A NEW CLASS OF FLUID-LOOP DAMPERS

A.BAZ , L.GUMUSEL
Mechanical Engineering Dept.
The Catholic University
Washington, DC 20064

and

J.FEDOR
NASA- Goddard Space Flight Center
Greenbelt, MD 20771

ABSTRACT

This paper presents a new class of fluid-loop dampers which is radically different from conventional nutation dampers routinely used on spinning spacecrafts. The new damper relies in its operation on the introduction of floating spheres into the fluid loops to enhance the energy dissipation mechanism . In this way the new damper can provide improved damping characteristics over a wide frequency band. It can also be lighter in weight than conventional dampers, as it requires shorter loops to achieve same damping ratio. Furthermore, the new damper eliminates the need for using the partially-filled fluid-loop approach to enhance the damping . Such an approach is found to be at the expense of altering the dynamic symmetry of the spacecraft when the liquid-gas mixture starts oscillating.

A prototype of the damper is built and tested to demonstrate the feasibility of this new class of dampers. The tests are used to study the effect of varying the concentration of the floating spheres on the dynamic characteristics of the damper.

The results obtained indicate the effectiveness of the new damper in suppressing the vibration of flexible systems as compared to the conventional fluid-loop damper. The results suggest also the potential of the proposed concept in providing a damper with multi-axes damping capability which can be used in various spacecraft applications.

1. INTRODUCTION

Fluid-loop dampers have been recognized for many years as simple and effective means for damping the vibration of spinning satellites. The damper consists of a loop, mounted in a plane perpendicular to the spin axis, which is filled with a moderately viscous fluid. When the satellite is subjected to excitations due to the deployment of antennas or booms, for example, it undergoes oscillatory motion that forces the fluid to flow relative to the loop walls. Such relative motion is resisted by the fluid viscous forces which results in dissipating the satellite's oscillation energy.

The fluid-loop damper was first considered , in 1965, for use on NASA's 21 Man Space Station[1,2] because it compares favorably with all other known dampers such as the mercury ring damper [1], the mechanical pendulum damper[1], the controlled damping pendulum[1] and the ball-in-tube pendulum[3]. Since then it has been extensively utilized in numerous space systems as, for example, the IMP-J[4] spacecraft and the Helios satellites[5]. Also, many future satellites , such as NASA's CRRES satellite[6], are now designed to incorporate a fluid-loop damper of one type or another.

In most cases[2,7,8,9], the loop dampers used are of the fully-filled type mainly because they do not alter the dynamic symmetry of the satellite. However, because of the low frequency nature of the encountered oscillations and subsequently the low flow velocities, the loops have to be long enough to render them effective. Accordingly, fully-filled loop dampers can be rather heavy if high damping characteristics are desired. For this reason, the parially-filled dampers have been inroduced[1,3,6,10]. These dampers are found to have considerably higher damping characteristics than their fully - filled counterparts but at the expense of altering the satellite dynamic symmetry as the liquid plug starts oscillating. Furthermore, for their operation to be effective additional offset from the spin axis is needed. Also, the design intricacies of this type of dampers are rather involved because the flow is no longer single-phase and laminar as in the case of the fully-filled dampers. Proper tuning is essential to achieve effective vibration damping when relying on the partially-filled damper. This tuning is not necessary in the case of the fully-filled damper.

To avoid the limitations of the fully-filled dampers and the drawbacks of the partially-filled dampers , this study has been initiated. The study aims primarily at investigating the feasibility of a new class of fluid-loop dampers that combines the advantages of the fully and the partially-filled loop dampers. In other words, the new dampers will maintain the dynamic symmetry of the satellite and , at the same time, have high damping characteristics .

The concept of the new damper is introduced in section 2 of this paper, its experimental performance is presented in section 3 in comparison with conventional loop dampers and section 4 includes the conclusions.

2. CONCEPT OF THE NEW DAMPER

The idea of the new damper is conceived to avoid the above mentioned drawbacks of conventional fluid-loop dampers whether of the fully or the partially-filled types. The new damper belongs to the class of fully-filled dampers whose damping characteristics are enhanced by introducing floating spheres into its fluid loops.

The introduced spheres tend to increase the effective shear resistance of the resulting solid-liquid mixture due to several reasons. The first is attributed to the increase of the surface area of interaction between the solid and the liquid components which , in turn, increases proportionately the viscous drag resistance of the mixture. Secondly, additional form drag forces are developed by virtue of the relative motion between the spheres and the liquid layers. These forces are accompanied with flow seperation on the spheres' surfaces which results in the generation of eddies and vortices. Both the viscous and the form drag components contribute considerably to the dissipation of the energy imparted to the loop. This is more and above the energy disspiated by the viscous friction resistance between the liquid and the tube walls as well as between the adjacent liquid layers as is the case in conventional fluid-loop dampers.

A third source of energy dissipation , in the new damper, results from the continuous acceleration and deceleration of the floating spheres as the fluid-loop undergoes its oscillatory motion.

All the above mentioned sources of energy dissipation account for the improved damping characteristics of the new damper.

The merits of the new damper can best be understood by considering the pressure drop-flow characteristics of solid-liquid mixtures flowing in straight tubes. Such characteristics is shown in Figure 1 along with that of pure liquid flowing in straight tubes[11,12]

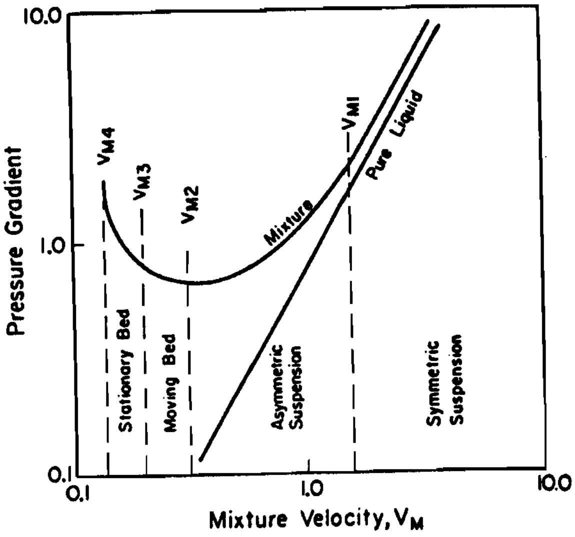


Figure 1 - Frictional resistance of solid-liquid mixtures.

From the figure, it can be seen that liquid-filled loops exhibit low but linear pessure drop-flow characteristics . Accordingly, at low nutation frequencies, the flow velocity of the fluid relative to the loop will be also low so will be the friction resistance and the energy dissipation. But, once the floating spheres are introduced , the frictional characteristics are improved particularly at low relative velocities as can be seen from Figure 1. Such an improvement is attributed to the fact that damping is not only limited to the frictional resistance at the boundaries of the loop but is enhanced by the additional energy dissipation mechanisms resulting from the relative motion between the fluid and the floating spheres.

Accordingly, it is expected that the new damper will have high damping characteristics which extend over a wide flow velocities (i.e. frequency bandwidth). Fewer number of fluid loops will be necessary to suppress the encountered vibrations. Furthermore and most importantly, the proposed damper can be effective in damping out multi-directional vibrations unlike conventional fluid-loop dampers which are only effective in resisting vibration in the plane of the loop. Such multi-directional damping capabilities result from the ability of the floating spheres to move in the vibration direction relative to the fluid.

With such features, the new damper can be very practical and simple means for damping vibrations, isolating payloads and solar panels as well as other space applications.

3.EXPERIMENTAL PERFORMANCE OF THE DAMPER

3.1. Experimental set-up

A prototype of the fluid-loop damper is built from a transparent tygon tubing (A) that has an internal radius $a = 1.1$ cm. The tube is formed into a loop that has a radius $R = 25$ cm. The ends of the tube are joined by a plastic union which is machined to provide a smooth joint. The union is provided with a bleed valve to ensure that the loop is completely filled with liquid without any entrapped air.

The loop is mounted on a pendulum (B) which is pivoted around pivot (O) as shown in Figure 2. A weight ($W = 1.95$ kg) is fixed to the pendulum at a distance (L_p) from the pivot (O). The pendulum is displaced , in all the tests, an initial angle $\vartheta_o = 20^\circ$ from the vertical and then allowed to oscillate freely until it comes to complete stop. The instantaneous angular position of the pendulum is monitored by a position sensor (C) of the potentiometeric type. The sensor signal is recorded on a chart recorder for further analysis.

3.2. Experimental procedures

The performance of the new damper is evaluated by conducting three series of tests . These tests aim at measuring the decay of the amplitude of oscillation of the pendulum alone, the pendulum with the in-active damper and the pendulum with the active damper. The tests are repeated for different levels of concentration of the floating spheres. The results obtained are compared with those of conventional liquid-filled dampers to define the merits and the limitations of the new damper.

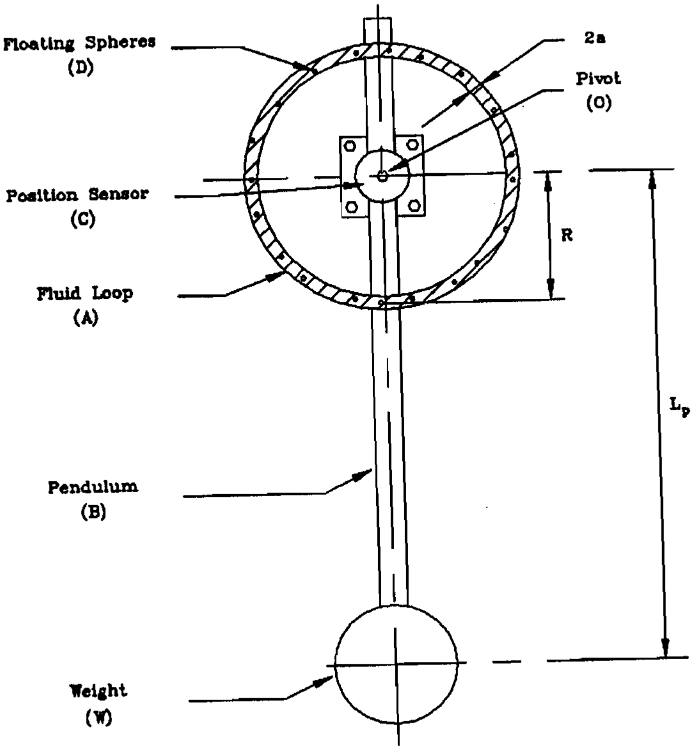


Figure 2 - Schematic drawing of the experimental set-up.

In the first series of tests, the pendulum alone is displaced from the vertical an angle $\vartheta_o = 20^\circ$ and left to oscillate freely until it stops. The time history of the angular position of the pendulum is recorded. The decay of the amplitude of oscillations is used to compute the inherent natural damping of the pendulum resulting from the friction in the pivot, the friction in the position sensor and the air drag on the pendulum arm.

In the second series of tests, the fluid-loop is filled with the working fluid which is a mixture of water and alcohol. The loop is plugged by placing a flat disc inside the plastic union. In this way, the liquid is prevented from flowing through the loop and the damper becomes in-active. The plugged damper is placed on the pendulum and the decay of the amplitude is measured using the logarithmic decrement δ approach[13]. The obtained value of δ serves as a datum for measuring the effectiveness of the damper when it is activated by unplugging its loop as well as when the floating spheres are introduced in it during the third group of tests.

3.3. Experimental results

Figure (3) shows a sample of the time history of the amplitude of oscillation of the pendulum when tested alone and with conventional liquid damper. Figure (4) shows the corresponding characteristics of the new damper for different concentrations of the floating spheres. The displayed results are obtained when the pendulum arm length (L_p) is set at 0.55 m to give a natural frequency of oscillation (ω_n) of 0.66 Hz. For the case of the new damper, polyethylene spheres are used which are 1.125 cm in diameter and have specific gravity of 0.92.

Figures (3-a), (3-b) and (3-c) show the response of the pendulum alone, with plugged liquid-loop and with un-plugged liquid-loop respectively. It can be seen , in these three cases, that the amplitude of oscillation decays to half its initial magnitude after 45 , 34 and 17 cycles respectively. Therefore, activating the liquid-filled damper results in doubling the damping rate as compared to the case of plugged liquid-damper.

Figures (4-a) through (4-d) display the time response of the new damper for floating sphere concentrations ranging between 2.6% to 18.6%. Reviewing the figures indicate that introducing the floating spheres into the loops has produced significant improvement in the damping of vibration as compared to the conventional liquid-filled damper. For example, the amplitude of oscillation drops to half its initial value after 10 cycles when the concentration of the spheres is 10%. Increasing the concentration to 18.6% results in halfing the amplitude after 7 cycles.

It is essential here to note that the resulting improvement in the damping is obtained without any increase in the weight of the damper as the floating spheres are nearly of the same density as the liquid (liquid / sphere density = 1.01).

3.4. Analysis of the results

The time response characteristics of the conventional and the new dampers are analyzed to obtain the damping ratio (ζ) approach as well as the energy dissipated per cycle (ΔE). The calculation of these parameters is obtained from plotting the amplitude of oscillation of the pendulum (ϑ_N) as a function of the oscillation cycle (N). Figure 5 shows such a plot with the pendulum amplitude normalized with respect to the initial amplitude ϑ_o.

The logarithmic decrement (δ) can be calculated from the figure as follows

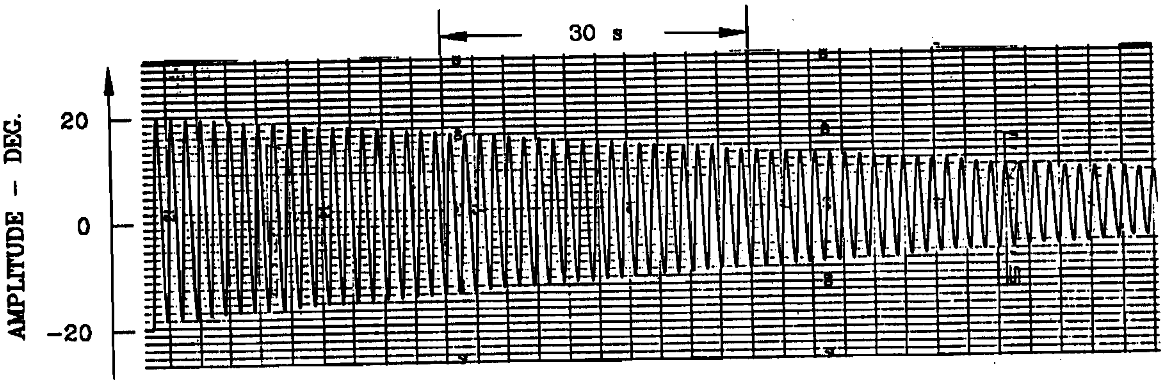
$$\delta = (1/N) \ln (\vartheta_0 / \vartheta_N) \quad (1)$$

If the number of cycles to decay to half the initial amplitude is $N_{1/2}$, then the equation (2) reduces to

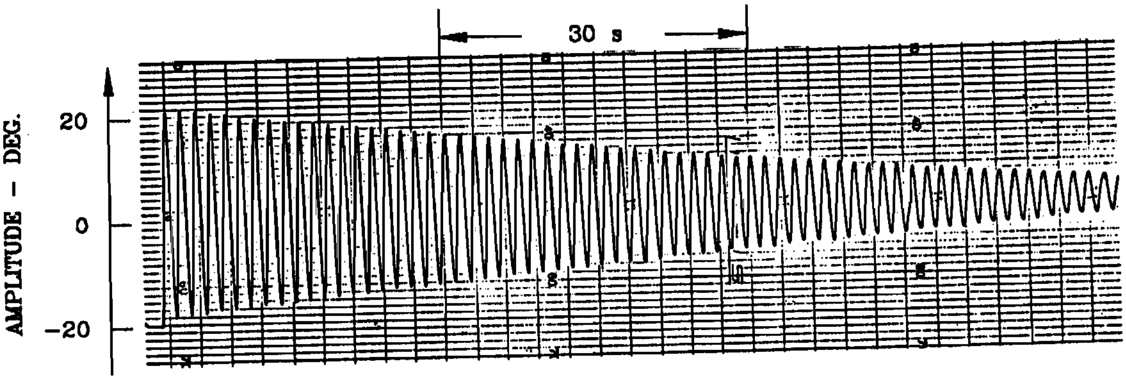
$$\delta = 0.693 / N_{1/2} \quad (2)$$

The damping ratio (ζ) can then be calculated from

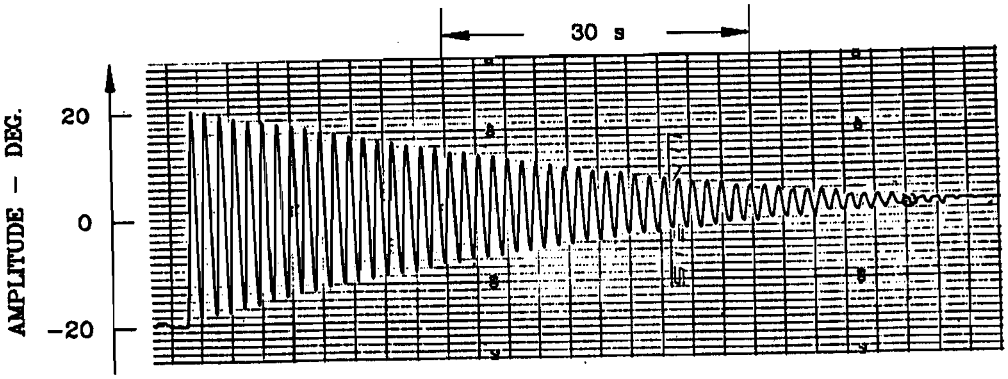
$$\zeta = \delta / (2 \pi) \quad (3)$$



(a) PENDULUM ALONE

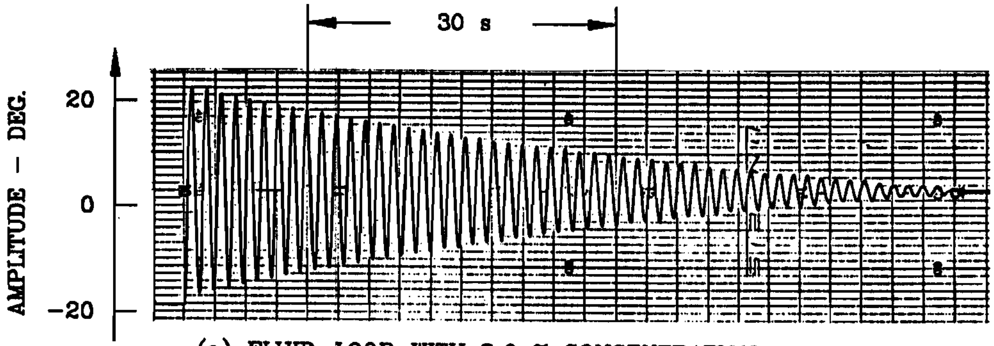


(b) PLUGGED FLUID-LOOP

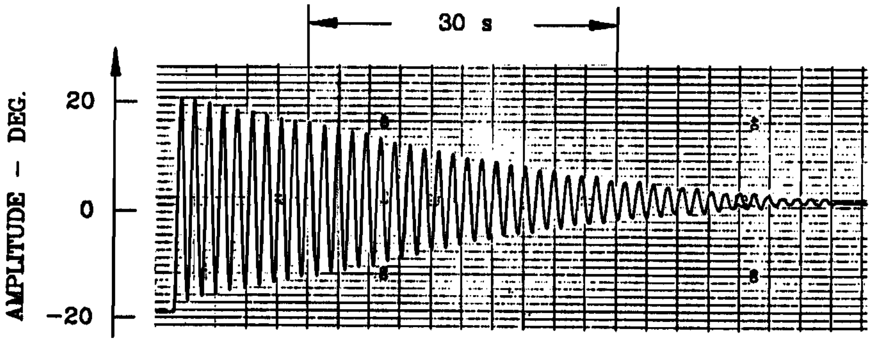


(c) UNPLUGGED FLUID-LOOP

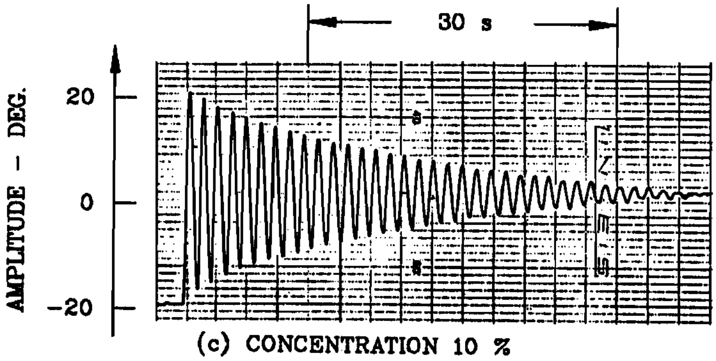
Figure 3 - Time response of a conventional fluid-loop damper.



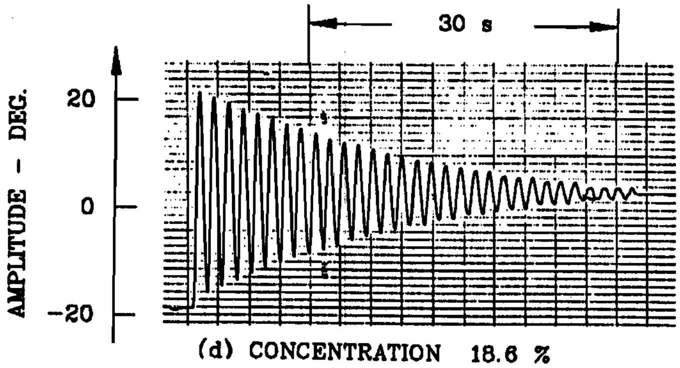
(a) FLUID-LOOP WITH 2.6 % CONCENTRATION



(b) CONCENTRATION 6.6 %



(c) CONCENTRATION 10 %



(d) CONCENTRATION 18.6 %

Figure 4 - Time response of the new fluid-loop damper.

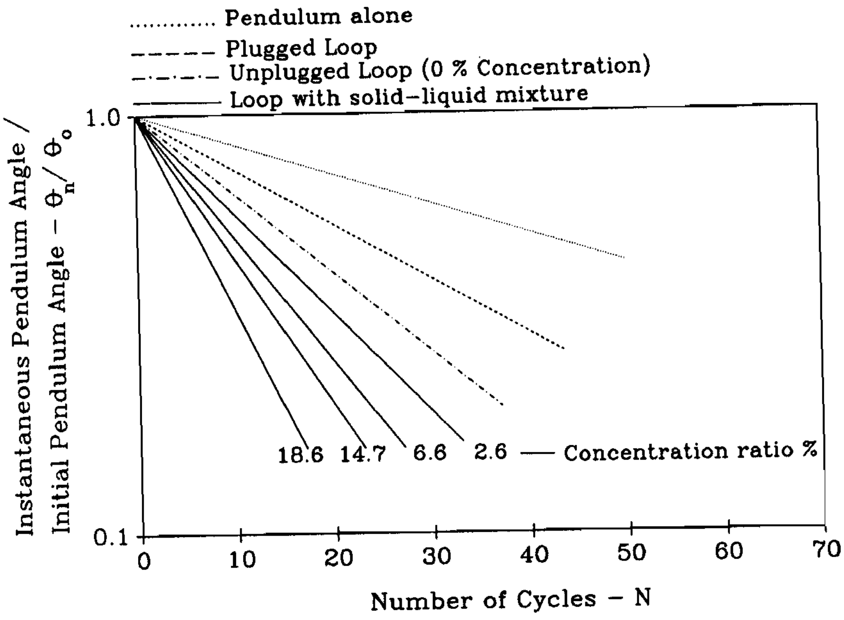


Figure 5 - Decay of amplitude as function of the number of oscillation cycles.

Figure 6 summarizes the effect of varying the volumetric concentration ratio of the spheres on the resulting damping ratio (ζ) of the damper for pendulum natural frequencies ranging between 0.66 to 0.33 Hz. These frequencies are obtained by varying the length of the pendulum arm (L_p) from o.55 m to 2.1 m respectively.

It can be seen , at oscillation frequency of 0.66 Hz, that increasing the concentration of the spheres results in significant increase in the damping ratio of the new damper as compared to the conventional damper (which has sphere concentration ratio = 0 %). Such an increase amounts to more than doubling the damping ratio of the conventional damper. However, the extent of the improvement decreases as the oscillation frequency is reduced. When the frequency drops to 0.5 the improvement becomes to 50% .Further decrease of the frequency to 0.33 Hz results in insignificant improvement.

Another parameter that is important in evaluating the performance of the new damper is the energy dissipated by the damper per cycle (ΔE) . This parameter is calculated from the following equation

$$\Delta E = (\delta - \delta_p) [I \, \omega_n^2 \, \vartheta_o^2] \tag{4}$$

where

δ_p is the logarithmic decrement of the pendulum carrying the plugged loop.

and I is the inertia of the pendulum-loop system around the pivot, (kgm^2)

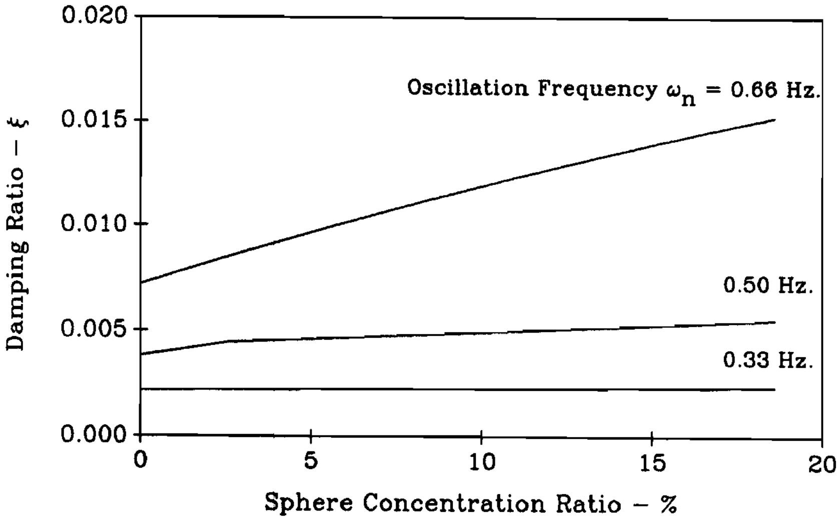


Figure 6 - Effect of volumetric concentration ratio of the floating spheres on the damping ratio for different oscillation frequencies.

In equation (4), the friction losses in the pivot and the sensor as well as the air drag on the pendulum are accounted for by the term δ_p. These losses are subtracted from the logarithmic decrement (δ) of the activated damper to obtain the portion (ΔE) of the pendulum total energy ($I\,\omega_n^2\,\vartheta_o^2$) dissipated in the loop. In dimensionless form, the energy dissipated per cycle ($\Delta\hat{E}$) can be written as

$$\Delta\hat{E} = \Delta E \,/ \left[m \;(R\, \omega_n\, \vartheta_o)^2 \right] \qquad (5)$$

where

m is the mass of the liquid filling the loop, (kg)

In equation (2), the energy dissipated is normalized with respect to the kinetic energy of the fluid inside the loop.

Combining equations (4) and (5) gives

$$\Delta\hat{E} = (\delta - \delta_p) \,/\, (m\, R^2 / I) \qquad (6)$$

In the above equation, the denomenator represents the ratio of the inertias of the fluid loop to that of the pendulum. The parameter $\Delta\hat{E}$ will be used to compare the experimental results of the new damper with the optimal performance of conventional dampers as obtained by Bhuta and Koval[2].

Figure 7 shows such a comparison for oscillation frequency of 0.66 Hz. It can be seen that the new damper can produce significant improvement in the amount of energy dissipated per unit inertia $(\Delta \bar{E})$ as compared to the optimal conventional loop damper. Such improvement occurs when the concentration ratio of the spheres exceeds 12%. When the concentration becomes 18.6%, the measured improvement is 31.1% . In other words, the new damper can produce higher damping than an equal weight conventional damper or alternatively, it will be lighter than a conventional damper that has the same damping ratio.

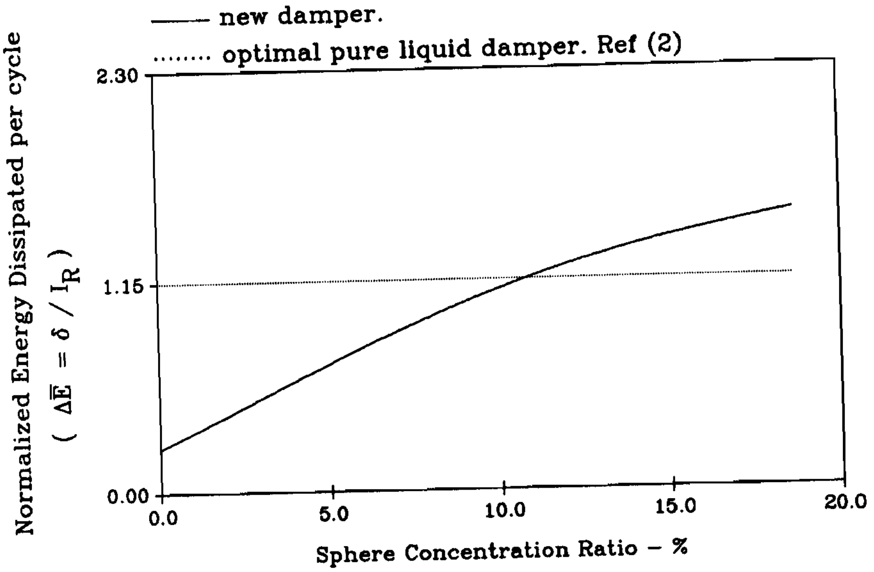


Figure 7 - Comparison between the energy dissipation capabilities of conventional and new fluid-loop dampers.

4. CONCLUSIONS

This paper has presented a new fluid-loop damper which has improved damping characteristics as compared to conventional fully-filled loop dampers routinely used in spinning satellites. The improved performance is obtained byintroducing floating spheres into the damper's loops.

Experimental evaluation of a prototype of the damper indicated that it can be , at 0.66 Hz, about 31.1% more effective and lighter than the optimally tuned fully-filled damper of Bhuta and Koval^2.

The obtained results suggest the potential of the new damper as simple and effective means for damping the vibration of spinning satellites and many other space applications. The damper can be equally invaluable in suppressing multi-axes vibrations . Such a capability is impossible to achieve by current fluid-loop dampers.

Experiments are planned to investigate the performance of the damper over a wide range of frequencies , different types of working fluids and floating spheres. Also mathematical models will developed to model the dynamics of the damper as influenced by its design parameters. The multi-axes damping capabilities of the damper will be tested alone and in-conjuction with flexible structures. The tests will aim at demonstrating its feasibility in isolating the vibration of the various appendages attatched to these structures.

ACKNOWLEDGEMENTS

This work was funded by NASA - Goddard Space Flight Center under grant number NAG 5-1037.

REFERENCES

1. M.V.BARTON 1965 *NASA Technical Report number* NASA CR-163. *Feasibility study of passive dampers for manned rotating space station.*

2. P.G.BHUTA and L.R.KOVAL 1966 *Intl. J. of Mech. Sci.* 8, 383-395. A viscous ring damper for a freely precessing satellite.

3. J.E.COCHRAN and J.A.THOMPSON 1980 *J.of Guidance and Control* 3, 22-28. Nutation dampers for asymmetric spacecrafts.

4. J.V.FEDOR 1973 *NASA Technical Report number* X-732-73-293. *Wire Antenna motion damper for IMP-J spacecraft.*

5. K.T.ALFRIEND 1974 *J.of Spacecraft*, 11, 456-462. Partially filled viscous ring nutation damper.

6. B.G.KING and R.P.WOOLEY 1985 *Ball Aerospace Systems paper number* AAS 85-054, *Boulder, CO*. Modeling, tuning and effectiveness of partially -filled ring nutation dampers.

7. G.F.CARRIER and J.W.MILES 1960 *ASME Trans. J.of Applied Mechanics* 27, 237-240. On the annular damper of a freely precessing gyroscope.

8. J.W.MILES 1963 *ASME Trans.J.of Applied Mechanics*, 30, 189-192. On the annular damper for a freely precessing gyroscope II.

9. W. F. CARTWRIGHT, E. MASSINGILL AND R. TRUEBLOOD 1963 *AIAA Journal*, 1, 1375-1380. Circular constraint nutation damper.

10. K.T.ALFRIEND and T. SPENCER 1983 *J. of Astronautical Sciences*, XXXI, 189-202 . Comparison of filled and partially filled nutation dampers.

11. G.W.GOVIER AND K.AZIZ 1983 *The flow of Complex mixtures in pipes*. New York : Van Nostrand Reinhold Co.

12. R.H.PERRY and C.H. CHILTON 1973 *Chemical Engineer's Handbook*. (5th Edition) . New York : McGraw-Hill Book Co.

13. J.T.BROCH 1980 *Mechanical Vibration and Shock Measurements*. Denmark : Bruel and Kjaer.