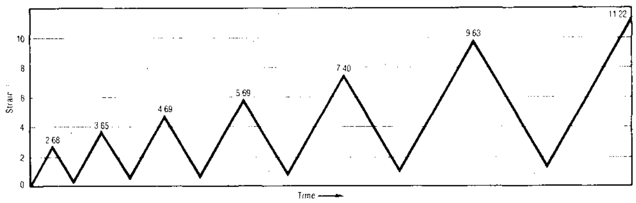

Fig. 2 Strain history.

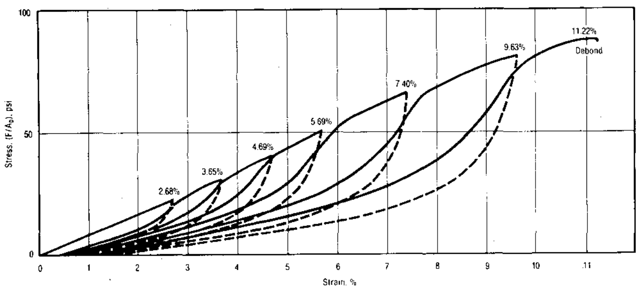

Fig. 3 Stress-strain response.

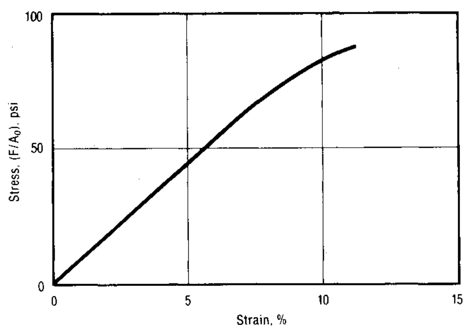

Fig. 4 Virgin stress-strain response.

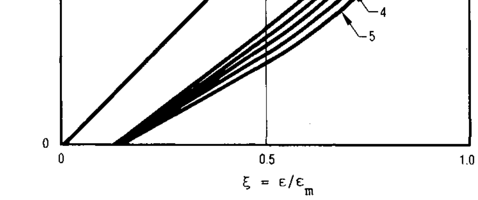

Fig. 5 Damage curves for loading.

End-bonded test specimens of dimensions $6 \times 0.5 \times 0.5$ in.[3] were placed on an Instron test machine and loaded using the strain history shown in Fig. 1. The test was performed at 70°F and a strain rate of 0.03 min^{-1}. The values of maximum strain for loading were selected to increase the strain level by 1% strain or more on each cycle. On unloading, the crosshead direction was reversed each time the stress reached zero.

The stress response for the six-cycle history of Fig. 1 is presented in Fig. 2. Note that in accord with the earlier hypothesis, the stress returns to the virgin curve once the previous maximum strain has been exceeded. The unloading-reloading curves show the same form for all strain levels.

The *virgin curve* is shown in Fig. 3. This curve was established by taking the envelope of the curves in Fig. 2 and also by performing a separate test in which the strain history was increased monotonically (at the same strain rate); the two curves coincide almost exactly. Interestingly the virgin curve demonstrates linear response up to 7% strain.

The unloading curves in Fig. 2 were normalized to generate the damage curves of Eq. (7). These appear to form a family of curves that depend on the strain level but intersect on the ξ axis at a value of ξ approximately equal to 0.14.

While the damage curves in Fig. 4 do not collapse to a single curve, for some applications, it might be reasonable to approximate the resulting family of curves by a single master damage curve as represented by Eq. (9).

It should be noted that in Fig. 4 only the unloading curves are graphed. The discrepancy in Fig. 2 between loading and unloading below the maximum strain level is due to rate effects and is less pronounced at lower strain rates. Of course, since this theory is rate independent, it cannot account for effects such as these without modification.

Finally, it should be remarked that graphs of the virgin curves and damage curves, such as those shown in Figs. 3 and 4, seem to yield an organized method of cataloging the stress-strain behavior of highly filled solid propellants. This procedure may also be useful in studies of other materials that undergo damage.

Acknowledgment

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Void Characteristics of a Liquid-Filled Cylinder Undergoing Spinning and Coning Motion

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RECENT studies have revealed a new type of flight instability experienced by spin-stabilized projectiles having liquid fills of relatively high viscosity.[1] The instability is characterized by a growth in projectile yaw angle and a concurrent loss in projectile spin with a consequent

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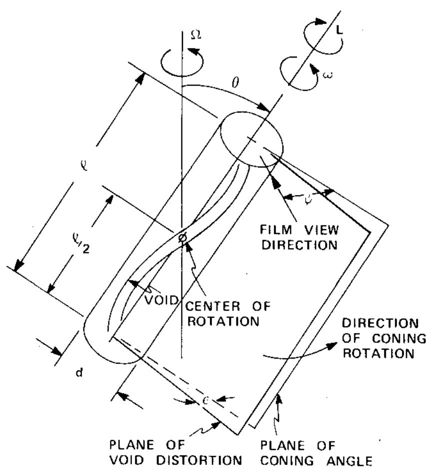

Fig. 1 Definition of terms.

degradation in range and accuracy.[2,3] The destabilizing effect of the liquid fill increases with liquid viscosity, achieving a maximum at a viscosity of about 100,000 CS, thereupon diminishing to zero at very large values of viscosity.

A series of tests was conducted using a special laboratory test fixture[4] to experimentally determine the internal flow characteristics of a liquid-filled container undergoing simultaneous spin and coning motion. Of specific interest was the distortion of the air void formed in the liquid due to the motion of the container in that the air void represents the center of rotation of the liquid fill. The resultant data are intended to provide an insight into the internal flow, particularly the shape of the liquid free surface, in order to support theoretical analyses of this flight instability.

The liquid-filled cylindrical container was held in the laboratory test fixture frame at a fixed angle θ to the vertical. The container was spun at a rate ω about its longitudinal axis using an air turbine, while the frame was spun at a rate Ω about the vertical axis by means of an electric motor. The spinning container thus assumed a fixed-angle coning motion simulating the simple spin and nutation motion of a spin-stabilized projectile in flight. The data obtained consisted of still photographs, high-speed film records, and measurement of the container despin moment about its longitudinal axis L. The spin fixture measures only the despin component of the total destabilizing moment induced by the liquid fill. Assessment of the destabilizing potential of a particular fill is based on the assumption that a destabilizing yawing moment is present that is proportional to the magnitude of the liquid-fill-induced despin moment measured on the test fixture. Based on this approach, container despin moments measured on the test fixture have shown good qualitative correlation with instabilities experienced during actual flight tests.[2,3] Figure 1 defines the terms used.

A right circular cylinder having an internal diameter d of 12.06 cm and an inside length l of 53.66 cm was tested. These dimensions result in a length to diameter ratio l/d, of 4.45 and is representative of the payload canister incorporated in a current family of U.S. Army 155-mm artillery shells. The body of the container was fabricated from transparent, cast acrylic tubing having a 0.973-cm wall thickness. A 0.318-cm diameter wire was located down the centerline of the container to provide a reference index for measurement of the void distortion.

Four different silicone oils were evaluated having kinematic viscosities ν of 1, 1000, 10,000, and 100,000 CS. Mass densities were 0.821, 0.971, 0.975, and 0.977 g/cm^3, respectively. The container was 95% full for all tests. Previous tests[5] with 100% fills had demonstrated that the presence of a void was not the cause of the instability. A 5% void was selected to allow a virtually full condition while providing adequate visualization of the void. The transverse location and orientation of the void represents the center of rotation of the liquid fill at that location in the cylinder. Tests were conducted with each liquid at fixed coning angles θ of 5, 10, 15, and 20 deg and fixed coning rates Ω ranging from 0 to 500 rev/min. Container spin rates ω of 3000 through 6000 rev/min representative of flight conditions were used. Despin moments measured on the test fixture for the viscosity range considered in this study were not a function of the canister spin rate for the 3000 through 6000 rev/min investigated.

Analysis of high-speed film records from the tests revealed that the void assumed a sinusoidal-like shaping about the center of rotation of the container. The sinusoidal-like void distortion does not change with time relative to the plane of the coning angle, and the distortion is restricted essentially to that plane. These effects are illustrated in Fig. 2 which presents two frames from a high-speed film record of a representative test and shows the void distortion from two opposite views during a single coning cycle. The steady nature of the void is illustrated by the frames depicting these views at $\psi = 90$ and 270 deg. Physical interference due to the spin fixture frame vertical upright supports prevented an exact determination of the angle of the plane containing the void distortion, but it appears that the void distortion is restricted to a plane which is within 10 deg of the plane of the coning angle (i.e., $\epsilon < \pm 10$ deg). Thus, when the canister is viewed along the plane of the coning angle, $\psi \simeq 0$ and 180 deg, the void appears to be essentially undistorted.

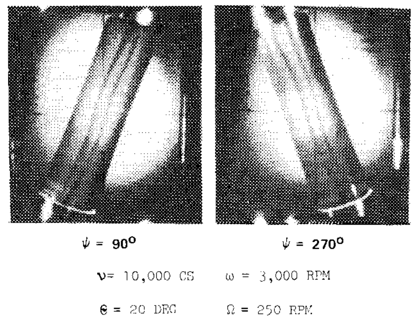

Fig. 2 Void distortion viewed from $\psi = 90$ and 270 deg.

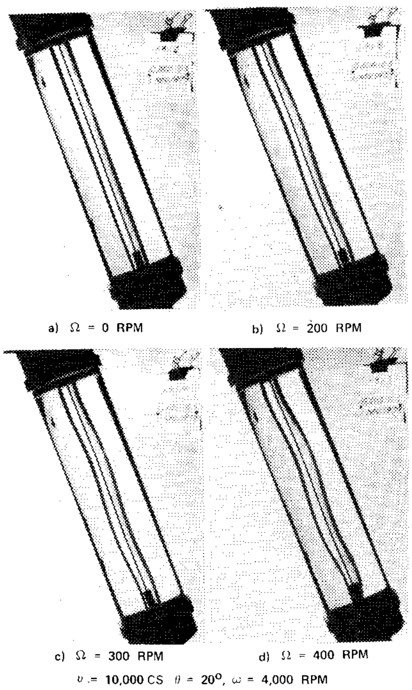

Fig. 3 Effect of coning rate on maximum void distortion ($\psi = 270$ deg).

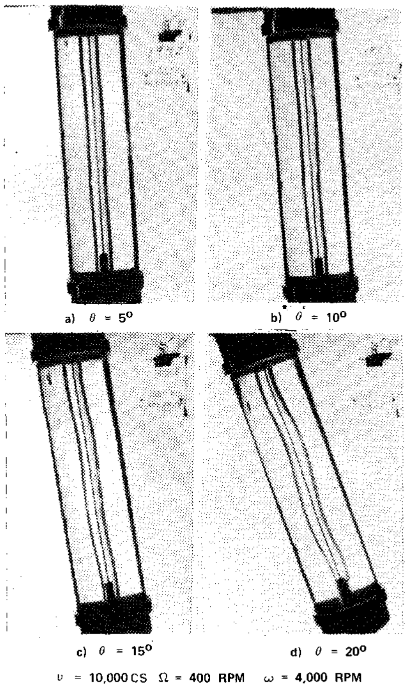

Fig. 4 Effect of coning angle on maximum void distortion ($\psi = 270$ deg).

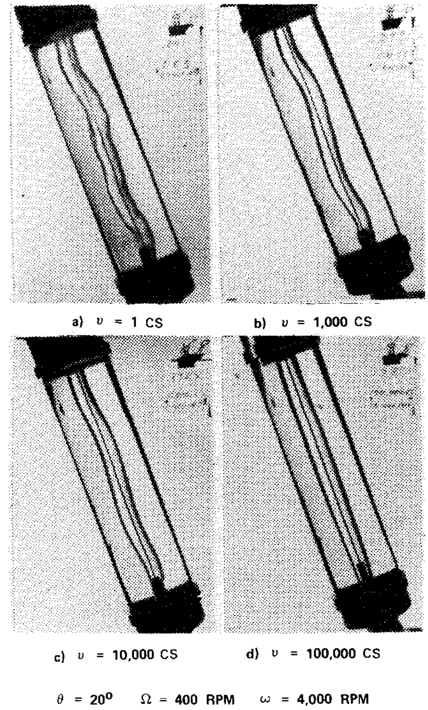

Fig. 5 Effect of viscosity on maximum void distortion ($\psi = 270$ deg).

Figure 3 contains photographs of the spinning-coning container as viewed normal to the plane of the coning angle, $\psi = 270$ deg, indicating the maximum void distortion. These photographs illustrate that the void distortion increases with increasing coning rate. Although the data shown are for the 10,000-CS liquid, similar trends occurred for all the liquids tested. Note that no void distortion is present for the non-coning case. The container despin moment induced by the liquid fill was found to increase nonlinearly with increasing coning rate for all liquids tested.

The effect of coning angle on void distortion is included in Fig. 4, showing that the void distortion increases with increasing coning angle. Although void distortion is most pronounced for the 20-deg coning angle, the basic void shaping is still discernable at a 5-deg angle. The corresponding liquid-fill-induced container despin moment indicated a nonlinear increase with increasing coning angle.

Figure 5 illustrates the influence of liquid viscosity on void formation. For the 1-CS liquid, the void assumes the basic sinusoidal-like shape, but superimposed on the void/liquid interface surface are small-amplitude, high-frequency wave formations. These latter perturbations are completely absent for the 1000-CS and higher-viscosity cases. As can be seen, increasing liquid viscosity acts to *reduce* void distortion. Significantly, there is virtually no sinusoidal-like void distortion for the 100,000-CS liquid, which is in the liquid viscosity range where the flight instability was observed to be the most severe!

This type of flight instability has been observed for payloads composed of a combination of liquid/solid elements as well as for the homogeneous, viscous liquids considered here.[6] These experiments were intended to investigate the void characteristics related to the flight instability associated with viscous liquid fills. However, the results could also be of interest for other types of liquid-induced instabilities. For example, the sinusoidal shaping and planar aspects of the low-viscosity-liquid void is not considered in current theoretical analyses of liquid-resonance (i.e., Stewartson-type) instabilities.[7,8] These experimental observations are presented to aid development of a fluid-dynamic model of internal flow within the container and the subsequent effect on flight stability.

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