Use of Baffles to Suppress Energy Dissipation in Liquid-Filled Precessing Cavities

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Theme

ENERGY dissipation rates caused by introducing baffles of various sizes into a liquid-filled, precessing, spherical cavity are presented. It is shown that energy dissipation can be significantly reduced by adding fine mesh baffles into the cavity. A contrary effect can be achieved by using relatively large mesh baffles such that the nonspherical cells induce turbulence and larger energy dissipation rates than for the smooth walled spherical cavity.

Content

Motivated by the influence of energy dissipation on the attitude stability of spinning and dual-spin spacecraft,[1] and recognizing that analytical approximations of energy losses in enclosed fluids are extremely difficult to obtain, the authors conducted a series of experimental investigations.[2–4] On the basis of knowledge gained in previous studies (especially Ref. 4), a speculation was made that a properly constructed set of baffles would reduce energy losses in a precessing tank of any geometry containing any amount of fluid.

Figure 1 of Ref. 2 shows the apparatus which rotates a test cavity about the spin axis ($\dot{\psi}$) while the spin axis precesses ($\dot{\phi}$) at a fixed coning angle θ. Energy dissipation is computed as $P = M_s\dot{\psi}$, where M_s is the measured component of moment in the direction of the spin axis. Figure 1 shows a survey of prior results. Curves A and A1 show the often dramatic increase in M_s (and therefore P) that occurs as the fluid makes the transition from laminar to turbulent flow. The characteristic difference between results for prograde and retrograde precession is shown by the difference between curves A and A1. Another characteristic is that once turbulence is achieved, P becomes independent of further increases in $\dot{\phi}$. Curve B shows the effect of reducing θ by a factor of 2, and curve C shows the further effect of reducing $\dot{\psi}$ by a factor of 2. Curves C, D, and E show the effect of progressively increasing the kinematic viscosity of the fluid (ν) from 1 cs, to 20 cs, to 1000 cs, respectively. Curve F then shows the further effect of reducing $\dot{\psi}$ by a factor of 5. Flow represented by the conditions of curve F remains laminar throughout the $\dot{\phi}$ range shown and has correspondingly small rates for P.

The typical baffle used in these experiments consisted of an array of parallel cells with square cross-section bounded on the ends by the spherical cavity surface and completely filling the interior of the 22-cm-diam spherical cavity. Photographs are included in the original paper. Three sizes were used: ½ in.², 1 in.², and 2 in.². Each baffle was tested with its cells

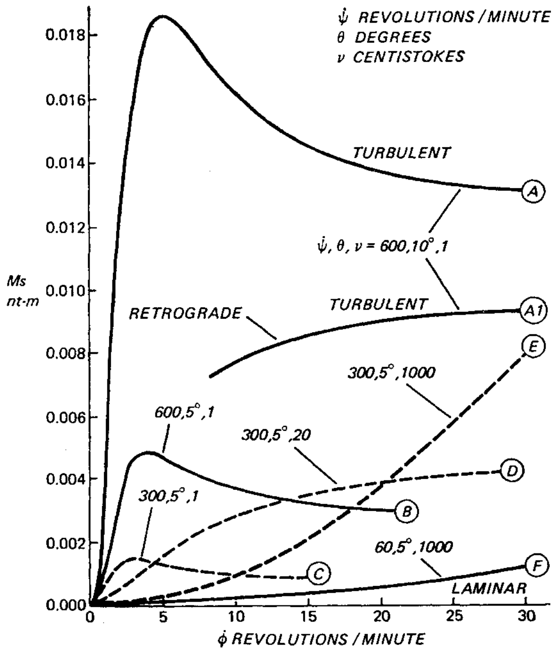

Fig. 1 Survey of prior results: turbulent vs laminar flow. All results for a 22-cm-diam liquid-filled spherical cavity in prograde precession (except A1).

first parallel to the $\dot{\psi}$ axis and then perpendicular to it to test the effect, if any, on orientation. Figure 2 shows the test results which indicate several trends.

1) Energy dissipation is always reduced by reducing θ, $\dot{\psi}$, or $\dot{\phi}$, and follows the typical results for laminar and near laminar flow.

2) Energy dissipation is always reduced by reducing cell size.

3) A direct comparison between the baffled results and the unbaffled results can be made by comparing corresponding curves in Fig. 1 and Fig. 2 for $\dot{\psi} = 600$ rpm and $\theta = 5°$ and 10° (e.g., compare curve M with curve B or curve L2 with curve A).

4) The results for the unbaffled spherical cavity yielded smooth curves, within experimental accuracy, for $M_s = M_s(\dot{\phi})$. The experiments using a baffled cavity, at some parameters and baffle sizes, yielded data that deviated from smooth curves. The curves in Fig. 2 are smoothed to give average results; the deviations, however, are not greater than about 10% of the ordinate and are probably due to complex resonant phenomena within the liquid.

5) The results for prograde and retrograde precession were generally within 10% of each other as indicated in Fig. 2a, however, the top four curves of Fig. 2b indicate retrograde results (R) exceeding prograde results (P) by significant amounts. Reference 3 shows a similar phenomenon (retrograde > prograde results) for flow in the unbaffled cavity for the region where laminar flow is beginning to break down.

Received February 15, 1973; synoptic received June 14, 1973. Full paper available from National Technical Information Service, Springfield, Va., 22151, as N73-25280 at the standard price (available upon request).

Index category: Spacecraft Attitude Dynamics and Control.

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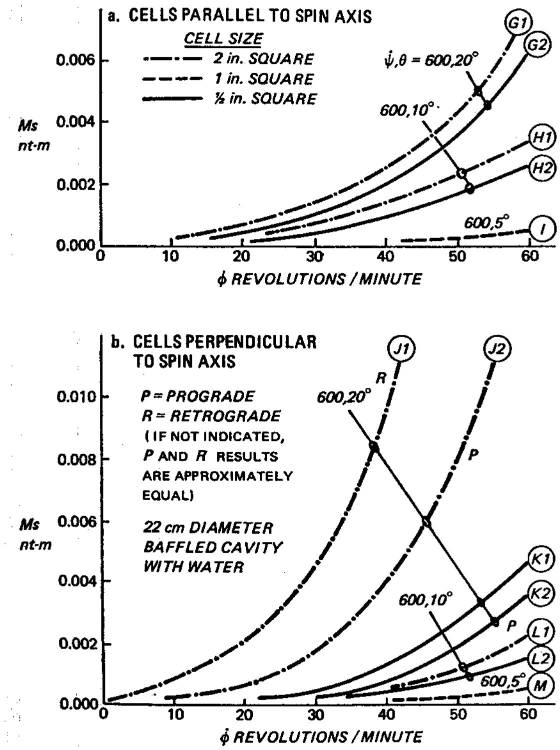

Fig. 2 Selected baffle results showing effects of baffle cell size and baffle orientation as functions of the kinematic parameters.

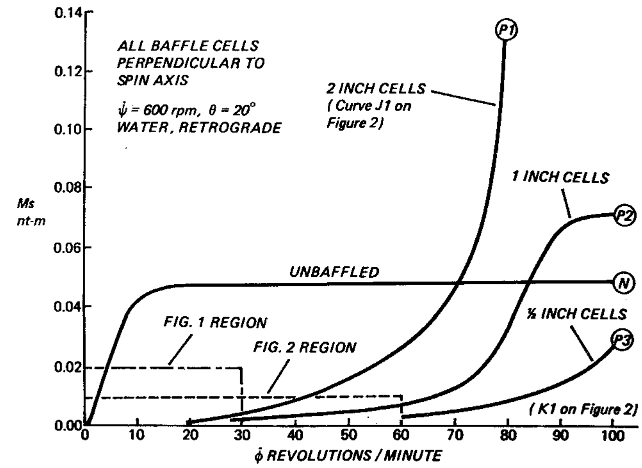

Fig. 3 Comparison of unbaffled and baffled results for water in a 22-cm-diam cavity at $\dot{\psi} = 600$ rpm, $\theta = 20°$, and retrograde precession.

But as the region of saturated turbulence is approached, the situation reverses and the prograde results significantly exceed the retrograde results (curves A and A1 of Fig. 1).

6) Having the cells parallel or perpendicular to the spin axis may have relevance in maximizing fuel feedrate and minimizing trapped fuel within the baffle structure. In the laminar region the cell orientation did not significantly affect energy dissipation rates. However, in several tests at $\theta = 20°$, the perpendicular cell position appeared to lead to more turbulence and greater energy dissipation rates, as discussed next.

7) The use of 1-in. and 2-in. cells perpendicular to the spin axis at $\dot{\phi} = 600$ rpm and $\theta = 20°$ (retrograde) gave data characteristic of turbulent flow. The 2-in. cell data are shown as curve J1 in Fig. 2. In Fig. 3 the same test (shown as curve P1) is continued out to $\dot{\phi} \approx 80$ rpm. Also shown are results for 1-in. cells (curve P2), $\frac{1}{2}$-in. cells (curve P3), and the unbaffled cavity (curve N) all at the same kinematic parameters. While it is possible to achieve saturated turbulence with the 1-in. cells, note that it can only be achieved in the parameter region above the region of useful aerospace interest. The $\frac{1}{2}$-in. cell curve has not reached a turbulent limit at $\dot{\phi} = 100$ rpm.

8) Reference 4 compares three different sizes of spherical cavities and develops relationships $P \propto R^k$. These relationships need not apply to the nonspherical cavities formed by the baffle structure. In a filled, spherical cavity, all motion in the liquid is driven through the viscous boundary layer. In a filled, nonspherical cavity, motion of the liquid is additionally induced by movement of the cavity walls normal to the liquid-wall surface leading to increased energy dissipation rates. This explains the results of paragraph 7 above where 1- and 2-in. baffle data (nonspherical) exceeds the unbaffled (spherical) data at large parameters. However, the use of many, very small nonspherical cavities can and usually does offset the disadvantage of nonsphericity. It the baffles are fine enough to maintain laminar flow, then the reduction in energy dissipation rate can reach several orders of magnitude. For example, compare curves P3 and N of Fig. 3 and note that P3 is shown to an enlarged scale in Fig. 2 as curve K1. At $\dot{\phi} = 20$ rpm (appropriate for some dual spin satellites), the ratio of the baffled to unbaffled results is 1 : 200.

Since the reduction of energy losses in fuel tanks on dual spin spacecraft is a major objective in achieving attitude stabilization, these results should have a substantial impact on design practice in this area. It should be emphasized that indiscriminate baffling is dangerous; in some cases coarse mesh baffles (and perhaps also ring baffles) can induce turbulence and increase energy dissipation. An experimental program of optimum baffle design should be undertaken, for specific fuel tanks and spacecraft dynamic characteristics, in order to provide maximum reduction in energy dissipation for minimum cost in tank weight. The relaxation of demands placed upon the "nutation damper" of a dual spin satellite, with its associated mass, reliability, cost, and (sometimes) power requirements may more than offset the disadvantages associated with the addition of baffles.

Of course, liquids in the fuel tanks of a spacecraft are gradually depleted, whereas the cavities in the experiments presented here were always full. However, if a fine mesh baffle consisting of roughly cubical cells were used in a fuel tank, with negligible exception, each cell would be either filled or empty even as the fuel is depleted. Because cell size then becomes the characteristic cavity size, neither the shape of the over-all tank nor its location in the vehicle would appear to be relevant.

References

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