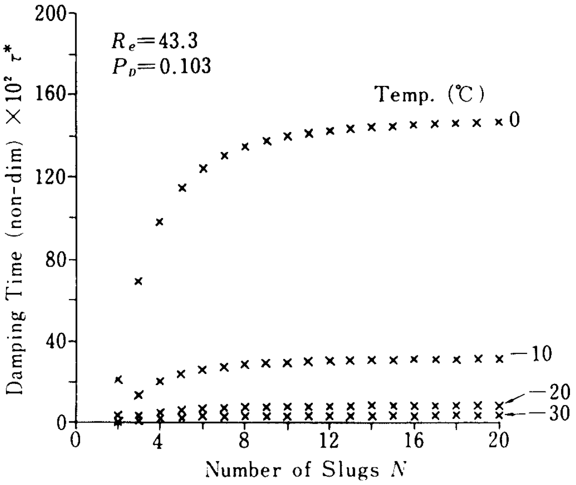

Fig. 5. Damping time as a function of number of slugs.

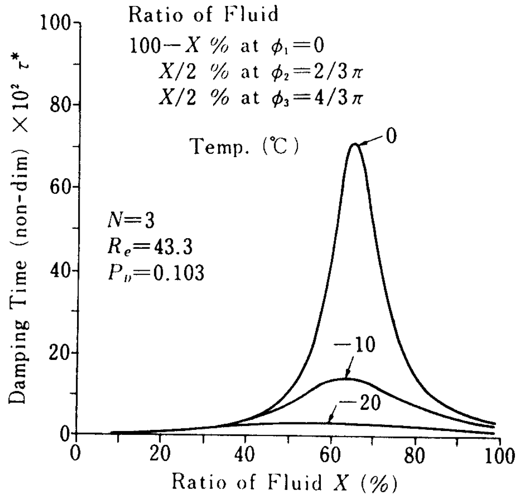

Fig. 6. Damping time as a function of ratio of fluid that is away from the stable point.

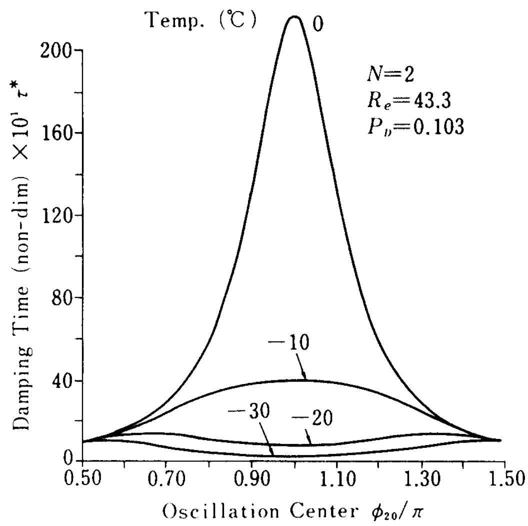

Fig. 7. Damping time as a function of the oscillation center of a generated slug.

As seen in Fig. 6 the separation ratio of the damper fluid which gives the maximum value of τ^* is varying with the initial void pressure P_0. To give τ^*_{max} the ratio of the fluid that is not at the stable point comes up close to 2/3 according as the pressure rises, which means that the three fluid slugs are of the same size.

The effect of the position of the oscillation center of a generated slug ϕ_{20} on the damping time τ^* is shown in fig. 7 for $N=2$. The two slugs are of the same size. There are opposite tendencies between the cases of higher and lower void pressure P_0, which is explained in the following manner. When $\phi_{20}=\pi$ the two slugs always tend to move in the opposite directions by the inertial force, which is interfered by the void pressure. Therefore the maximum τ^* is given if the void pressure is higher. But in case the pressure becomes lower, the braking effect reduces, and on the contrary, when the two slugs are motioning close to each other, the pressure difference between both sides of each slug changes much more rapidly with the same displacement, and so in

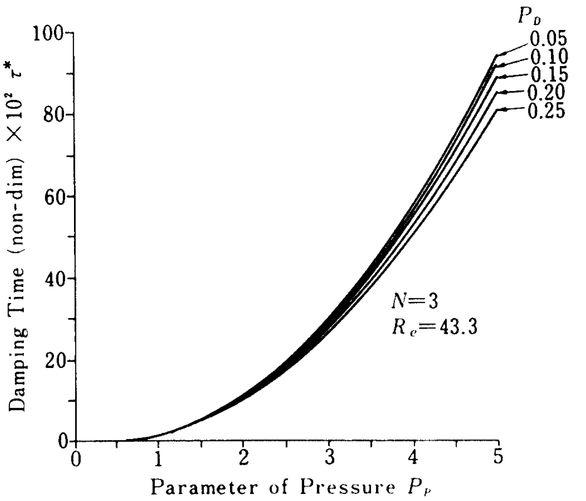

Fig. 8. Damping time as a function of pressure.

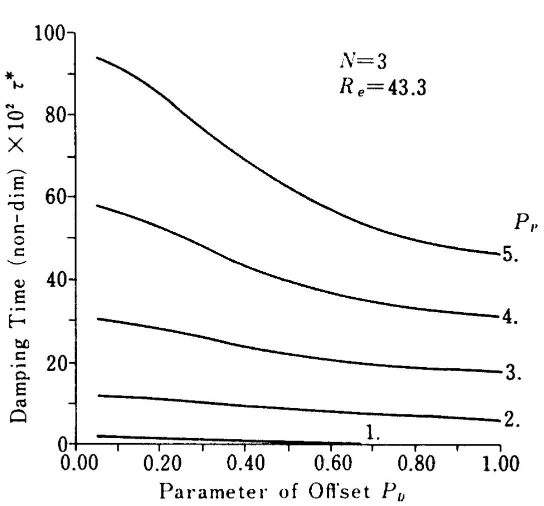

Fig. 9. Damping time as a function of offset.

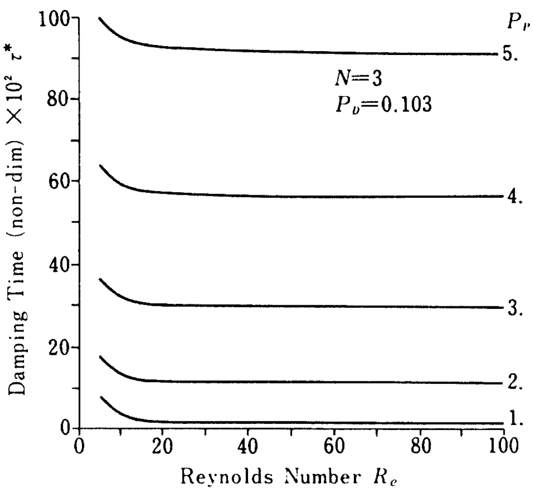

Fig. 10. Damping time as a function of Reynolds Number.

this case the condition $\phi_{20}=\pi$ gives the minimum vlaue of τ^*.

Calculations have been executed under the conditions that;

$$N=3, \quad m_1=m_2=m_3, \quad \phi_{i0}=(i-1)\times 2\pi/3 \tag{48}$$

and the results are shown in Figs. 8–10.

Definitely higher the void pressure P_0, larger the damping time τ^*, as seen in Fig. 8. The time τ^* is expected to be expressed as $\tau^*=P_r \cdot P_P^{\alpha}$, where α is the function of three other parameters, N, Re, and P_D. This is easily understood considering that P_P is somewhat of a spring constant.

Fig. 9 shows the relation between the offset D and the damping time τ^*. It is more advantageous for the damping characteristics when the offset becomes greater. It should be within a reasonable value, however, as little disturbance is allowed as to the displacement of the principal axis of inertia of the satellite.

The effect of Reynolds Number R_e on τ^* is shown in Fig. 10. Here R_e is varied by the change in the inner radius r in order not to charge the value of P_r in Eq. (43). We can see that too little Reynolds Number makes the damping characteristics worse, but that there is no sense of designing a damper with quite a large size of inner radius r. The time τ^* is in the inverse proportion to kinematic viscosity ν of the fluid as seen in Eq. (42), and so the method is advantageous to use fluids having a large value of ν, and consequently the permissible minimum value of r is given to keep Reynolds Number above a certain value.

4. Concluding Remarks

We have started from the standpoint that the increase in the damping time of 'SAKIGAKE' mounted with a nutation damper was caused by the separation of the damper fluid into several slugs, and examined the parameters that detrmine the damping characteristics by nondimensionalizing the basic simultaneous equations. Assuming 'spin synchronous mode', the equations are linearized and an analytical solution is obtained to clarify the effect of each parameter on the damping time in some figures. It becomes clear that there is no use of examining models for too many separated slugs. The number of slugs we may adopt for a reasonable model is at most 5 or so.

As the offset grows greater, the damping time becomes shorter, but there is little merit in designing too large value of inner radius r. It is advantageous to adopt some liquid as the working fluid that has a large value of kinematic viscosity ν. It is also shown better to mount the damper in an equatorial plane that is as far from the center of gravity of the satellite as possible. Although all these requirements are satisfied, the damping characteristics of models discussed in this paper are worse by far than those of a model for a non-separated slug, and so there is no doubt of the significance of temperature control of the damper.

This analytical method based on the linearized equations gives a satisfactory interpretation of the change in the damping time of 'SAKIGAKE', and is thought to be quite useful for a couple of slugs in nutation dampers. Assumptions made here also seem to be reasonable in a wide range of void pressure between the slugs.

References

[1] Hinda, M., *et al.*: "A Consideration on Nutation Damper of SAKIGAKE" (in Japanese), Proc. of the 17th Annual Conf., 1986, pp. 51–52.

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