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Active Control of Asymmetric Vortex Effects

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Active control of asymmetric vortex effects on a pointed, slender body at high angles of attack has been achieved by rotating portions of the body about the axis. The leeward asymmetric vortex patterns and their associated yaw-plane forces and moments have been varied in cyclic, repeatable fashion at rates up to 100 cycles/s. As the spin rate increased, the peak-to-peak variations in side force decreased. The mean value was relatively insensitive to spin rate. The effect was obtained by rotating the nose, the nose tip, and a band of the body surface just aft of the nose.

Nomenclature

C_M = pitching moment coefficient
C_N = normal force coefficient
C_n = yawing moment coefficient
C_Y = side force coefficient
D = body diameter
M = Mach number
n = spin rate, rps
α = angle of attack
ϕ = roll angle

Introduction

THE effects of asymmetric vortex formation in the wakes of slender missiles and aircraft flying at angles of attack between say 30 and 60 deg and Mach numbers less than about 1.2 give rise to potentially serious control problems. For vehicles in this pitch range the asymmetric flow patterns produce large forces and moments in the yaw plane. These effects have been investigated by several workers.[1-4] If the induced, out-of-plane effects were constant in direction, the problem of control might not be too severe. However, the forces and moments can change sign unpredictably, with consequent more serious implications for the possibility of control.

The potential seriousness of the controllability problems has prompted several investigations into means for modifying or alleviating asymmetric vortex effects.[3,6-8] These have made use of specially shaped bodies, disturbance of the flow by ejecting air from the body, and strakes or vanes to influence flow development.

The changing sign of the yaw plane forces and moments is held to have at least two possible origins: 1) circulation-bearing eddies in the freestream which may strike the body, causing a change in the net circulation about it and thus producing a different wake configuration[5]; and 2) the influence of manufacturing imperfections on the body surface, which are thought to be the basic cause of steady asymmetric wake development. It is hypothesized that they cause the boundary layer to develop asymmetrically on the body, resulting in premature separation on one side before the other and leading ultimately to the formation of asymmetric wake vortices. The changing disposition of these imperfections relative to the wind vector as the angles of attack or roll are changed produces changing sign and/or varying magnitudes of the out-of-plane forces and moments. The variations with change in attitude have been the more widely observed in practice. The present work concentrates on the effects of changing roll angles. In what follows the term "roll" will be used to denote static situations where the angle is changed incrementally.

The importance of roll attitude on out-of-plane force and moment signs and magnitudes has been noted by several authors.[1-3] It was found that by changing roll angle, the forces and moments could be changed in cyclically repeatable fashion. It was possible to produce the effect by rolling a complete nose-cylinder body, the nose section, and the cylindrical section aft of the nose.[3] Even rolling the nose tip alone produced the effect.[1] Since missiles and aircraft may change roll attitude in flight, the consequences for controllability are clear. However, the cyclic, repeatable nature of the changes in out-of-plane forces and moments with roll angle leads directly to the present concept for control. In what follows the terms "rotation" and "spin" will be used to denote dynamic situations where the angle is changed continuously.

It had been observed that if the body is rotated about its axis, the forces and moments vary cyclically with time.[3] This means that the force variations are cyclical and determinate instead of random. In addition, if the rate of variation is high compared with the response time of the vehicle, then it would be expected that the body would behave as though subjected to the time average of the out-of-plane effects, leaving the vehicle free, on the average, from varying forces and moments. However, spinning the entire body is not usually a feature of vehicle design. On the other hand, it had been found that the nose, nose tip, or afterbody could also be rolled incrementally to produce a repeatable effect. The present investigation was undertaken to determine if these pieces could be rotated to yield cyclical rather than random variations and the time-averaged effect.

A further effect of rotating the body pieces was hoped for; a reduction in magnitude of the out-of-plane quantities. Since the wake vortices are supplied with vorticity from the separating boundary layer, changes in boundary-layer development might alter the quantity of vorticity being shed from the body. Any reduction should be reflected in reduced vortex strength and in the related forces and moments. In addition, since the wake pattern was expected to change, the vortices might not have enough time to develop their flowfields fully before switching to a new pattern. This might also lead to reduced effects. Indeed, Kruse[4] found during recent tests on a cone spinning up to about 8 rps that the magnitude of the side forces reduced with increasing spin rate.

It was decided, with ultimate hardware application in mind, to test models which featured a spinning nose and nose tip. In

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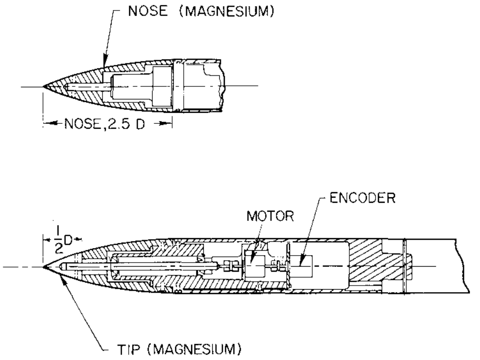

Fig. 1 Spinning nose and tip models.

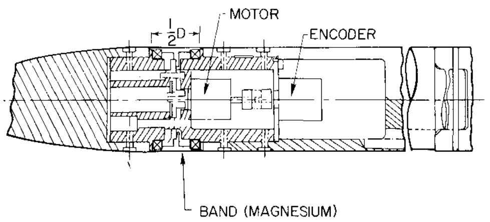

Fig. 2 Spinning band model.

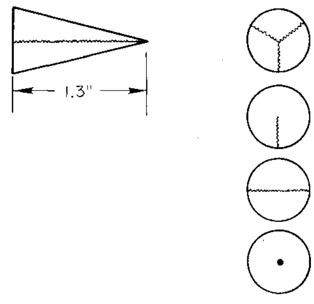

Fig. 3 Tip grit patterns.

addition, since it seems impractical to spin a complete afterbody, a band of the body surface just aft of the nose was spun also.

Models and Instrumentation

The basic model was a 2.6 in. diam cylinder with a tangent-ogive-nose, 2.5 calibers long. Overall length was 15.5 calibers. The model was deliberately made quite slender to permit development of an extensive vortex pattern. The body was composed of two major sections. At the upstream end, the first 6.5 calibers contained the spinning devices and their drive mechanisms. Two separate arrangements were used. One permitted test of the spinning nose and nose tip (Fig. 1), the other contained the spinning band (Fig. 2). Spin was accomplished by means of dc motors. Spinning-segment angular position was recorded by means of a 256-step optical encoder so that out-of-plane quantities could be compared at the same roll positions. Spin rate was monitored by a photoelectric cell. The models were made mainly of steel and aluminum. However, the spinning devices were made of magnesium to reduce possible dynamic effects due to imbalance. Subsequent investigations showed no measurable imbalances during test. The devices could be spun at 2-100 Hz in the clockwise and counterclockwise directions. They could also be rolled incrementally, a few degrees at a time, to investigate the detailed behavior during a roll cycle. Aft of the spinning-device section was a cylindrical section 9 calibers long. This contained the six-component balance.

Flow patterns were recorded by means of four cameras. One still and one movie camera were positioned downstream of the model, fixed to the support assembly. These were focused upstream and were used in conjunction with the tunnel vapor-screen apparatus. One still and one movie camera were located outside the tunnel. These operated when the tunnel was filled with enough water vapor to produce "vortex trails" under ordinary tunnel lighting.

Tests

The tests were carried out in the 6×6 ft Supersonic Wind Tunnel at NASA Ames Research Center. The tunnel was run in the subsonic mode at Mach numbers of 0.25, 0.6, and 0.85. Both force and moment tests and flow visualization were performed. Moments were referred to the approximate center of model length. Model angle of attack was varied between 30 and 58 deg. Data from the balance were recorded in three ways:

1) On the standard data acquisition system, which essentially passes balance output through a 5 Hz low-pass filter and produces an average of three readings.

2) On magnetic tape. Analog data were taken and subsequently digitized for analysis.

3) On visicorder paper strip. This provided an instantaneous record of model behavior.

The testing typically proceeded as follows: first, the model was pitched at 30-58 deg and out-of-plane quantities were monitored every 5 deg. Angles at which the maximum magnitudes were observed were selected for further study. The model was set at one of these angles and the incremental-stepping capability was used to roll the devices to various angular positions, a few degrees at a time. In this way, the detailed behavior of side force and yawing moment could be observed during a cycle. Because of an instrumentation difficulty with the encoder, the incremental stepping data were not completely accurate in the roll position. Thus it was not possible to compare the curves of C_Y at zero and nonzero spin rates. However, the zero-spin-rate extrema in forces and moments could be determined for comparison with the spinning variations. Following the incremental-roll tests, the devices were spun at rates from ±2 to ±100 Hz (+ spin was defined as clockwise, looking forward).

The devices were spun with their surfaces smooth and then with artificial disturbances fixed to them. This permitted examination of the effect of small disturbances under controlled conditions. The disturbances took the form of axial strips of grit or tape.

More detail of the 1/2 caliber nose tip grit patterns is shown in Fig. 3. The various arrangements were: a smooth tip, one axial grit strip, two strips 180 deg apart, three equally spaced strips, and a completely gritted tip. The nose was tested smooth and with three tape strips running along its length. The strips were tapered toward the tip. The 1/2 caliber spinning band was tested only with three axial tape strips.

Following the aerodynamic testing, simple dynamic tests were carried out to determine the resonant frequencies of the complete test setup including model, balance, and support system. By means of a shaker and of artificially induced imbalances, these natural frequencies were found to occur at about 12, 18, 24, 33, and 42 Hz. The entire system was found to have faithful frequency response up to at least 70 Hz.

Results

Flow visualization studies showed that the wake vortices could be changed to a large variety of apparently stable patterns by incrementally rolling the nose, nose tip, and band. In addition, the patterns could be changed at various frequencies by spinning the devices. The most striking results were obtained with artificial disturbances present (grit and tape strips). However, the smooth nose and nose tip were also effective in changing the flow.

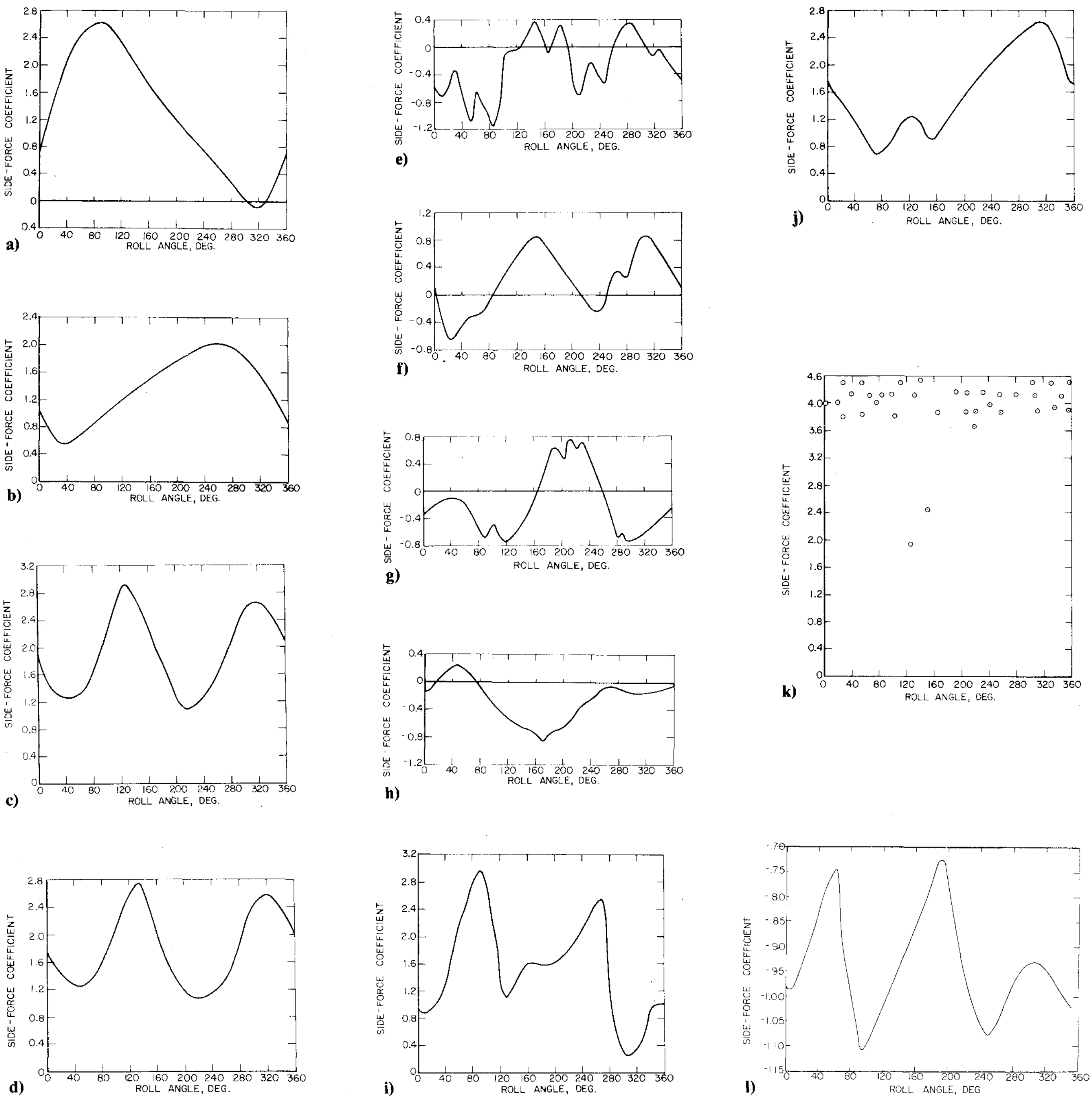

Fig. 4 Variation of side force coefficient with roll angle. a) Tip with one grit strip, + 20 rps, $M = 0.25$, $\alpha = 45$ deg. b) Tip with one grit strip, − 20 rps, $M = 0.25$, $\alpha = 45$ deg. c) Tip with two grit strips, − 10 rps, $M = 0.25$, $\alpha = 50$ deg. d) Tip with two grit strips, + 10 rps, $M = 0.25$, $\alpha = 50$ deg. e) Tip with three grit strips, + 2 rps, $M = 0.6$, $\alpha = 30$ deg. f) Tip with three grit strips, + 5 rps, $M = 0.6$, $\alpha = 30$ deg. g) Tip with three grit strips, + 10 rps, $M = 0.6$, $\alpha = 30$ deg. h) Tip with three grit strips, + 20 rps, $M = 0.6$, $\alpha = 30$ deg. i) Nose with three tape strips, + 10 rps, $M = 0.25$, $\alpha = 50$ deg. j) Nose with three tape strips, + 20 rps, $M = 0.25$, $\alpha = 50$ deg. k) Nose with three tape strips, + 50 rps, $M = 0.25$, $\alpha = 50$ deg. l) Band with three tape strips, − 10 rps, $M = 0.25$, $\alpha = 40$ deg.

It was observed that the vortex pattern switching was approximately synchronized with the device rotation rate and the number of disturbances. In the cases of the nose and nose tip, the entire wake switched from the tip of the nose to the base. With the band, the two vortices generated on the nose upstream of the band remained unchanged, but the rest of the pattern varied with spin rate. At low rotation rates the individual vortices retained their definition and their motion could be followed visually. At high rotation rates, the pattern varied so rapidly that it became impossible to identify individual vortices. However, at these speeds the evidence of the balance showed that the pattern continued to change with spin rate (see next section). The response was probably related to the time required for disturbances to traverse the length of the body. At the lowest Mach number (0.25) the time required for a fluid particle to traverse the length of the body was about 1/50 s at $\alpha = 50$ deg. With a maximum rotation rate of 100 Hz, disturbances produced near the nose would be transmitted downstream at a maximum rate approximately equal to $1/100m$ where m is the number of disturbance-causing mechanisms (artificial or natural) per cycle. Hence, during the $M = 0.25$ tests disturbances were introduced at frequencies higher than required to ensure that more than one disturbance was influencing the pattern at a given time. At the higher

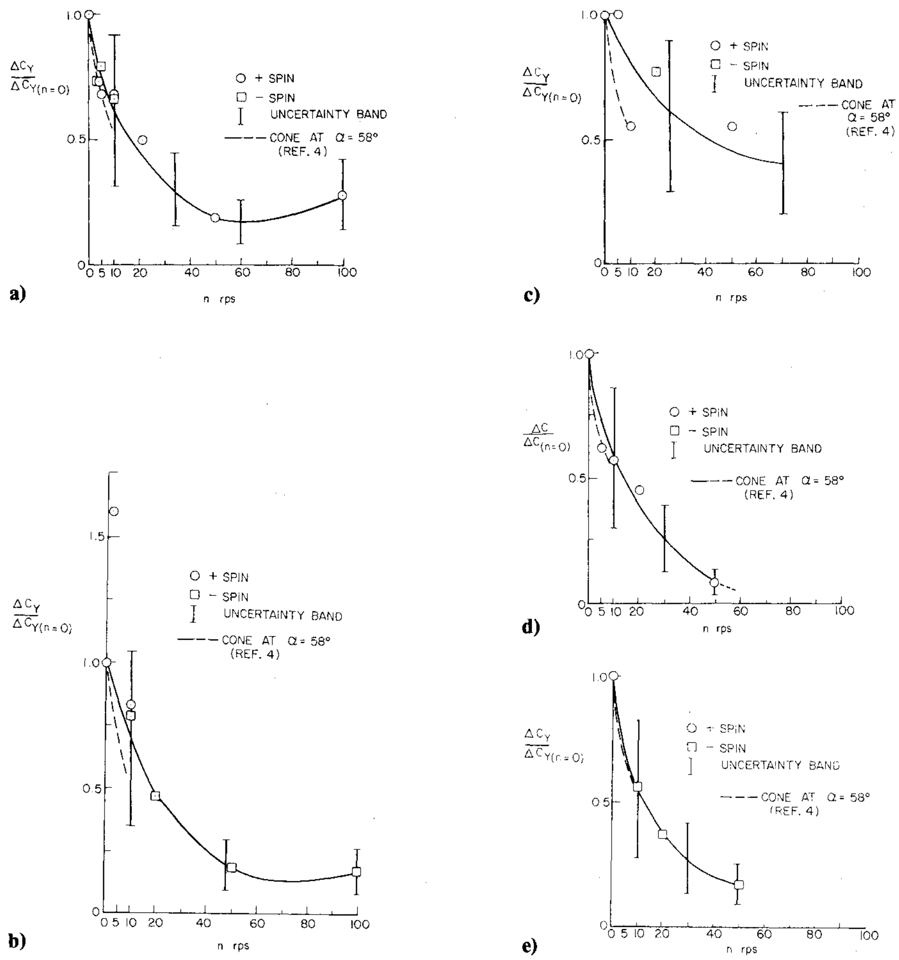

Fig. 5 Side force cyclical variation as function of spin rate. a) Tip with three grit strips, $M=0.6$, $\alpha=30$ deg. b) Tip with three grit strips, $M=0.6$, $\alpha=50$ deg. c) Tip with single grit strip, $M=0.25$, $\alpha=45$ deg. d) Nose with three tape strips, $M=0.25$, $\alpha=50$ deg. e) Nose with three tape strips, $M=0.6$, $\alpha=55$ deg.

Mach numbers (0.6, 0.85) fewer conditions existed where more than one disturbance was present in the flow pattern at a given instant.

Side Force Data

Turning now to the results from the six-component balance, attention will be focused on side forces. Yawing moment behavior was essentially the same as for side force. Some limited discussion of pitch plane quantities will be given later. Axial force and rolling moment were not expected to vary significantly and are not discussed.

The analog tape data were first digitized and then treated by linear ensemble averaging. This process involves averaging by the superposition of individual data cycles, one on top of the other. If a coherent signal is contained in the data but its form within a given cycle is masked by random noise, the process averages out the noise, leaving the signal. It was found in most cases that after superposing as few as five cycles the signal emerged. After 20-30 cycles were averaged the signal was found to be unchanged. Eventually 50 cycles were averaged, to ensure that the noise had been completely removed. Examples of ensemble-averaged side force coefficients are shown in Fig. 4, which shows the effects on C_Y of the various devices, their spin rates, and directions.

The repeatability of the data is clear, corroborating the evidence of the flow visualization studies. Cyclical switching of the vortex patterns is taking place repeatedly, resulting in cyclical force variations. Note that in Fig. 4, whether the spin is positive or negative, the abscissa always gives ϕ from 0-360 deg in the direction of spin, i.e., both positive and negative roll angles run from left to right. Figures 4a and 4b show the effects of the tip with a single grit strip at 20 rps. It will be seen that the force magnitudes are greater with positive spin. This may be due to the presence of other, natural disturbances on the body. However, the variations in the curve shape imply that when the grit strip was at a given angular location, the flow pattern was essentially the same, whether the strip arrived there from the positive or the negative direction. On the other hand, Figs. 4c and 4d show that the tip with two axial grit strips seems to generate a flow pattern which repeats each 180 deg but with an apparent phase shift of 90 deg. This is believed to be due to a damaged connection which allowed backlash in the drive mechanism to the encoder. The three-strip data were quite dissimilar for different spin directions. In addition, varying the spin rate changed the characteristics of the side force curves, as shown in Figs. 4e-4h, implying a distortion of the flow pattern. This result is different from that of Ref. 4 in which the side force curve shapes remained similar with changing spin rate. Figures 4i-4k show the nose with three tape strips at various speeds. It will be seen that here too the curves show distortion as speed is increased. Finally, a typical curve showing the effect of spinning the surface band with three tape strips is shown in Fig. 4l. It will be seen that the variations are much smaller than for the nose and tip. This may be due to the condition of the boundary layer at the band. The layer will be much thicker and more resistant to surface disturbances than that near the nose. The flow studies showed that the band changed only the wake aft of itself, leaving unchanged the two vortices on the nose. It may be that these vortices play a dominant role in side force variations. When they remain unchanged, this seems to reduce the force variation on the body over a cycle.

Another hoped-for effect, that of reduction in side force variation, may be seen by comparing the peak-to-peak variation in C_Y across the speed range with the static or incrementally rolled C_Y variation ($n=0$). The results are shown in Fig. 5 for the nose and nose tip. No zero-spin data are

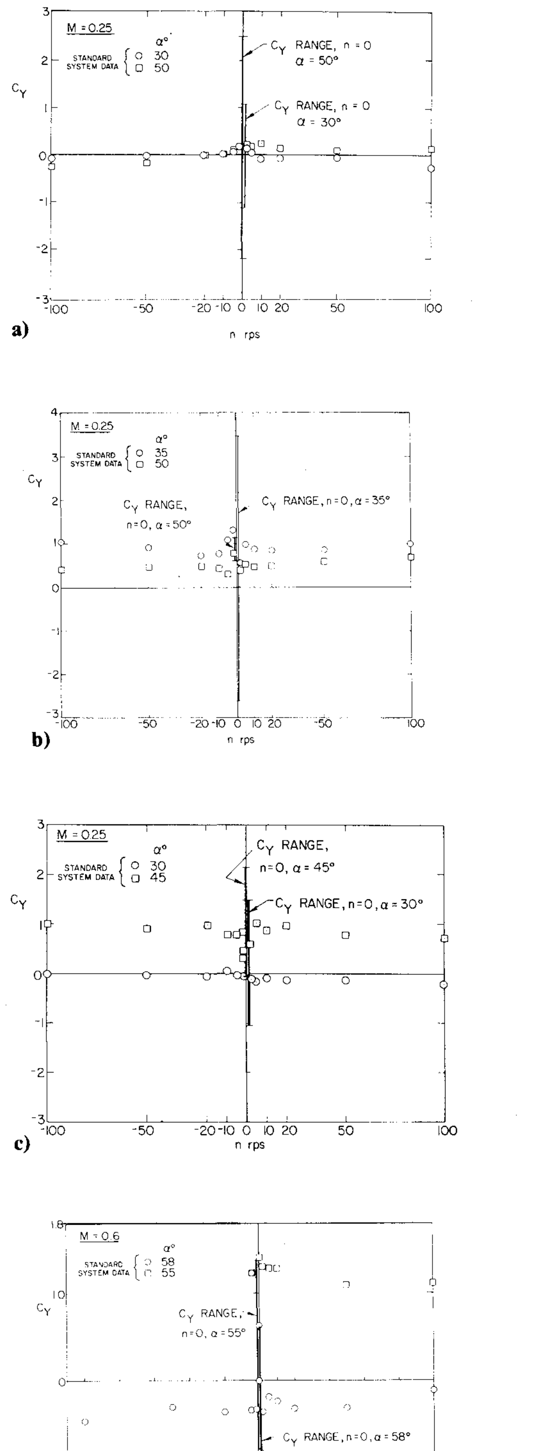

Fig. 6 Effect of tip spin on mean side force. a) Tip with three grit strips. b) Tip with two grit strips. c) Tip with one grit strip. d) Smooth tip.

available for the band. However, the spinning band data do show very small C_Y variations. The fully gritted nose tip and the smooth nose had only small effects and are not shown. It may be seen that in most cases the side force variation is reduced even at spin rates below the lowest resonance frequency of 12 Hz. From the known-imbalance tests, comparisons between applied centrifugal force and balance reading indicated that dynamic effects could cause uncertainties in the values of C_Y read from the balance. These

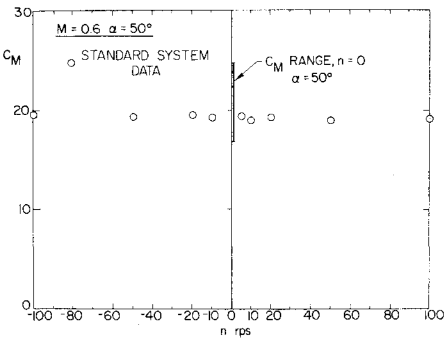

Fig. 7 Effect on pitching moment of nose tip with three grit strips.

effects were estimated to be about ±50% of the balance reading. Uncertainty bands are shown on the data in Fig. 5 for spin rates of 10 rps and above. Also shown in Fig. 5 is the mean of the data found by Kruse[4] for a spinning cone. It will be seen that in most cases the trends and magnitudes of the two sets of data are quite similar.

The reduction in peak-to-peak C_Y variation with increasing spin rate is thought to be due to two possible mechanisms. First, the vortices require a finite time to change their positions fully. As the switching rate increases, the vortices will be forced to travel shorter and shorter distances before switching back again. Ultimately, they will probably exhibit only small motions about some mean position. This will produce reduced peak-to-peak force variations. Second, even if a vortex were switched instantaneously to a new position, its associated flowfield (and that on the body) will not be established instantaneously. An increased switching rate will probably produce a mean vortex flowfield which will again ultimately exhibit only small variations from a mean pattern.

The cyclic side forces do not average out to zero in all cases. However, their rates of change are so rapid that when applied to a body with a low natural frequency of aerodynamic response (missiles typically have natural pitch and yaw frequencies of 3-5 Hz) the effect should be an averaging of the impulses by the system. This conclusion is supported by the standard retrieval system data shown in Fig. 6. Here, the range between maximum and minimum C_Y over a cycle at zero-spin rate is compared with the filtered, averaged data at spin rates up to ±100 rps. The zero-spin data indicate the range within which the side force on a body might lie during nonspinning operation. The data points indicate the level of side force which would be experienced by a vehicle having about a 5 Hz natural frequency in yaw. The considerable reductions in side force variation, even with quite low spin rates, is evident. It appears that the averages usually have values near the center of the zero-spin C_Y range. The single exception is the data with a smooth nose tip at $\alpha = 55$ deg. The effect of spin here is mainly to focus the average values of C_Y near the upper and lower ends of the C_Y range, depending on spin direction. However, not all of the points are focused in the same direction by a given spin direction (Fig. 6d). Because of the 5 Hz filter, some question arises of the validity of the filtered, averaged values in cases where (spin rate × number of disturbances) is less than 5 Hz. However, this does not apply to the bulk of the data. It should be noted that the averages obtained using the standard system did not always correspond to those from the magnetic tape. This discrepancy has not yet been resolved. However, the main conclusions on cyclic repeatability, side force reduction, and averaging should not be significantly altered because of this.

The results of Figs. 5 and 6 have important implications for the use of the spinning device concept in practical cases. It appears that a missile employing a spinning device and flying at a high angle of attack would probably experience a side force essentially constant in magnitude and direction. It would also experience some vibration whose severity would decrease with increasing spin rate.

The discussions so far have concentrated on side forces but a brief mention of pitch angle quantities is in order. Normal force and pitching moment proved to be influenced by the vortex switching, particularly when artificial disturbances were present. The cyclic variations at zero-spin rate could be as much as ±20% in the case of pitching moment (Fig. 7). Figure 7 shows the range of C_M as the nose tip with three grit strips was first rolled incrementally and then spun up to ±100 rps. The standard system data (which again are seen to be close to the average of the rolled data) show the spread to be collapsed into a very small mean range. This is an additional advantage of the spinning device concept.

Conclusions

The spinning device concept has been shown to have significant capabilities for influencing asymmetric vortex effects. By rotating the nose, nose tip, and a band of the body surface just aft of the nose, the wake pattern and the associated side forces and moments were cyclically altered. The rate of variation was dependent upon spin rate and the number of artificial disturbances fixed to the spinning portion. It appeared that if the two body nose vortices were unchanged, as was the case with the band, the variations in the remainder of the wake produced significantly smaller variations in side force. Thus, the nose vortices appear to play a dominant role in determining side force magnitude and variation with angle change. For the nose and nose tip, increased spin rate produced decreased peak-to-peak variations in side force. Possible mechanisms for this effect are that the vortices cannot change their positions, or perhaps fully establish their flowfields at their new positions, fast enough to produce the full effect on the body.

Filtered cyclic data from the balance showed that the average side force experienced by the body was essentially constant throughout the spin range. By varying the number of artificial disturbances fixed to the nose and nose tip, the mean value of side force could be changed. The best results were obtained using the nose tip with three axial grit strips. This brought the mean side force to zero.

It is felt that the spinning device concept should work regardless of the direction in which the body is pitched or yawed. This is an advantage relative to vortex control schemes which may be yaw sensitive. In addition, the concept requires no special body shaping or ejectable-fluid generation or storage. Future work is required to investigate the effects of nose bluntness, body length, and the presence of fins.

Acknowledgments

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