Engineering Notes

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Design and Ground Test of a Pendulum-Type Active Nutation Damper

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Nomenclature

A, B, C = moments of inertia of the undeformed structure ($\alpha = 0$)
C_0 = stall torque
F = plant matrix
G = control matrix
I_1, I_2, I_3 = pendulum moments of inertia
J_2 = potentiometer and clutch inertia
J_3 = motor and gear inertia
K = gain matrix
N = gear ratio
T = damping time-constant
U = control variable $0 \leq U \leq 1$
f = motor damping coefficient
g = steady-state gain $= (\alpha/\omega_1)_{s \cdot s}$
$g_i, i = 1, \ldots, 4$ = feedback gains
α = pendulum angular deviation
θ = location of the gyro input axis with respect to the (x, z) plane
λ = nutation frequency $= \sigma\omega_3$
σ = $[(C-A)(C-B)/AB]^{1/2}$
ω_1, ω_2 = transverse angular velocity components
ω_3 = spin rate

Introduction

BESIDES mass expulsion systems, the principles of active inertial damping have been studied by several authors, for example, instantaneous mass-shift system,[1] and CMG[2] driven from the signal of an accelerometer. These systems are based on the principle of momentum exchange. Thus, the acceleration of a moving mass on a linear track can be used to reduce the tumbling motion of a space vehicle, but ground tests of an experimental device appear to be delicate to implement. In addition, the CMGs necessitate a practically permanent operation because of the start-up time, this leads to an appreciable electric energy consumption. The work[3] presented in this Note concerns the theoretical study and the ground tests of a control system for the active damping and, eventually, the automatic dynamic balancing of spinning satellites by means of the principle of controlled modification of inertias. The ground tests on an air-bearing facility are facilitated by use of a rate gyro for nutation sensing and by the design of a balanced actuator of the pendulum type, in preference to the use of accelerometers and push-pull masses which are difficult to pair mechanically.

Active Nutation Damper and Test Assembly

The experimental actuator, shown in Fig. 1, consists of two statically balanced weights driven by a two-phase 400 Hz motor-generator size 8 (right), a gear train, a friction clutch, and an induction potentiometer size 11 (left), as shown schematically in Fig. 2. The motor voltage is controlled by a linear regulator; the feedback signals are issued from a rate gyro, the tachometer, and the potentiometer.

The balanced configuration and the use of a rate gyro allow us to ignore the gravity effects and make possible ground test experiments. This damping device has been tested on an air-bearing mounted structure used by the C.N.E.S. for the qualification of the attitude control system of the French D2 satellite. The test facility allows three degrees of freedom for spinning satellites and induces negligible unbalance and friction torques. The onboard information is delivered through FM-FM telemetry and the required attitude maneuvers are obtained by telecommand.

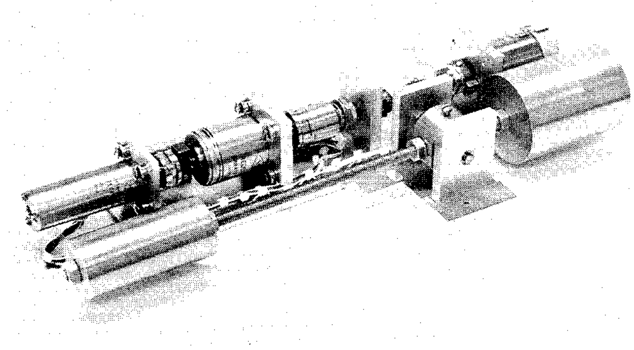

Fig. 1 The experimental active nutation damper.

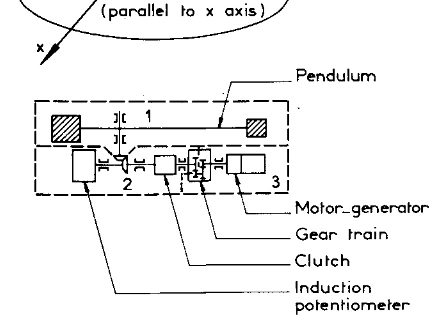

Fig. 2 Geometry of the test assembly.

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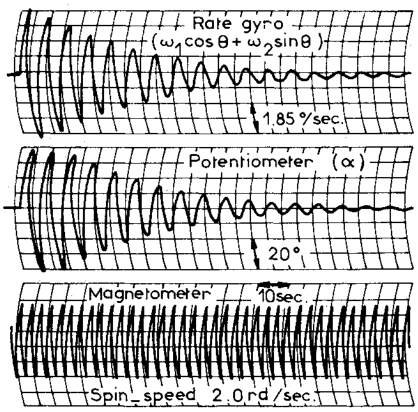

Fig. 3 Telemetry records of a damping phase.

Derivation of the Control Law

A proper dynamic balancing,[4] with the nutation damper locked in the null position, insures that the inertia matrix of the undeformed structure is diagonal. Therefore, if we neglect the disturbing torques, the linearized equations of rotational motion are[3]

$$A\dot{\omega}_1+(C-B)\omega_3\omega_2+I_1\ddot{\alpha}-(NJ_3+J_2)\omega_3\dot{\alpha}+(I_3-I_2)\omega_3{}^2\alpha=0 \quad (1a)$$

$$B\dot{\omega}_2-(C-A)\omega_3\omega_1+(NJ_3+J_2)\ddot{\alpha}+(I_1+I_2-I_3)\omega_3\dot{\alpha}=0 \quad (1b)$$

$$(I_1+J_2+N^2J_3)\ddot{\alpha}+N^2f\dot{\alpha}+(I_3-I_2)(\omega_2+\omega_3\alpha)\omega_3+(J_2+NJ_3)\dot{\omega}_2+I_1\dot{\omega}_1=NC_0U \quad (1c)$$

Here the spin rate ω_3 is high with respect to the transverse components ω_1 and ω_2. Equation (1c) is obtained by adding the moment equations of parts numbered 1, 2, and 3 in the lower part of Fig. 2.

In the state space, Eq. (1) can be written as

$$X=FX+GU \quad (2)$$

with the state vector

$$X^T=(\omega_1,\omega_2,\dot{\alpha},\alpha) \quad (3)$$

and the initial conditions

$$X(0)=X_0 \quad (4)$$

To design a constant gain linear regulator, we use this state-space formulation and the infinite horizon quadratic index

$$J=\frac{1}{2}\int_0^\infty [X^TQX+U^2]\,dt \quad (5)$$

A proper index is found to be[3]

$$Q=\mathrm{diag}\left\{\frac{1}{\omega_0{}^2},\frac{1}{\omega_0{}^2},\frac{1}{\dot{\alpha}_M{}^2},\frac{1}{\alpha_M{}^2}\right\} \quad (6)$$

where ω_0 is the maximum expected value of the transverse rate and $\dot{\alpha}_M$, α_M are the maximum values of pendulum rate and position. From the theory of optimal control it is known that the control law is of the general form

$$U=-G^TKX=g_1\omega_1+g_2\omega_2+g_3\dot{\alpha}+g_4\alpha \quad (7)$$

where the gains g_i are given by the definite positive solution of the Riccati matrix equation

$$KF+F^TK-KGG^TK+Q=0 \quad (8)$$

which can be solved numerically using Kleinman's iteration scheme.[5]

The choice of Eq. (6) prevents any saturation in the control loops. The maximum pendulum deviation thus corresponds to the maximum nutation angle.

Experimental Results

The numerical data of the apparatus are: $A=6.19$, $B=6.20$, $C=9.07$ m^{2}kg; $\omega_3=2$rd/sec (19.1 rpm); $I_1=I_3=1.04\ 10^{-2}$, $I_2=5.7\,10^{-4}$m^{2}kg; $N=300$; $J_2=4.10^{-7}$; $J_3=1.22\,10^{-7}$m^{2}kg; $\omega_0=3.88°$/sec; $\alpha_M=40°$; $\dot{\alpha}_M=41.5°$/sec; $f=3.7\ 10^{-6}$ Nmsec/rd; $C_0=2.3\ 10^{-3}$ Nm. The computer program solving digitally Eq. (8) then leads to the optimal control used to modulate the voltage to the servomotor

$$U=15.50\omega_1-13.97\omega_2-0.98\dot{\alpha}-1.47\alpha \quad (9)$$

this control law has been practically implemented as

$$U=20.87\,(\omega_1\cos\theta+\omega_2\sin\theta)-0.98\dot{\alpha}-1.47\alpha$$

by the control electronics, and the proper positioning $\theta=-42°$ of the rate gyro.

Results of an experimental test are illustrated in Fig. 3, which demonstrates the good transient behavior of the damping mechanism. Furthermore, the exponential decrease of the nutation angle confirms the validity of the above synthesis based on the simplified mathematical model.

Phasing Considerations and Computation of the Time-Constant

Neglecting the longitudinal inertias of the driving mechanism and taking into account Eq. (7), Eq. (1c) is written as

$$(I_1+J_2+N^2J_3)\ddot{\alpha}+N(C_0g_3+Nf)\dot{\alpha}+[NC_0g_4+(I_3-I_2)\omega_3{}^2]\alpha=NC_0g_1\omega_1+[NC_0g_2-(I_3-I_2)\omega_3]\,\omega_2 \quad (10)$$

Numerically, if we assume a slow decay of the transverse rates ω_1 and ω_2 (i.e., $\omega_1\simeq\omega_s\cos\lambda t$, $\omega_2\simeq\omega_s\sin\lambda t$), then Eq. (10) is, with $\omega_3=2$

$$\ddot{\alpha}+47.7\dot{\alpha}+49.9\alpha=505.0\omega_1-455.7\omega_2=608.2\omega_s\cos(\lambda t+\phi) \quad (11)$$

with $\phi=42°1$. The steady-state solution of Eq. (11) is found to be of the form

$$\alpha=g\omega_s\cos(\lambda t+\phi+\psi) \quad (12)$$

with $g=10.3$ and $\psi=-42°.1$. Thus $\psi+\phi=0$, as it could have been expected in order to get maximum torque from the centrifugal forces: the damper motion is phased with the transverse component ω_1.

Following these results, the optimal time constant T is then analytically obtained from the Eqs. (1) when small terms are neglected and $B\simeq A$

$$\ddot{\omega}_1+(I_3/A)(1-\sigma^2)\omega_3{}^2g\dot{\omega}_1+\lambda^2\omega_1\simeq 0 \quad (13)$$

which leads to

$$T=2A/I_3(1-\sigma^2)g\omega_3{}^2 \quad (14)$$

Experimental tests have confirmed the validity of this formula for a large range of spin rate values and have shown that the performances are not sensitive to small changes of the satellite's inertias and of control loop parameters. So Eq. (14) can be used to evaluate rapidly the optimal damping that can be expected for a given damper-satellite configuration when the gyroscopic coupling terms can be ignored. Then the digital computation of the gains g_i gives the appropriate optimal control law which leads to a compromise between a small time-constant and the mass and power expenditure of the damping mechanism.

Conclusion

This Note shows the validity of the principle of the pendulum-type active damper, using the controlled variation of an inertia product in a spinning structure. An experimental device was constructed; its principal advantage is linked to its balanced configuration which makes possible experiments on air-bearing facilities. Compared to passive dampers, the proposed device presents a lower reliability and a greater complexity, but presents no tuning problem; we have presented a simple means of evaluating the damping time constant. The method of positioning the nutation sensor and computing the loop gains has been also given.

References

[1] Kane, T. R. and Scher, M. P., "A Method of Active Attitude Control Based on Energy Considerations," *Journal of Spacecraft and Rockets*, Vol. 6, No. 5, May 1969, pp. 633–636.

[2] Mingori, D. L., Harrisson, J. A., and Tseng, G. T., "Semi-Passive and Active Nutation Dampers for Dual-Spin Spacecraft,"

Journal of Spacecraft and Rockets, Vol. 8, No. 5, May 1971, pp. 448–455.

[3] Amieux, J. C., "Contribution à l'Étude de la Stabilisation de Satellites Gyroscopiques; Conception et Réalisation d'un Amortisseur Actif de Nutation," Thesis, Oct. 1972, Univ. of Toulouse, France.

[4] Hernandez, G., Alengrin, G., and Amieux, J. C., "Sequential Estimation of Spacecraft Inertia Tensor," presented as Paper 2-10, *5th I.F.A.C. Symposium on Automatic Control in Space,* Genoa, Italy, June 4–8, 1973.

[5] Kleinman, D. L., "On an Iterative Technique for Riccati Equation Computations," *IEEE Transactions on Automatic Control,* Vol. AC-13, No. 2, Feb. 1968, pp. 114–115.

Minuteman III Liquid Propulsion System Storage Surveillance Program

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Introduction

SINCE 1966, Textron's Bell Aerospace Company has been conducting a program of storage surveillance on the Minuteman III, Stage IIIa liquid bipropellant system. The objective of the surveillance program is to predict the life of deployed systems with sufficient warning of ageout to allow replacement or refurbishment to be planned. Hardware tests, ranging from full-scale systems to laboratory specimens after predetermined periods of storage, have been made. Test parameters which are judged to be sensitive to aging and critical to the successful performance of the mission are monitored for age regressions to detect significant trends toward a particular mode of failure. This Note reports the progress which has been made in identifying potential weak link components and estimating the likelihood of reliability degradation with continued storage of the system.

System Description

Before discussing the service life investigation, it will be useful to identify the system and its function. The system is characterized by a 52-in.-diam, cork-insulated, magnesium shell within which various assemblies are enclosed (Fig. 1). The system attaches to the aft end of the missile guidance set (MGS) and re-entry vehicle and to the forward end of the third stage solid propellant booster. Electrical signals are transmitted from the MGS to each of five isolation valves, to each of ten low-thrust bipropellant valves, to a high-thrust bipropellant valve, and to an interstage connector.

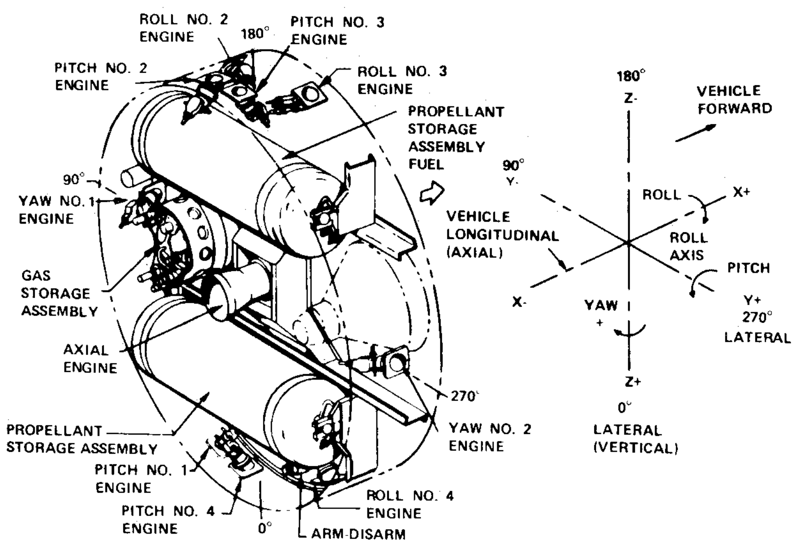
The function of the system is to provide the necessary maneuvering capability to deploy the re-entry vehicles at altitudes above 300,000 ft. When not functioning—that is, during storage—the system has a storage requirement of 3 yr fully loaded with pressurant and propellants. Part of this storage time is logistic storage, which covers the interval from the time the system is pressurized and loaded with propellant to the time the system is declared operational in the silo, and requires that the system withstand a range of temperatures from 20–125°F at 60% maximum relative humidity. In the silo environment, the conditions are 60–80°F at 60% maximum relative humidity.

Reliability During Operational Storage and Flight

There are two mission phases to be considered in evaluating the service life of Minuteman Stage IIIa: a storage phase and a flight phase. The probability of no failure (ageout) during the storage phase of the mission, can be readily evaluated by considering the number of aged systems (11 months or older) which have been stored successfully to date.

It can be shown that the probability curve has the time dependency shown in Fig. 2, from which the probability of no ageout within the 3 yr storage period at 90% confidence, is interpolated to be over 98%. In a similar manner, the probability of no ageout during the flight mission phase, within a 3-yr storage period, can be derived.

The probability curve (Fig. 3) shows a demonstrated probability of over 90% at 90% confidence. From the foregoing, it is clear that there is considerable margin for aging. The problem is to determine what the margins are for critical parameters of the



LIQUID PROPULSION SYSTEM

Fig. 1 Propulsion system rocket engine.

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