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Forebody Vortex Control Using Small, Rotatable Strakes

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Aerodynamic control using a rotatable, miniature nose-tip strake system was investigated in a water tunnel using a forebody model of an F/A-18. Flow visualizations and yawing moment measurements were performed. Flow visualization results revealed that the small nose-tip strake functioned by generating vortices off its leading and trailing edges that then controlled the flow at the tip region. The system was shown to be highly effective in controlling the forebody vortices and producing controlled yawing moments at moderate-to-high angles of attack. The system was effective over a wide range of sideslip angles. A dual-strake produced a more gradual change in yawing moment with strake position than a single strake.

Nomenclature

A_{ref} = reference wing area, 37.2 m^2 full-scale
C_n = yawing moment coefficient, $yM/q_\infty A_{ref} l$
L = model length, 60.2 cm
l = reference length, mean wing chord
q_∞ = freestream dynamic pressure
t = time
t^* = convective time, tU_∞/L
U_∞ = freestream velocity
X_{ref} = moment reference point; 87.6 cm from the tip of the model (85.6% of the total length of a 6% F-18)
α = angle of attack
β = angle of sideslip
ϕ = angular position from the windward meridian

I. Introduction

THE aerodynamic forces on the forebody are a major contributor to the overall stability of modern aircraft. High-speed flight requirements dictate the forebody to be highly slender in configuration. The flow over such a configuration at high angles of attack is dominated by vortices. One potential stability problem at high angles of attack is that these vortices can become asymmetric at zero sideslip, resulting in a large side force. Another potential problem is that the vortex flow can produce destabilizing yawing moments at sideslip conditions, thereby contributing negatively to the overall directional stability of the aircraft.

The typical effectiveness of the vertical tail and rudder to control the yawing moment on an aircraft falls off as the angle of attack increases because the vertical tail gradually becomes enveloped in the wake of the wing and fuselage. The demand for high agility, however, requires an increase in the control power with the angle of attack. In addition, at the same time the rudder effectiveness is decreasing, the asymmetric forces of the forebody vortices are increasing. In modern fighters such as the F/A-18 the problem is compounded by the close coupling between the forebody and LEX vortices. An asymmetry in the forebody vortices usually leads to an asymmetry in the LEX vortices. On the other hand, if there are means to control locally these vortex-flows on the aircraft, one may be able to use this powerful force input to enhance the overall airplane controllability.

One of the more effective methods of controlling the forebody vortex flow is by using forebody strakes. The strakes are either fixed to the forebody to enhance the stability characteristics, or deployed actively to provide additional control. The use of a fixed pair of forebody strakes attached symmetrically to the forebody (e.g., Refs. 1–4) has been shown to be effective in forcing naturally occurring asymmetric vortices at zero sideslip at high angles of attack to be symmetric. The large forebody sideforces and resulting yawing moments are therefore eliminated. While the strakes can be effective in this regard, they can lead to a degradation in the static directional stability. Stahl[5] demonstrates that, instead of a pair of strakes, a single, large strake deployed along the leeward meridian of the entire forebody can also maintain vortex symmetry. The single strake in effect acts as a splitter plate and thus forces the forebody flow to be symmetric. Ng[6] shows that, due to the stabilizing effect of the flow at the nose tip on the overall vortex flow, similar effect can be achieved by a small strake that extended over only a small portion of the tip region.

Actively deployed forebody strakes have been investigated as a potential means for enhancing high angle of attack controllability. Some examples of the investigations are Refs. 7 and 8. Murri and Rao[7] studied the effectiveness of deflectable strakes in providing controlled yawing moments for a generic fighter configuration at high angles of attack. The strakes extended essentially along the entire length of the forebody and were deflectable to different angles about a hinge line fixed along a meridian line. While a single strake was found to be effective in producing large yawing moments, the control was rather nonlinear and the strake was ineffective in eliminating the naturally occurring vortex asymmetry and associated yawing moment at zero sideslip. A pair of differentially deflectable strakes was found to be more satisfactory in these regards, although the asymmetry at zero sideslip still could not be totally eliminated by a symmetric deployment of the strakes. Malcolm et al.[8] used a different form of deployable strakes that pivoted out of the forebody about a hinge point while the strakes stay normal to the local surface. Several

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different strake lengths were tested. It was found that strakes extending over only a portion of the forebody were sufficient to provide similar control to longer strakes.

Large, asymmetrically-deployed strakes in effect create a significantly asymmetrical forebody geometry and would naturally be expected to produce yawing moments even at zero sideslip. In practice, however, the size of the devices is a key issue. Many numerical and experimental studies (e.g., Refs. 9–13) have demonstrated that, under suitable conditions, a small perturbation at the tip region can lead to large asymmetries in the forebody flow and therefore large controlled yawing moments.

Two recent studies[13,14] on rotatable tip devices for forebody vortex control are particularly relevant to the present study. The control devices used in these two studies were substantially smaller than the strakes used by Murri and Rao[7] and Malcolm et al.[8] Zilliac et al.[13] studied the effect of tip geometry on the vortex flow over a slender body of revolution. Rotatable nose-tip asymmetries in forms of a small cylinder and machined flats were found to be highly effective in producing controlled side forces, although the emphasis of the study was more on the effect of perturbations than on control. The study by Moskovitz et al.[14] on the other hand, addresses directly the use of a rotatable nose-tip perturbation in the form of an elliptic tip as a control device. Predictable and repeatable side force with nose-tip roll was obtained even at relatively moderate angles of attack and sideslip angles as large as 15 deg.

One important question is how small the device can be and still be effective in providing the desired control. Small nose-tip devices such as those in Refs. 13 and 14 produce very little vorticity of their own. They seem to function mainly by providing a bias to the flow asymmetry near the tip region. Therefore, they would be expected to function most effectively when the forebody flow is at or near regimes where the vortices are highly sensitive to perturbations. Large forebody devices such as the strakes used in Refs. 4 and 10 do produce sizable vorticity locally. Thus, one would expect these devices to be effective in controlling the forebody flow over a wider range of flow conditions when compared with the miniature devices. Naturally, a large device is also more likely to produce large and perhaps unacceptable interference on other operations such as the radar.

Many fundamental questions remain concerning the causes of vortex asymmetries and the natures of the asymmetries. There is continuous disagreement on whether vortex asymmetries are a viscous or inviscid phenomenon. Relating to this is the question of whether the continuous presence of a perturbation is necessary for maintainig a vortex asymmetry. Unfortunately, it is impossible in any experimental studies and even numerical studies to remove completely all model asymmetries. As demonstrated by Hartwich et al.,[12] even computer machine accuracy can sometimes dictate the form of vortex asymmetry over a forebody. The experimental study by Zilliac et al.[13] shows that even minute perturbations such as dust particles can strongly affect the vortex flow.

Another question of interest is how the various forms of vortex control function. There is, no doubt, more than one means by which the vortex flow can be controlled and that a sufficiently strong perturbation can alter the forebody flow under any circumstances. Nevertheless, there may be certain fundamental mechanisms that are common to various control concepts such as jet blowing, slot blowing, suction, and strakes. The understanding of these mechanisms will likely lead to the development of more effective means of vortex control.

The present study will provide information that may help in answering the above questions. The specific objectives are: 1) to provide insights into the fluid mechanisms that control the forebody vortex flow, and 2) to explore the potential of a control device in the form of small, rotatable nose-tip strake for controlling the forebody flow and thus providing controlled yawing moments. To achieve these objectives, flow visualizations and yawing moment measurements were performed in a water tunnel experiment.

II. Experimental Setup

The experiment was conducted in the Eidetics 2436 Flow Visualization Water Tunnel. The facility is a continuous horizontal flow tunnel with a test section 0.91 m high × 0.61 m wide × 1.83 m long. The test section is a channel constructed of tempered glass that allows both side and planform views. In addition, a downstream transverse window provides an upstream end view without any obstruction. The tunnel speed can be varied from 0 to 30.5 cm/s. Most of the tests were conducted at flow speed of 7.6 cm/s, corresponding to a Reynolds number range of about 0.7×10^3 per cm. The low Reynolds number minimized the transitional effect. A pressurized dye-injection system was used for flow visualization that was recorded using both a 35 mm camera and a video tape recorder.

The model used for the tests, shown in Fig. 1, was a truncated F/A-18 model with a cutoff point a short distance aft of the LEX-wing junction. Dye ports were located along the windward sides of the forebody, the LEX, and the wings. The baseline flow was established with a forebody that was "clean" except for a few small nozzles located along the ±135-deg meridians. The nozzles were used for a companion study[15] to evaluate jet blowing for forebody vortex control. The rotatable strake was 1.04 cm in length that was about $\frac{1}{10}$ the length of the model radome, and 0.19 cm in height that was about $\frac{1}{5}$ of the local forebody diameter at the base of the strake. Tests were conducted with a dual-strake that consisted of a pair of fixed strakes that were 150 deg apart circumferentially, and a single strake. The nose tip with the strake was rotated manually using an internal shaft that extended through the back of the model. The angular position was determined by marks on the surface of the model.

Yawing moments were measured using a strain gauge setup. The strain gauges, arranged in a standard bridge configuration on the model supporting sting, were located 87.6 cm from the tip of the model. This was equivalent to 85.6% of the total body length of a 6% F/A-18 model. One of the limitations with this simple setup was that the choice of moment reference was arbitrary, and without a second set of strain gauges it was not possible to transfer the reference center to other locations. The natural resonant frequency of the model mounted on the model support was revealed by the bridge output in response to a force pulse. The result indicated that the resonant frequency was about 1.5 Hz. A 0.33-Hz, first-order low-pass

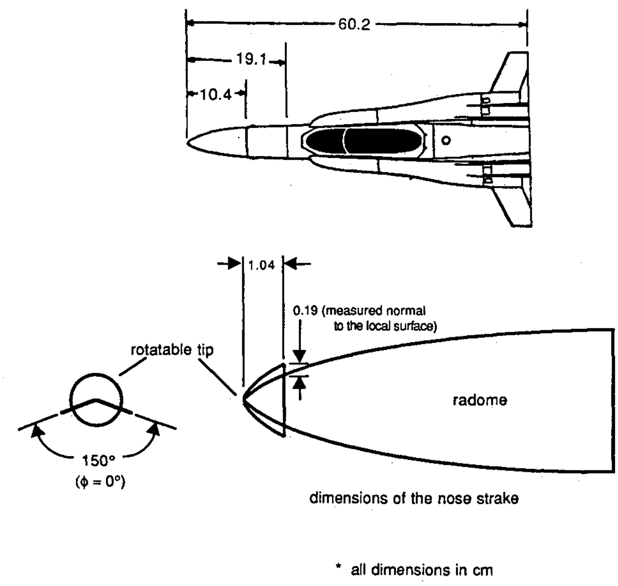

Fig. 1 Schematic of the 6% scale F/A-18 forebody section model.

filter was subsequently used to filter out the model-support natural frequency. The bridge output was calibrated by hanging small weights through a pulley system to create known moment loads. Right and left-pointing moments were designated as positive and negative respectively. The calibration was essentially linear and symmetric over the range of interest.

III. Results and Discussion

A. Flow Visualization

The main purpose of the flow visualization results is to demonstrate qualitatively characteristics of the baseline flow and the effect of the nose-tip strakes on the vortices.

1. Visualization of the Baseline Flow

For the α range (15–65 deg) tested, the forebody vortical flow around the baseline configuration can be divided roughly into three distinct regimes. From $\alpha \approx 15$ deg to approximately 55 deg, the flow is visibly symmetric. From $\alpha \approx 55$ to 60 deg, the forebody vortices are asymmetric and stable with the right vortex assuming a high position regardless of the history of model attitude. At α's among 60 deg and 65 deg, the flow becomes nearly bistable. At this condition, the steady vortical flow assumes one of two mirror-image flow patterns at a given combination of α and β (see Ref. 15 for detailed discussions). Tests performed on a $\frac{1}{32}$-scale F/A-18 model show similar vortex behaviors. These flow regimes are similar to those identified by Zilliac et al.[13] in their study of a tangent ogive forebody, although the angle of attack ranges over which they occur are different due to the difference in geometry.

2. Visualization of the Effect of the Dual-Strake on the Vortex Flow

The flow visualization results show that the rotatable dual-strake on the F/A-18 starts to affect the forebody vortices at α's above 30 deg. The effect is dependent on the angle of attack and the nature of the baseline flow.

From $\alpha \approx 30$ to 50 deg, the baseline flow is symmetric. That is, small model imperfections that are present naturally are not sufficient in perturbing the flow from the symmetric state. On the other hand, rotating the strake to different positions perturbs the vortical flow from a symmetric configuration into various degrees of asymmetry. At any angle of attack, there appears to be a maximum attainable vortex asymmetry. The magnitude of available control, as revealed by the maximum attainable vortex asymmetry, is the same for the left and right side and increases with the angle of attack. Examples of the results at $\alpha = 50$ deg with no-sideslip in Fig. 2 demonstrate the various degrees of vortex asymmetry that can be achieved. As indicated by the accompanied sketches in Fig. 2, a symmetric deployment of the strake is associated with a symmetric pair of forebody vortices. When the dual-strake is rotated to an asymmetric configuration, the side with a strake closer to the windward meridian is associated with a vortex closer to the forebody. This vortex orientation implies a yawing moment pointing towards the same side.

Results in Fig. 2 show a strong coupling between the forebody and the LEX vortices. A high forebody vortex on one side is associated with a delayed LEX vortex breakdown on the same side. Thus at zero sideslip, a right-wing-down rolling moment (associated with a delayed breakdown of the left LEX vortex) would be induced whenever a nose-right yawing moment (associated with a high left forebody vortex) is generated and vice versa. Therefore, the yawing and rolling moments would be such that a coordinated turn is produced.

Figure 3 shows the effectiveness of the control at sideslip conditions at $\alpha = 50$ deg. It can be seen that the control is effective even at a sideslip angle of -20 deg. The vortex pattern can be manipulated from a naturally left-vortex-high configuration to a right-vortex-high configuration. Therefore, the nature of the yawing moment on the forebody has likely been changed from destabilizing to stabilizing.

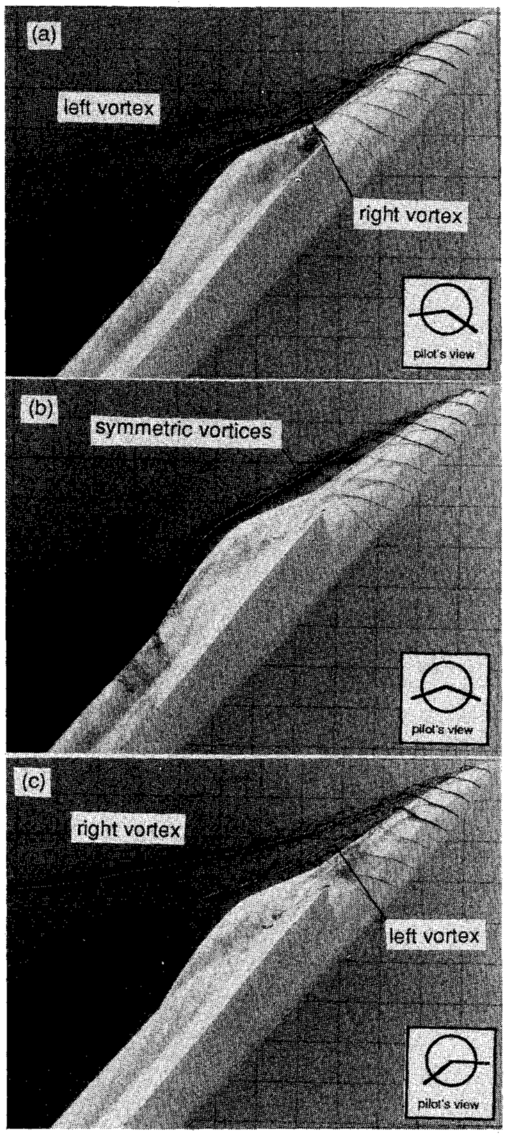

Fig. 2 Effect of varying the nose-tip roll angle on the forebody flow pattern at $\alpha = 50$ deg and $\beta = 0$ deg for the model with the dual-strake.

For $\alpha \approx 55$ to 60 deg, the baseline flow is asymmetric. The effect of the dual-strake is sufficiently strong to overcome the baseline asymmetry, and the vortices can be manipulated to become symmetric or into different degrees of asymmetry. The general behavior of the flow is similar to that at lower angles of attack.

For α's above about 60 deg, the baseline vortex flow becomes "bistable." Flow visualizations indicate that the effect of the dual-strake is apparently not sufficiently strong to overcome the natural asymmetry and force the flow into a symmetric state. Nevertheless, the results also show that the dual-strake do affect the degree of vortex asymmetry of the baseline flow. Thus, even in this "bistable" regime the flow off the nose-tip region still can exert certain degree of control on the overall vortex flow. A comparison with the baseline flow shows that the natural asymmetry can be reduced or increased by a small amount by moving the strake to different positions. Also of interest is that, when compared with the baseline flow, the degree of asymmetry is reduced when the strakes are deployed symmetrically at $\phi = \pm 75$ deg.

While at $\alpha = 60$ deg a symmetric vortex pattern cannot be induced by placing the strake statically at any position, flow visualization reveals that a quasi-steady symmetric pattern can be maintained by oscillating the dual-strake rapidly with a small amplitude about a symmetric position. Thus, an ac-

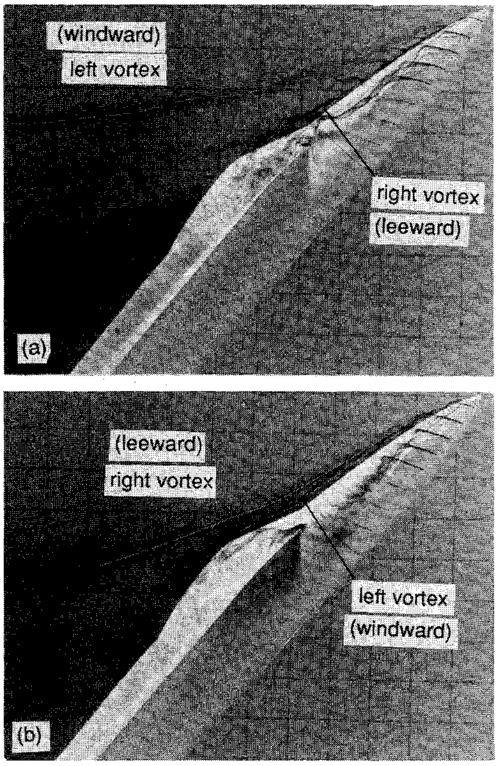

Fig. 3 Effect of varying the nose-tip roll angle on the forebody flow pattern at α = 50 deg and β = −20 deg for the model with the dual-strake.

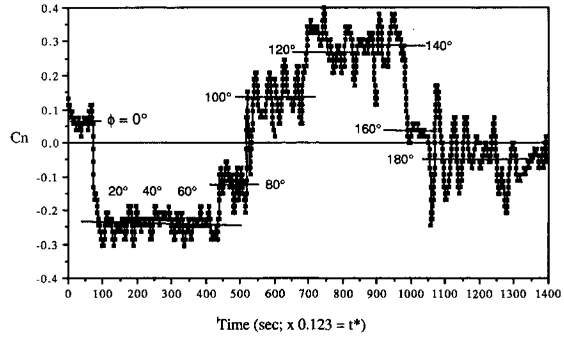

Fig. 4 Yawing moment history for the model with the dual-strake at α = 50 deg and β = 0 deg.

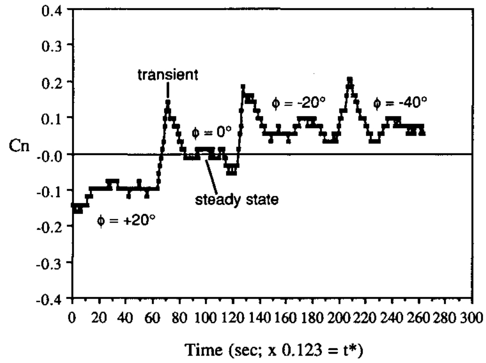

Fig. 5 Yawing moment history for the model with the dual-strake at α = 40 deg and β = 0 deg.

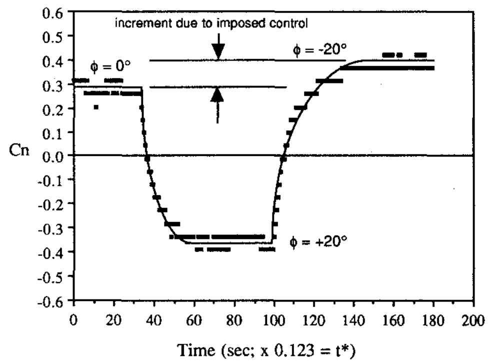

Fig. 6 Yawing moment history for the model with the dual-strake α = 60 deg and β = 0 deg.

tively-controlled strake system can potentially be a powerful means of alleviating the asymmetric aerodynamic forces at conditions where conventional passive systems are not effective.

Overall, the flow visualization results demonstrated that the nose-tip strakes provide similar kinds of control on the forebody vortices to many other control methods such as large deployable strakes[7,8] and blowing.[8] The control is effective over wide ranges of sideslip (0 to >20 deg) and angles of attack (~30 to 65 deg or higher). The vortices can be manipulated into different patterns by rotating the strakes to different angular positions.

B. Yawing Moment Results

The main purpose of the yawing moment results is to quantify the controlling effect of the nose-tip strake. In addition to the dual-strake, a single strake was tested to aid in the understanding of the control mechanism. For the single strake, the zero roll angle was defined, as when the strake is at the windward meridian (ϕ = 0 deg). For the dual-strake, the zero position was when the strakes were symmetrically located at ϕ = ±75 deg.

1. Transient and Temporal Behaviors

Due to the slow testing speed of the water tunnel and within the limitations on the signal phase and amplitude imposed by the filtering, certain transient and temporal behaviors can be revealed by the yawing moment measurements. Figure 4 shows the results at α = 50 deg for the dual-strake with the nose-tip roll angle being changed from 0 to 180 deg in 20-deg steps. In most cases, the results reveal that the yawing moment can be highly unsteady. The unsteadiness is higher in magnitude when the time-average flow is closer to being symmetric. Note also that the characteristic frequency of the unsteadiness is substantially lower than the natural frequency of the model support, indicating that it is not a result of the model support oscillation.

Figures 5 and 6 show the results at angles of attack of 40 and 60 deg. The yawing moment at α = 40 deg, shown in Fig. 5, is more steady compared with that at α = 50 deg. The steady-state yawing moment that can be produced by the strakes is substantially smaller than at α = 50 deg. However, a large transient overshoot in the yawing moment can be observed when the nose-tip with the strakes is rotated to a new position. The overshoot lasts about 20 s, corresponding to a t^* of 2.46. The yawing moment at α = 60 deg, shown in Fig. 6, is relatively steady. The yawing moment can be switched between two essentially steady values by rotating the nose-tip from +20 to −20 deg. In agreement with the flow visualization, by moving the strakes to different positions the natural asymmetry at this angle of attack can be increased or reduced by a small amount as reflected by the yawing moment measurements. The effect of the strakes, however, is apparently not sufficiently strong to overcome the natural asymmetry and eliminate the zero-sideslip yawing moment even when the strakes are deployed symmetrically.

2. Time-Average Behaviors

Examples of steady-state (after the initial response period), time-averaged yawing moments for the rotatable single-strake were plotted against the nose-tip roll angle in Fig. 7. At α =

40 deg, the yawing moment changes continuously with the nose-tip roll angle. A certain asymmetry can be observed in the yawing moment distribution especially around the zero roll angle. This could be a result of a small misalignment when fixing the strake to the rotatable nose-tip, or other imperfections in the nose tip. When the angle of attack is increased to 50 deg, the yawing moment distribution takes on a more square-wave-like appearance. The moment can be seen to switch between two extreme values. The accompanied sketch in Fig. 7 shows from a pilot's view point the angular ranges over which positive (right pointing) and negative (left pointing) yawing moments are generated by the single strake at α = 50 deg. The moment direction switching occurs over very narrow angular ranges centered approximately about four roll angles: 0, 60, 180, and 300 deg. When the strake is located at ϕ's from 0 to ± 60 deg, the yawing moment generated is toward the side with the strake. For the other angles, the yawing moment generated is away from the side with the strake. Flow visualization reveals that with the single strake in place the vortex flow tends to assume one of two highly asymmetric states. However, flow states inbetween the two extremes can also be maintained by carefully placing the strake near each of the four roll angles where the moment switches signs. Apparently, the single strake creates rather sizable asymmetric disturbances at most circumferential angles. Thus with the single strake the flow is "locked" into highly asymmetric states under most situations, even though the baseline flow is essentially symmetric.

The surface dye flow visualization results in Fig. 8 suggest an explanation for the relationship between the yawing moment and the strake position. Flow visualization reveals an interesting effect when the small strake is located sufficiently far upstream ($\phi < \sim 60$ deg) of the natural separation such as in Fig. 8a. A vortex originated from the trailing edge of the strake seemingly energizes the boundary layer flow and delays separation in the region immediately aft of the strake. Correspondingly, on the side with the strake, the forebody vortex moves closer to the surface and the primary separation is delayed along the forebody. A yawing moment toward the side where the strake is located is therefore generated. This suggests that shaping the trailing edge to increase the strength of the trailing vortex can potentially improve the effectiveness of the strake. The vortex formed over the side edge of the strake begins to dominate when the strake is moved sufficiently far towards the leeward side ($\phi > \sim 60$ deg) as in Fig. 8b. The strake vortex acts as an initiation point and merges with the forebody flow downstream to form the forebody vortex. Since the side-edge vortex of the strake moves farther away from the forebody surface as the nose-tip roll angle increases, the eventual effect is to pull the forebody vortex farther away from the surface. A yawing moment away from the side where the strake is located is thus generated. Near ϕ = 0 deg and 180 deg, the strake does not produce strong vortices. The main function of the strake would seem to be to create an asymmetry in the primary or secondary flow at the tip region that dictates the asymmetry of the vortex flow farther downstream.

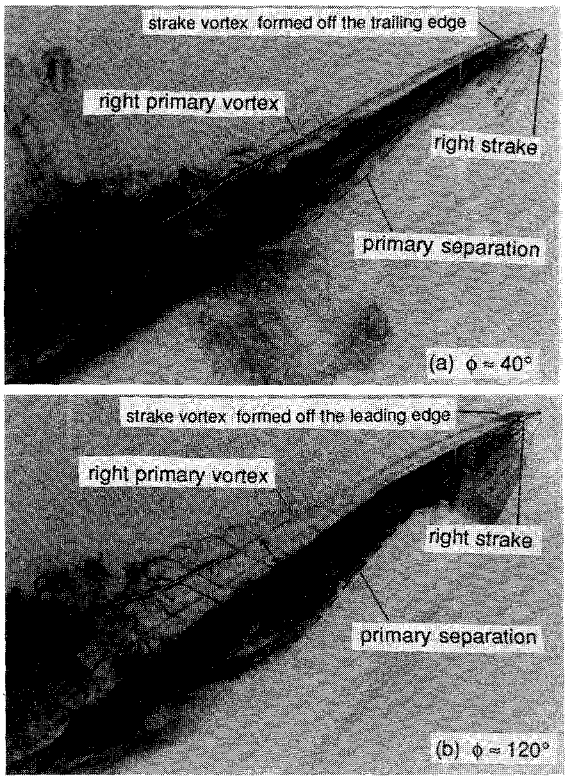

Fig. 8 Effect of a single strake on the forebody surface flow pattern at α = 50 deg and β = 0 deg.

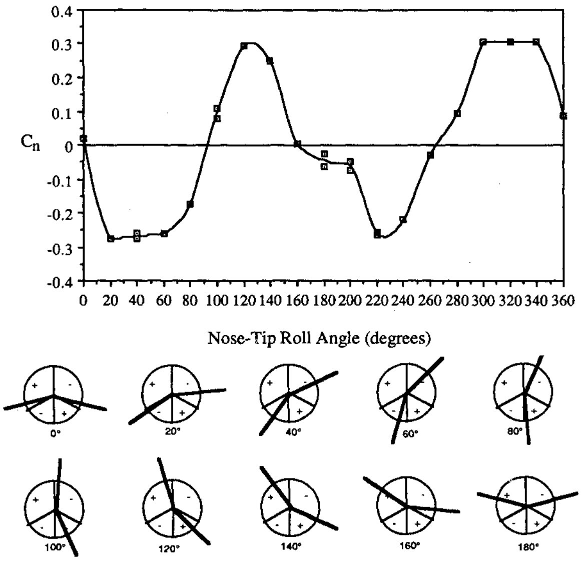

Fig. 9 Steady-state mean yawing moment as a function of the nose-tip roll angle at α = 50 deg and β = 0 deg for the model with the dual-strake.

As shown in Fig. 9, the yawing moment generated by the dual-strake at α = 50 deg behaves rather differently from that of the single-strake at the same α. While the maximum yawing moments that can be generated are similar in magnitude to that of the single-strake, the dual-strake moment varies much more gradually with the nose-tip roll angle. Therefore, the second strake has a significant modulating effect on the first. An inspection of the relative positions of the strakes sketched in Fig. 9 demonstrates the mechanisms at work. At ϕ = 0 deg, the two strakes are symmetrically located in the positive and negative moment angular zones. The result is a near-zero net yawing moment. At ϕ = 20, 40, and 60

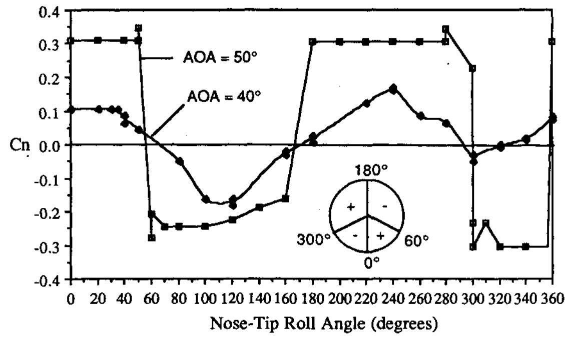

Fig. 7 Steady-state mean yawing moment as a function of the nose-tip roll angle at β = 0 deg for the model with the single strake.

deg, both strakes are located in the negative moment zone and thus the maximum negative yawing moment is generated. At ϕ = 80 deg, one of the strakes crosses into a positive zone and thus the negative yawing moment is reduced. The trend continues until at ϕ = 120 deg where both strakes are in positive zones and the maximum positive yawing moment is generated. At ϕ = 140 deg, one of the strakes crosses into a negative zone and thus the yawing moment is reduced from the maximum positive value. The behavior of the yawing moment at other roll angles can essentially be explained in a similar way.

Above α of about 60 deg, flow visualization reveals that the flow becomes "bi-stable." Results at α = 60 deg, as demonstrated in Fig. 7, show that the yawing moment can be controlled by the nose-tip angle but to a much lesser degree. A symmetric flow cannot be maintained with the strakes deployed symmetrically. The magnitude of the yawing moment, however, can be increased or decreased by a moderate amount by deploying the strakes asymmetrically. Overall, the yawing moment results are in qualitative agreement with the flow visualization results.

3. Discussions on Functions of Strakes

The rotatable nose-tip strake appear to be quite effective in controlling the forebody vortices to produce controlled yawing moments even at relatively moderate angles of attack. Very effective control on the vortex asymmetry can be obtained by controlling the separation near the tip region. In essence, the flow pattern is modified so that the effective geometry of the tip is altered. The rotatable nose-tip strakes function by creating in-effect an asymmetric forebody apex. While the method is somewhat similar to the deflectable and deployable strakes reported in Refs. 7 and 8, there are several significant differences. The rotatable nose-tip strakes are intended to influence directly only a small region near the tip of the forebody, whereas the large strakes directly affect a much larger region aft of the tip. The nose-tip strakes are therefore significantly smaller. Large strakes essentially dictate that a large portion of the forebody flow separates at the leading edges of the strakes. The small nose-tip strakes, on the other hand, can behave much like the vortex generators on many existing aircraft wings. One of the functions of the strakes is to generate small vortices that energize the boundary layer farther aft to delay flow separation. While the deflectable strake has a fixed hinge-line, the nose-tip strakes are free to rotate to any angular position. This may allow the nose-tip strakes to be positioned more optimally relative to the forebody vortices and separation locations for a wider range of angles of attack and sideslip.

The presence of a second strake has a strong modulating effect on the first strake, resulting in a more gradual variation of yawing moment with the nose-tip roll angle. This behavior is probably more desirable from a control standpoint in being able to maintain a symmetric flow and to provide different magnitudes of control. The results also indicate that the characteristics of the dual-strake system may be tailored to a large extent by altering the included angle between the two fixed strakes. Naturally, maximum flexibility is achieved if the strakes can be rotated independently, with the tradeoff being an increase in the system complexity. Continuously oscillating the strakes in the roll axis can potentially be a means of minimizing vortex symmetries at high angles of attack.

IV. Effect on Static Stability

Since the rotatable strake system may not be actuated during all operation modes of the aircraft, the effect of the strakes on the overall aircraft stability is of concern. Previous studies have shown that the presence of forebody strakes can potentially lead to a degradation in the static directional stability. Specifically, strakes that are positioned to fix the separation locations on the forebody at zero-sideslip can promote early separation on the windward side during sideslip conditions, resulting in a vortex flow that produces a destabilizing yawing moment.

An alternative way of applying a strake is to use the vortices generated by the strake on the windward side to delay rather than promote separation. Proper shaping and locating of the strakes can produce vortices of sufficient strength and with the desired trajectory to control the separation at the nose-tip. At sideslip conditions, the strake on the windward side moves farther forward of the natural separation and therefore retains its function of delaying separation. On the leeward

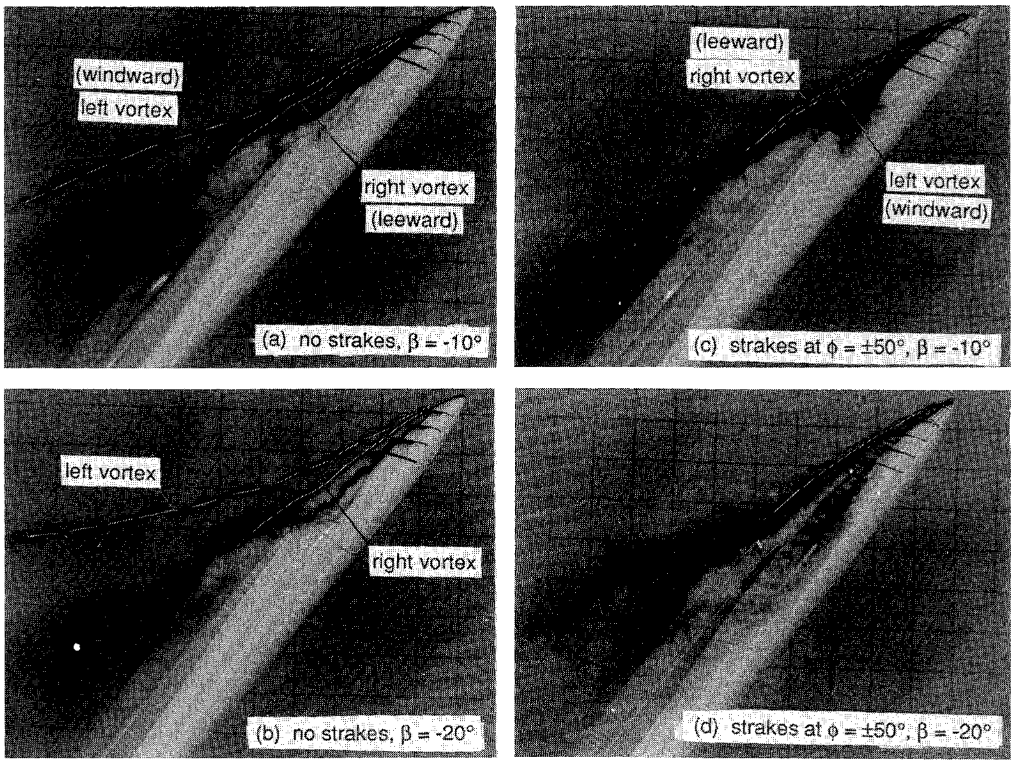

Fig. 10 Effect of a pair of strakes at ϕ = ±50 deg on the forebody flow at α = 50 deg.

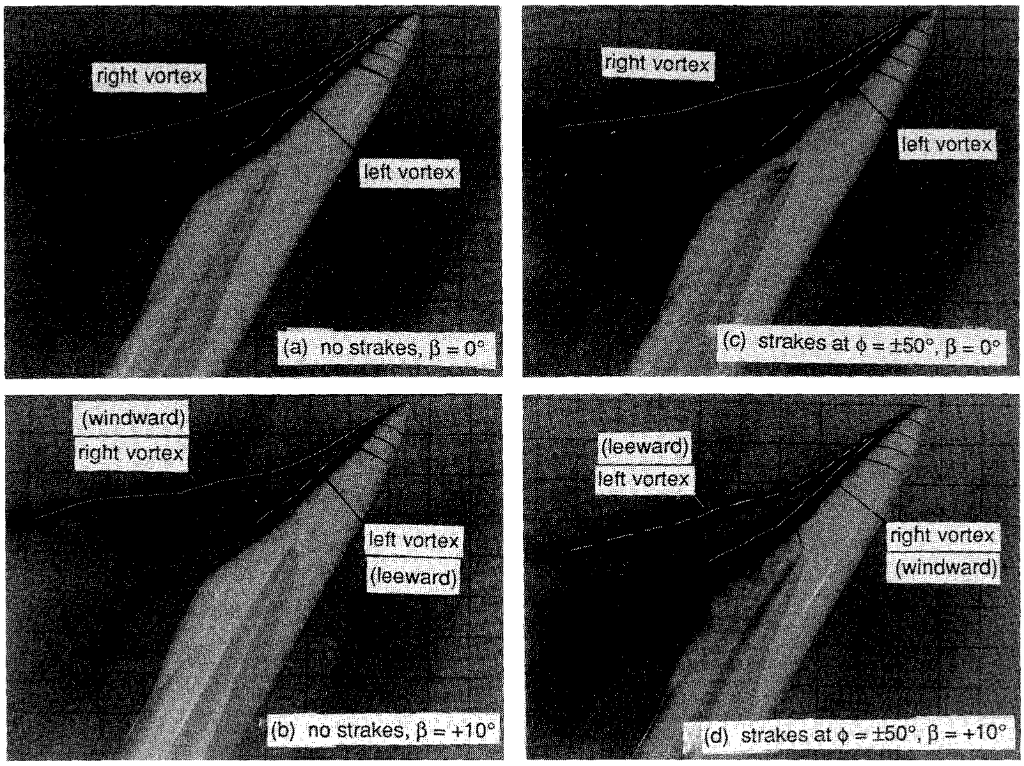

Fig. 11 Effect of a pair of strakes at $\phi = \pm 50$ deg on the forebody flow at $\alpha = 60$ deg.

side, the strake moves aft relatively to the natural separation, and the effect of the strake is to promote early separation on this side. The net result is that the naturally destabilizing yawing moment at sideslip is either reduced or reversed.

To verify this idea, further water tunnel experiments were performed with a pair of fixed strakes. The single-strake results suggest that the proper location for a strake to delay separation at 50-deg angle of attack is forward of the ± 60-deg meridians. It was decided to perform flow visualization experiments with the strakes at $\phi = \pm 50$ deg. At these positions, as demonstrated by results presented earlier, the strakes promote flow attachment on both sides at zero sideslip. The static stability should be improved from the baseline case with the maximum benefit being at around $\alpha = 50$ deg.

The flow over the model with and without the strakes was studied. Below $\alpha = 40$ deg, the strakes do not affect significantly the forebody vortices except at very large sideslip angles where the strakes cause the windward vortex to move closer to the surface. This change in the vortex position, as indicated by the yawing moment results presented earlier, would imply a reduction in the right-pointing (destabilizing) yawing moment.

At $\alpha = 50$ deg, the baseline flow at no-sideslip is essentially unaffected by the presence of the strakes. At $\beta = -10$ deg and -20 deg, shown in Fig. 10, the strakes significantly reduce the vortex asymmetry induced by sideslip. It can be inferred from the vortex position that the negative contribution to static stability from the forebody has been significantly reduced if not reversed.

At $\alpha = 60$ deg, the baseline flow at no-sideslip is characterized by a stong vortex asymmetry that is bistable. The present strake arrangement is apparently not capable of eliminating this zero-sideslip asymmetry. At sideslip conditions, shown in Fig. 11, the vortex asymmetry over the baseline configuration always produces a destabilizing yawing moment. The orientation of the vortices will switch at sufficiently large sideslip angles only if the forebody is forced to yaw in a direction oppose to the natural yawing moment induced by the forebody vortex asymmetry. For instance, Fig. 11a shows a case of right-vortex-high flow orientation at zero sideslip and thus a negative yawing moment. In the absence of other restraining or driving forces the forebody will be yawing to the left, leading to a building up of positive sideslip. As demonstrated in Fig. 11b, the flow maintains the same right-vortex-high orientation at positive sideslip angles. Therefore, the yawing moment will continue to propel the motion. Figures 11c and 11d show that the situation is quite different for the forebody with the strakes. At small sideslip angles (~5 deg), the strakes cause the orientation of the vortices to switch and presumably the yawing moment to change from destabilizing to stabilizing. In a purely free-to-yaw situation, this vortex behavior may induce a finite-amplitude oscillation-in-yaw rather than a potential yaw-departure as in the baseline case.

V. Summary and Conclusions

Water tunnel experiments were performed with a forebody-section model that contained vortex generators in the form of rotatable, miniature strakes on the nose-tip. The results show that the forebody vortex asymmetry can be controlled and yawing moments of different magnitude can be generated by moving the strakes to different circumferential positions. The results can be summarized as follows:

1) The rotatable nose-tip strake system was shown to be highly effective in controlling the forebody flow over a wide range of angles of attack and sideslip. A small nose-tip strake functions by controlling the flow separation at the tip region. In essence, the flow pattern is modified so that the effective geometry of the tip is altered. Shaping the trailing edge of the strake to increase the strength of the trailing vortex may improve the overall effectiveness of the strake, thereby allowing smaller strakes to be used.

2) The characteristics of the control depend strongly on the baseline vortical flow that can take on different forms as dictated by the aircraft attitudes and the presence of external perturbations.

3) Compared with the forebody strakes used in many previous studies, the rotatable nose-tip strake system can potentially be much smaller and simpler in operation.

4) The static stability of an aircraft can potentially be improved by placing the strakes at locations where the strake

vortices delay separation on the windward side and promote separation on the leeward side during the sideslip conditions.

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