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Control of Forebody Vortex Orientation to Enhance Departure Recovery of Fighter Aircraft

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A combined experimental and analytical study was undertaken to develop active blowing concepts to control the asymmetric orientation of the vortex system emanating from an aircraft forebody at high angles of attack. The objective of the study was to utilize the side force associated with asymmetric vortices, in a controlled manner, to enhance the capability of a fighter to recover from a departure from controlled flight. Results from water tunnel and wind tunnel tests show that a small amount of tangential blowing along the forebody can effectively alter the forebody vortex system and generate large restoring yawing moments. Six degree-of-freedom digital simulation results show this concept can substantially enhance departure recovery characteristics of fighter aircraft having long, slender forebodies.

Nomenclature

C_l	= rolling moment coefficient
C_L	= lift coefficient
C_M	= pitching moment coefficient = $0.25\bar{c}$
C_μ	= blowing momentum coefficient = $\dot{m}_j u_j^*/q_\infty A_{\rm ref}$
C_n	= yawing moment coefficient = $0.25\bar{c}$
C_{n_0}	= yawing moment coefficient at $\beta = 0$
C_Y	= side-force coefficient
C_{Y_0}	= side-force coefficient at $\beta = 0$
d	= forebody diameter (planform width)
l	= length
l/d	= forebody fineness ratio
$\dot{m}_j$	= jet mass flow rate
PSG	= post-stall gyration
r	= yaw rate (body axis)
Re	= Reynolds number—based on unit length and tunnel freestream conditions
r_n	= nose radius
$r_{n/d}$	= bluntness
TTR	= time to recover
u_j^*	= jet exit velocity
X	= longitudinal position (from apex)
Y	= lateral position (from ℄)
α	= angle of attack (AOA)
α_t	= threshold AOA
β	= angle of sideslip
δ_a	= aileron deflection
δ_H	= horizontal tail deflection
δ_r	= rudder deflection
θ_n	= nose semi-apex angle
ϕ	= circumferential angle around forebody surface measured from windward generator: negative on port side

Introduction

FOR fighter aircraft which operate in the air combat maneuvering (ACM) arena, flight at high angles of attack (AOA), near the limits of controllability, is an inherent part of both offensive and defensive maneuvering. Reluctance to operate in this regime because of possible departure from controlled flight limits the capability of the man-machine combination to deliver its maximum performance. Pilot confidence is the key to effectively operating close to control boundaries, and pilot confidence is a function either of the natural resistance of the aircraft system to departure or of the pilot's ability to easily recover from the occasional out-of control condition associated with high AOA maneuvering. Unfortunately, there are many aircraft in the inventories of the free world's air forces that exhibit a high degree of susceptibility to departure and spin entry. Such aircraft have a departure threshold which is generally beyond maximum lift but well within the ACM gross maneuver envelope. Many of these aircraft also have poor departure recovery characteristics, generally requiring the pilot to act quickly in order to regain control of his aircraft. Since most pilots spend relatively little time near control limits in training or in normal operational flying, they are often unprepared for their first departure. The standard out-of-control reaction is frequently one of panic, followed by ejection.

In an attempt to improve this situation, military training commands have instituted programs to better prepare the pilot for the disorientation which he will experience in a departure and to give him a better chance of taking positive recovery action in a timely manner.

Engineers and scientists are also tackling the problem. One engineering approach has been to use motion and attitude sensors in conjunction with the aircraft's control system to "automatically" recover the aircraft from the departure. State-of-the-art sensors can determine whether the aircraft has departed from controlled flight and determine the direction of motion much quicker than can an average pilot. Relatively simple control laws can be programmed into a control system to respond to these sensor inputs and place the control surfaces in positions to optimize recovery chances in a manner that is much more reliable than an average pilot. The only drawback to concepts which have been developed using this approach is that, for most aircraft, control effectiveness in the departure AOA region is severely degraded when compared to the effectiveness at lower AOA. This sometimes forces the designer to lower the threshold AOA for the automatic recovery system into a region which could cause it to be activated when it is not needed. However, if more effective control devices could be developed, this general approach could be utilized to design a system which would have the potential to dramatically reduce the loss of life and equipment resulting from out-of-control flight accidents.

This paper describes an analytical and experimental study which was undertaken to develop a novel control concept

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which is highly effective in the angle-of-attack region above stall, and which could be mechanized in a manner as outlined in the preceding paragraph to enhance the capability of an aircraft to recover from loss of control. The vortex blowing control concepts tested in the present study were designed to alter the asymmetric orientation of the forebody vortex system, taking advantage of the large aerodynamic forces produced by this asymmetry.

This paper will concentrate on the effects which the blowing concepts have on the overall stability and control characteristics of an aircraft at high angles of attack (see also Ref. 1). See Peake, Owen, and Johnson[2,3] for a discussion of the fluid mechanics associated with forebody blowing about a slender cone model.

Background

Forebody Flowfields at High Angles of Attack

It is a well-known fact that an asymmetric vortex system forms on the leeside of aircraft and missile forebodies at high angles of attack.[4-9] The degree of asymmetry and the strength of the vortices are dependent on several parameters, the primary ones being AOA, fineness ratio (l/d), nose semiapex angle (θ_n), and nose bluntness (r_n/d).

At incidences generally greater than twice the nose semiapex angle, these asymmetric vortices become strong enough to produce values of side force and yawing moment large enough to influence the departure resistance of an aircraft.[10-15] These asymmetric side forces may not only generate a departure from controlled flight but, once the departure has occurred, they may aggravate the tendency of an aircraft to transition to a flat spin mode. In addition, since these vortices have been observed to remain in an asymmetric orientation even under coning conditions, they can oppose recovery from a spin.[16,17]

These vortices have been observed to behave in a bistable manner, preferring to orient in one of two mirror-image states.[18-20] The choice between the two mirror-image orientations is influenced by minute geometric imperfections, especially near the apex of the nose.

The Concept of Asymmetric Vortex Control

In the present study, the overall objective was to harness the power of this vortex system and utilize the side force generated by its asymmetric nature as a control device. Such a device would have effectiveness in the angle-of-attack region beyond stall and could be used, with the proper system design and following appropriate control laws, to greatly enhance the capability of an aircraft to recover from a departure from controlled flight.

Previous Research

The basic concept of controlling the yawing moments generated by long, slender forebodies to aid spin recovery was first proposed by Neihouse et al. in 1960.[10] Neihouse et al. pursued three means of controlling the yawing moments: strakes or spoiler strips placed along the inboard side of the nose (right side in a right spin), induced circulation about the forebody produced by rotating a conical nose section, and flap-type surfaces placed either on both sides or only on the inboard side of an aircraft nose. Each of these concepts proved effective in promoting rapid recovery from various types of spins on different models. Similar experiments using asymmetric nose strakes were reported by Chambers et al.[21] in 1970 and showed equally promising results on a different aircraft configuration. Kruse[22] conducted experiments on the effect of spinning an axisymmetric body about its longitudinal axis, noting that the peak-to-peak variation of side force decreases with increased spin rate. His data[22] also showed that the time-averaged side force is reduced as the body is spun. Cornish and Jenkins[23] conducted experiments with symmetrical tangential blowing near the nose of an aircraft but were unsuccessful in affecting the spin recovery characteristics of their particular configuration.

Present Studies

In a manner similar to some of the previously cited research, the present work concentrated on the experimental evaluation of concepts to control the forebody side force through asymmetric tangential blowing near the apex of the nose.

Several practical considerations were taken into account in order to screen devices which would not find application to a fighter aircraft regardless of their effectiveness. The screening criteria used follow:

1) The tangential blowing concepts must have sufficient effectiveness so as to not require abnormally large quantities of air or unattainable mass flow rates.

2) The blowing nozzles must be located in a region aft of the radar antenna where radar performance would not be affected adversely.

Experimental Apparatus and Test Program

Water Tunnel Tests

Preliminary tests of various forebody vortex blowing control concepts were conducted in the Northrop 16×24 in. Diagnostic Water Tunnel on a 0.025 scale model of an F-5F aircraft. The Northrop Diagnostic Water Tunnel is a single return, low turbulence facility. It is operated at a test section velocity of 0.1 m/s (0.35 ft/s), which corresponds to a Reynolds number of approximately 1×10^5/m (3×10^4/ft). The model used was equipped with two parallel rows of dye injection orifices located on the lower surface of the fuselage forebody. Visualization of the forebody flowfield is achieved when the dye flows out of these orifices and is entrained into the separated shear layer(s) which, in turn, roll(s) up into well-defined vortices.

The water tunnel tests were conducted to screen a large number of potentially useful blowing schemes by comparing, in a qualitative manner, the relative capability of each concept to control the forebody vortex orientation. The blowing concepts tested consisted of small nozzles located on the surface of the forebody at various locations. The angle of the blowing jet relative to the freestream was varied also. Water was supplied to the blowing nozzle through a small tube running down the centerline of the model. Accurate mass flow rates were set by using a water flow meter in the supply line, external to the tunnel. Additional water tunnel tests were conducted on two tangent-ogive-cylinder bodies to determine the effect of vortex blowing control on more generic shapes. The tangent-ogive forebodies had fineness ratios of $l/d = 3.5$ and 5.0. Each was tested with a common $l/d = 4.5$ circular-cylinder afterbody. Tangential blowing in a downstream direction was tested for a matrix of positions on the surface of both bodies.

The experiments were performed over an angle of attack range of 0-60 deg. All water tunnel tests were performed at zero sideslip angle. Vertical and lateral positions of the vortex cores were determined at a fixed longitudinal station for the matrix of nozzle geometries at various blowing rates. In this manner, the relative effectiveness of each concept was evaluated and optimum nozzle locations were determined.

Wind Tunnel Tests

Based on the results of the water tunnel tests, the most promising nozzle geometries were selected for proof-of-concept testing in the wind tunnel.

Testing was conducted in the Northrop Low-Speed Wind Tunnel. The tunnel is a horizontal, atmospheric, single return facility capable of test section Reynolds numbers up to 7.9×10^6/m (2.4×10^6/ft) and a dynamic pressure of up to 9580 N/m² (200 psf). The test section is 10 ft wide, 7 ft high, and 20 ft long. The tunnel has a contraction ratio of 12:1

which gives a streamwise turbulence level of less than 0.1% in the test section.

Tests were conducted using a 0.1 scale F-5F model, equipped for asymmetric blowing at two fuselage stations on the upper surface of the forebody. A plenum chamber for the blowing system was contained in the nose of the model. This plenum chamber was pressurized from an external source through an air supply line which was routed from a support near the back of the sting, forward along the top of the model until it became buried just aft of the canopy. Care was taken to ensure that the supply line was nonmetric. Figure 1 shows the model installation in the tunnel and illustrates the blowing apparatus.

The blowing nozzles were designed to provide choked flow at the nozzle exit plane. A nozzle calibration was performed to determine actual discharge coefficients. Plenum total pressure and temperature and nozzle mass flow rate were measured and used to compute nozzle jet velocity and, hence, blowing momentum coefficient, C_μ.

Wind tunnel tests were performed at a dynamic pressure of 2494 N/m^2 (50 psf), corresponding to a Reynolds number of 4.3×10^6/m (1.3×10^6/ft). Plenum pressures for the blowing system ranged from 1.1 to 4.2×10^6 N/m^2 (165-615 psi) yielding blowing momentum coefficients of between $C_\mu = 0.008$ and 0.032. Data were taken over an angle of attack range of $\alpha = 0$-90 deg in 2-deg increments and over a sideslip range of $\beta = \pm 25$ deg in 5-deg increments.

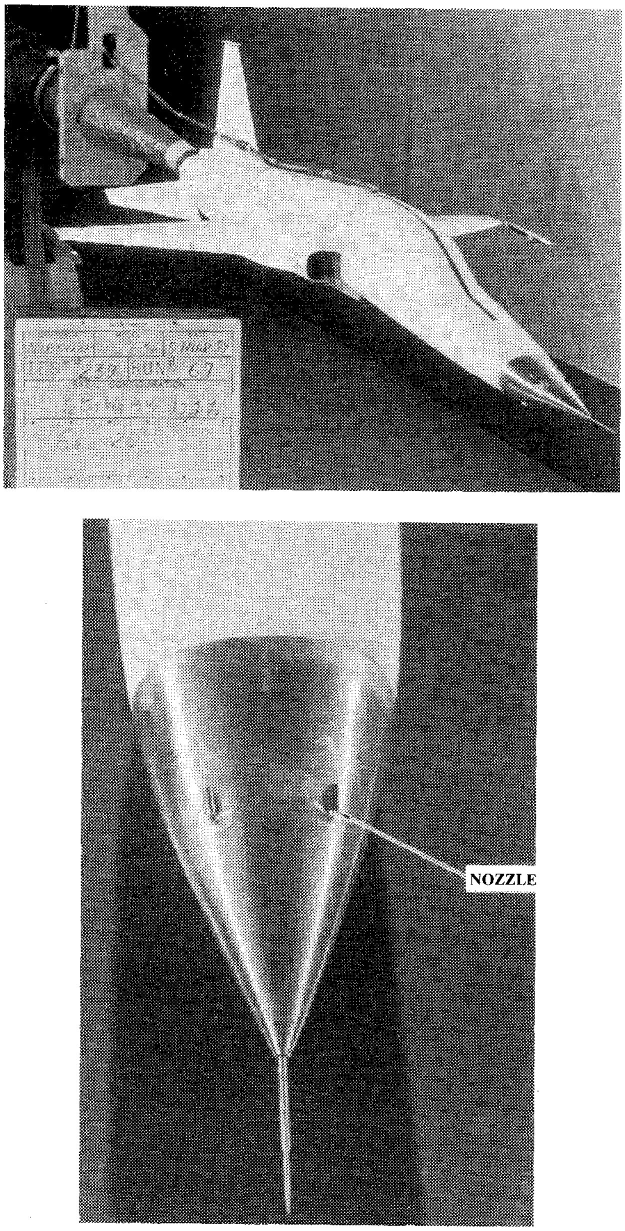

Fig. 1 F-5F model installation 7 × 10-ft low-speed wind tunnel.

Discussion of Results

Water Tunnel Tests

Asymmetric Tangential Blowing Concepts

Experiments performed in the water tunnel with the 3.5 fineness ratio tangent-ogive forebody indicated that, for the range of longitudinal positions tested (approximately 1.0-2.0 body diameters aft of the apex of the nose), the most effective tangential blowing arrangement was found to be with the nozzle directed aft and on the side of the body where the higher primary vortex was located. This would be on the side opposite to the direction of a departure or spin as the side force is produced by the vortex in the closest proximity to the surface. The topology of the asymmetric vortex development is discussed in Refs. 2 and 3.

As shown in Fig. 2, with the model at zero sideslip angle, when a sufficient quantity of mass flow is directed in a concentrated jet beneath the high primary vortex, the asymmetric primary vortex system can be induced to form in its mirror-image state. Blowing coefficients shown are referenced to the model base diameter. The blowing momentum required to induce a complete reversal of the vortex core positions was found to be a function of the longitudinal position of the nozzle relative to the apex of the nose, the radial position of the nozzle relative to the windward generator, and the angle of attack of the model. As seen in Fig. 3, significant reductions in required momentum coefficient are noted as the nozzle is moved toward the apex of the nose at a constant Y/d. The approximate location of a typical radar antenna is shown for reference. One can also note that significantly higher values of jet momentum are required to produce reversal at higher angles of attack.

Figure 4 illustrates the effect of nozzle radial position on blowing control effectiveness. As the nozzle is displaced angularly away from the leeward generator at a constant longitudinal position, an increase in blowing effectiveness is noted. The optimum radial position appears to correspond to a lateral position slightly outboard of the center of the higher vortex core.

Experiments performed in the water tunnel on the F-5F model using the tangential, aft-blowing concept yielded results as shown in Fig. 5. These results are consistent with those obtained with the tangent-ogive models and illustrate that at zero sideslip angle, it is possible to induce the vortices to switch to the reverse orientation (i.e., mirror-image state) with sufficient quantities of blowing on a realistic fighter aircraft configuration.

Wind Tunnel Tests

From the results of the water tunnel tests previously discussed, the most promising vortex control schemes were chosen for proof-of-concept testing in the low speed wind tunnel. Two blowing nozzle locations were selected.

Vortex Blowing Control Concepts

Figure 6 presents the measured effect of aft tangential blowing on yawing moment at $\beta = 0$ deg, ± 5 deg, for the F-5F aircraft. With blowing off, an asymmetry in the yawing moment at $\beta = 0$ deg begins to develop at approximately $\alpha = 32$ deg ($\alpha/\theta_n \approx 2.0$). With the blowing on, even at the lowest jet momentum coefficient tested ($C_\mu = 0.008$), the asymmetry begins to develop slightly earlier, $\alpha = 24$ deg ($\alpha/\theta_n = 1.5$) and, at zero sideslip, forms in the opposite sense to the blowing-off case. The change in the side force or yawing moment is very easy to see at a sideslip angle of zero degrees, but the vortex blowing concept also applies a strong bias to the forces and moments at non-zero sideslip as well.

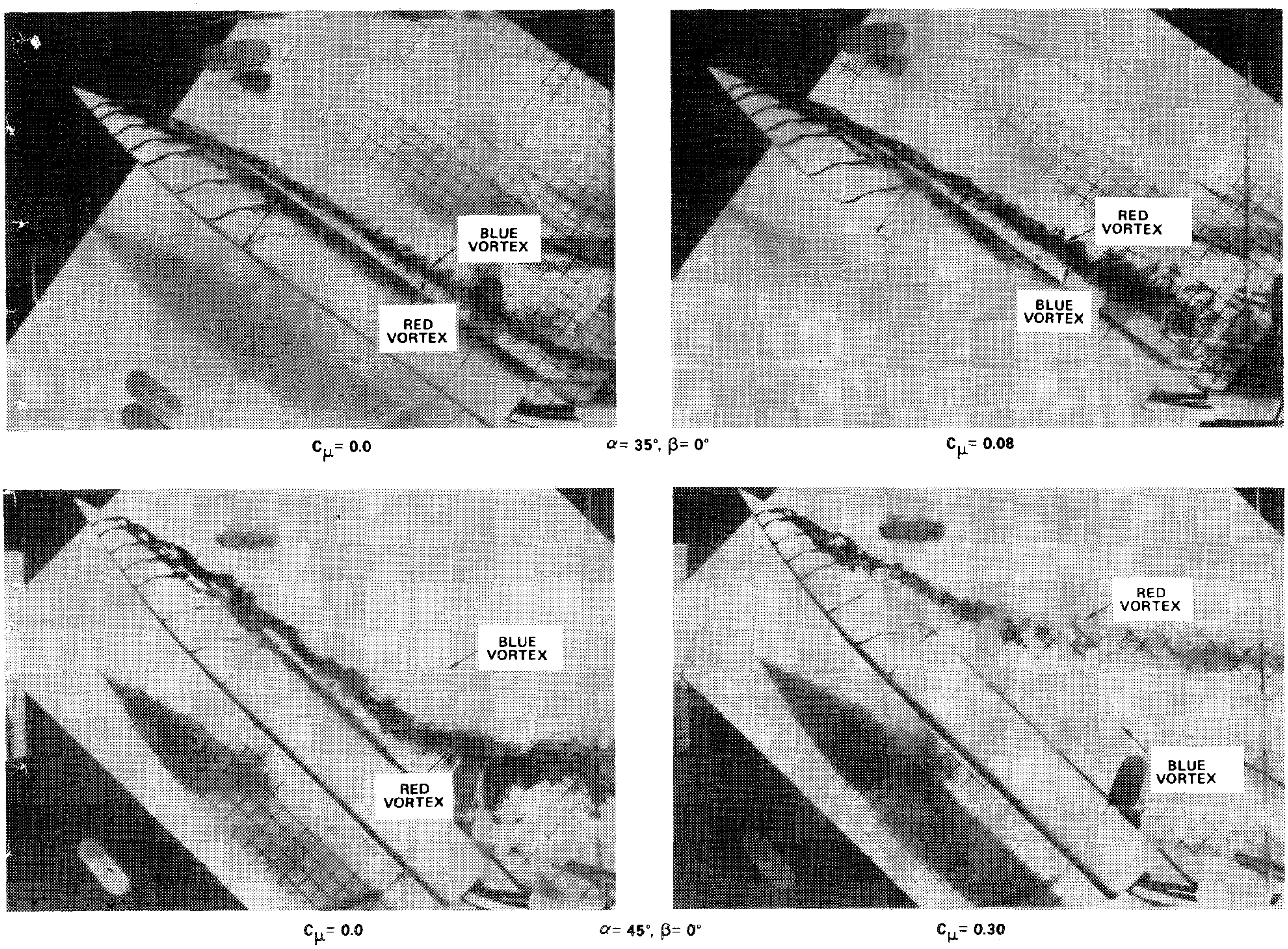

Fig. 2 Water tunnel results for aft blowing on a 3.5/4.5 tangent- ogive-cylinder model; nozzles located at $x/d = 1.54$.

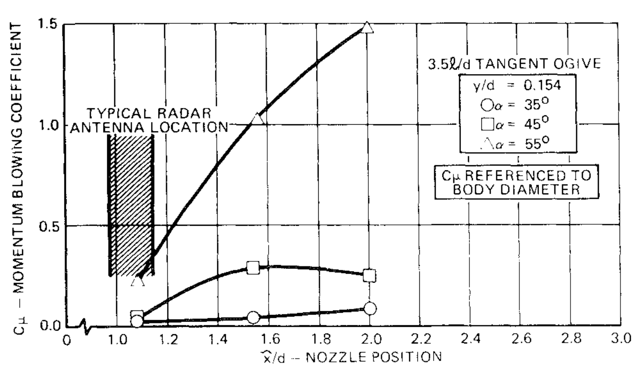

Fig. 3 Tangent-ogive blowing required to reverse asymmetry as a function of the nozzle longitudinal position.

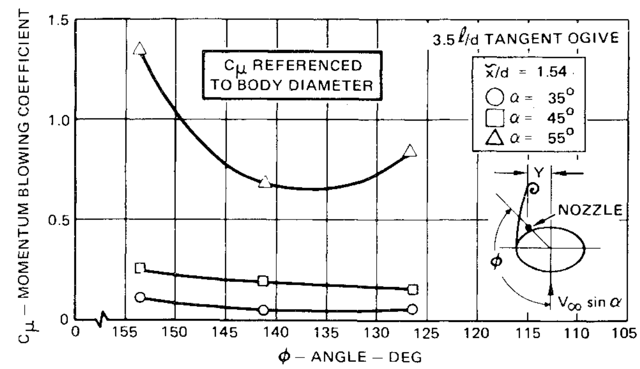

Fig. 4 Tangent-ogive blowing required to reverse asymmetry as a function of the nozzle ϕ position.

Inspection of the data in Fig. 6 at $\beta = \pm 5$ deg indicates that the vortex blowing concept produces a positive yawing moment increment at angles of attack up to approximately 50 deg. The positive yawing moment in sideslip is in opposition to the negative yawing moment and associated negative yaw rate produced by the blowing-off vortex asymmetry at zero sideslip.

At angles of attack beyond $\alpha = 24$ deg, the largest incremental change in yawing moment is obtained at the lowest momentum coefficient tested. The increment then increases approximately linearly as jet momentum coefficient is increased, up to the maximum mass flow rate tested.

Figure 7 presents the incremental yawing moment generated by the vortex control as a function of angle of attack. These data are compared with incremental yawing moment produced by full deflection of a conventional rudder. Note that even the lowest jet momentum coefficient tested provides yawing moments in the angle of attack range from $\alpha = 35$-55 deg which are comparable to those produced by the rudder at very low incidences. Also, it is interesting to note that the vortex control effectiveness begins to increase in the same angle of attack region where the rudder effectiveness is declining rapidly. At low angles of attack, directional stability and control are best provided by aerodynamic surfaces

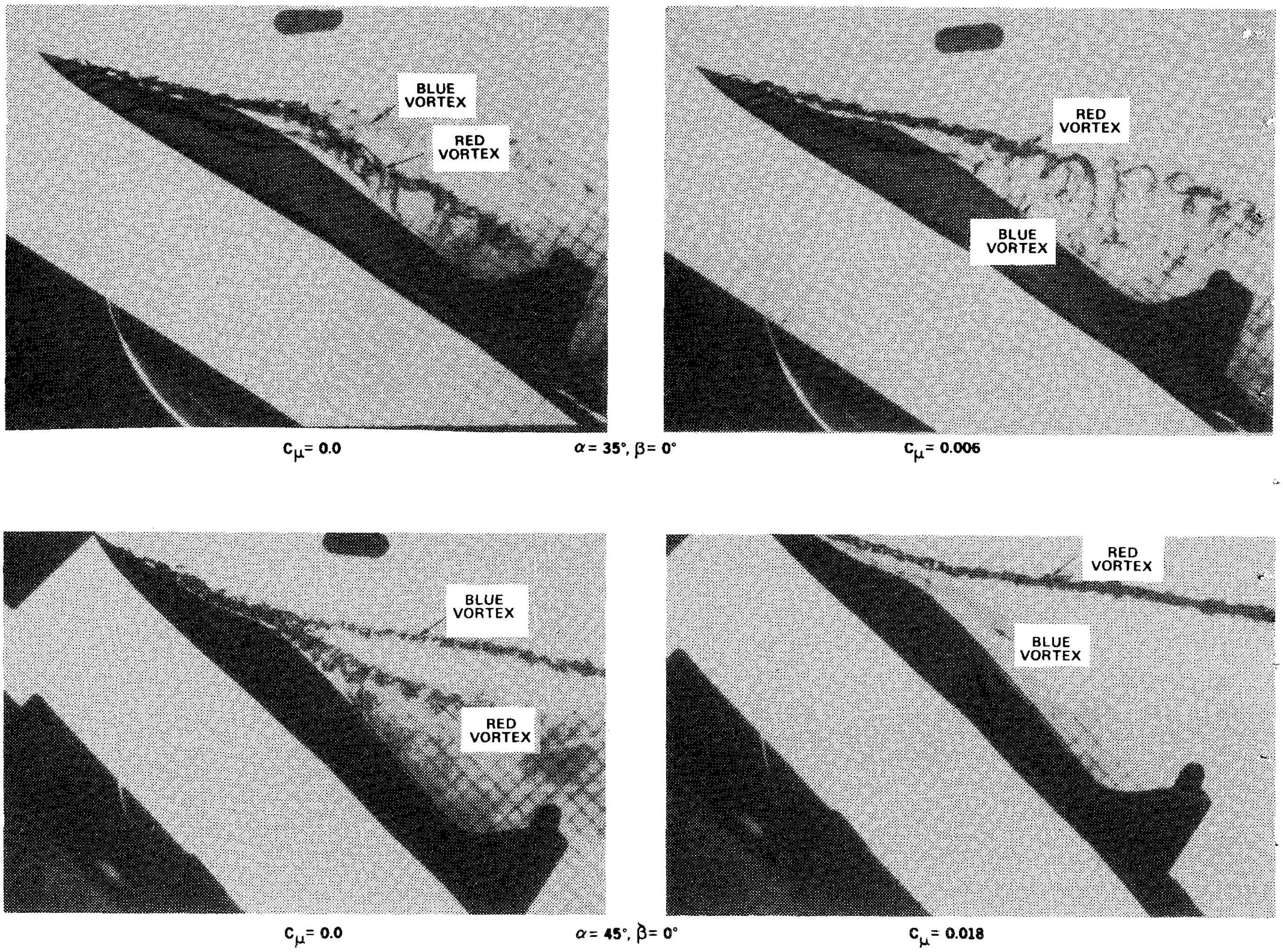

Fig. 5 Water tunnel results for aft blowing on the F-5F model; $x/d = 0.95$.

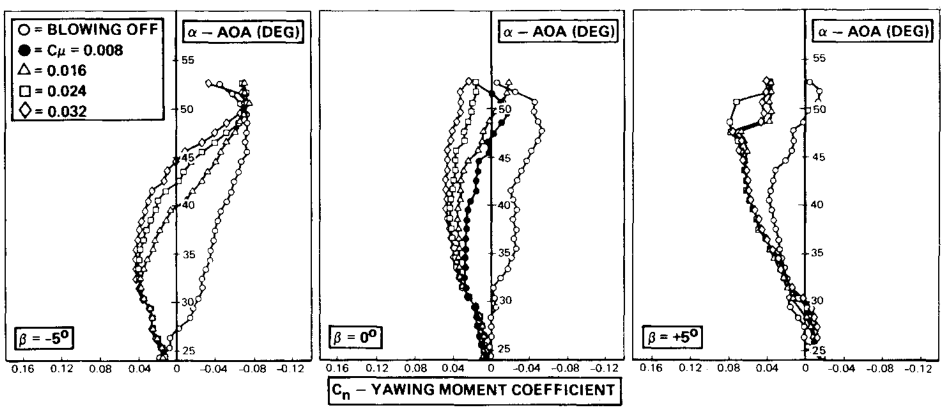

Fig. 6 Effect of aft tangential blowing on yawing moment.

located behind the aircraft center of gravity such as a vertical tail and a rudder. These data indicate that at high angles of attack, directional control as well as stability can best be provided by an aerodynamic device located ahead of the center of gravity, near the apex of the nose.

Figure 8 illustrates the effectiveness of the vortex blowing control device as a function of sideslip at a constant angle of attack, $\alpha = 47$ deg. These data indicate that over a very wide range of sideslip, the vortex blowing control device produces a healthy incremental yawing moment (in this case a yawing moment to the right in opposition to the yawing moment produced by the blowing-off vortex asymmetry). The reversal in incremental yawing moment at $\beta > 6$ deg caused some concern, but the impact of this phenomenon on the effectiveness of the device could not be assessed by inspection of the wind tunnel data only; simulation of the overall effectiveness was required.

Six Degree-of-Freedom Simulation

The capability of the blowing concepts to augment the departure and spin recovery capability of a fighter aircraft was evaluated by means of a digital six degree-of-freedom (6DOF) computer simulation. The baseline aerodynamic model used in this simulation has been validated by comparison of calculated and flight test trajectories of many, coupled, high AOA maneuvers, flown during spin tests of this

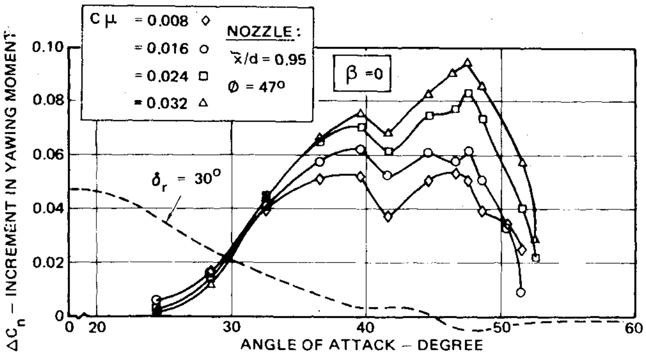

Fig. 7 Directional control effectiveness comparison; vortex blowing control vs rudder.

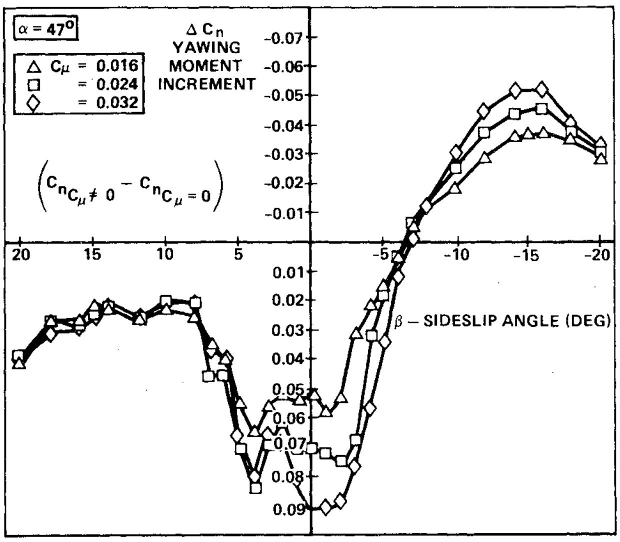

Fig. 8 Vortex blowing control effectiveness at non-zero sideslip.

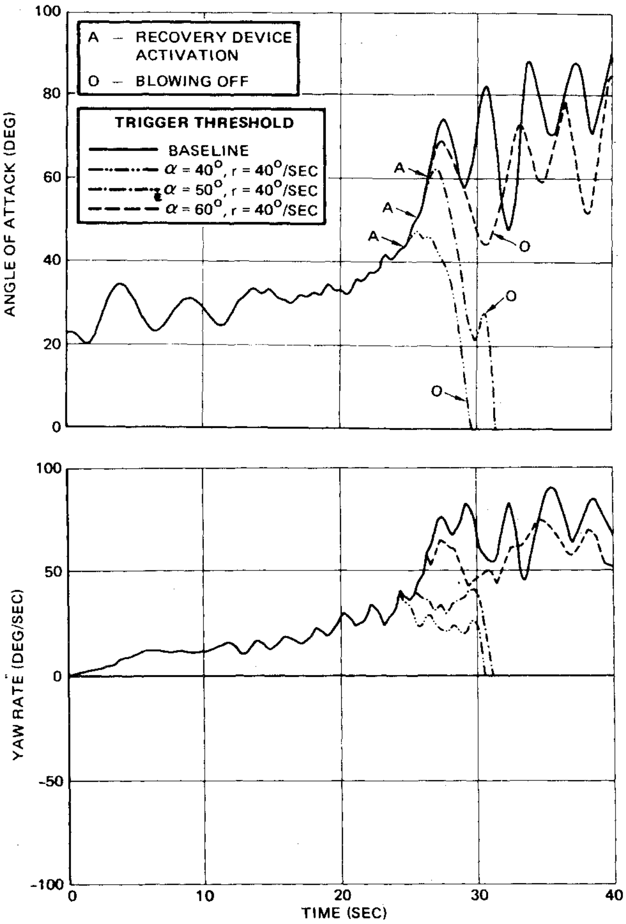

Fig. 9 Typical 6DOF time histories of departure recoveries aided by vortex blowing control.

aircraft. An algorithm was developed to model the incremental forces and moments generated by the blowing devices, as determined from the low-speed wind tunnel experiments.

Maneuvers were simulated by specifying grossly aggravated control inputs which were found, during spin susceptibility testing, to produce departures and spin entries. The departures and spins generated had been found to be difficult to recover from using traditional recovery control inputs both inflight and in the simulation.

The threshold angle of attack and yaw rate where the device was activated was varied in the simulation as was the blowing mass flow rate. The optimum yaw rate angle-of-attack threshold and the general effect of blowing momentum were determined in this manner. Figure 9 presents a typical series of time histories at a given mass flow rate where the threshold AOA was varied. Recoveries are seen to be significantly improved when the blowing device is activated early in the departure but severely degraded when the device is activated after the departure has been allowed to progress toward spin entry.

A blowing threshold angle of attack of $\alpha_T = 40$ deg provides good recovery augmentation and is well beyond the angle of attack for maximum lift coefficient, thereby not impacting the maneuver capability of the F-5F aircraft. For each simulation, a yaw rate dead-band of ± 40 deg/s at $\alpha = 40$ deg decaying linearly to ± 20 deg/s at $\alpha = 60$ deg was used. In this manner, the blowing device is not activated until the yaw rate exceeds the dead-band limit.

Figure 10 illustrates the final blowing activation schedule superimposed on the ACM gross maneuver boundary for the F-5F. An example trajectory of a typical air combat maneuver is also shown on the figure. The maneuver simulated is a high speed, high "g," maximum rate wind up turn to the left where the aircraft is placed at an angle of attack near $C_{L_{max}}$. From this initial condition (indicated by point 1 on the figure) the pilot initiates a high g turn reversal by applying full right rudder and aileron. Since most fighter aircraft are designed to roll about the flight path rather than the body axis, a large yaw rate develops in addition to the commanded roll rate (point 2). This yaw rate couples with the roll rate to produce a large nose-up pitch rate (point 3). The combination of yaw rate and high post-stall angle of attack produces a departure from controlled flight and a spin entry (points 4 and 5). At this point, the pilot senses loss of control and initiates a conventional recovery which is unsuccessful owing to the reduced control effectiveness at high AOA. The aircraft enters a developed spin (point 6). For the case of a vortex blowing assisted recovery, the blowing device is triggered when the maneuver trajectory crosses the activation threshold (indicated by point A on the figure). The blowing device generates a strong side force on the nose in opposition to the direction of yaw allowing an immediate recovery (point B).

Preliminary Assessment of Design Feasibility

Using the results of the experiments and simulation discussed, some preliminary system design work was done in order to assess the feasibility of applying the blowing control concept to fighter or trainer aircraft. Factors considered in the feasibility study included effectiveness, reliability, complexity, impact on other systems, and the suitability of the device for retrofit to in-service aircraft.

The wind tunnel experiments and 6DOF simulation showed that an acceptable level of departure recovery enhancement

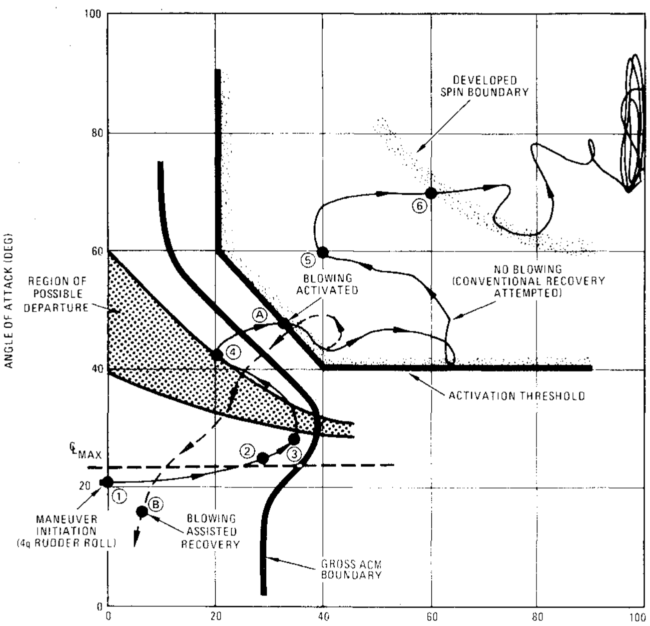

Fig. 10 Final vortex blowing control trigger threshold schedule.

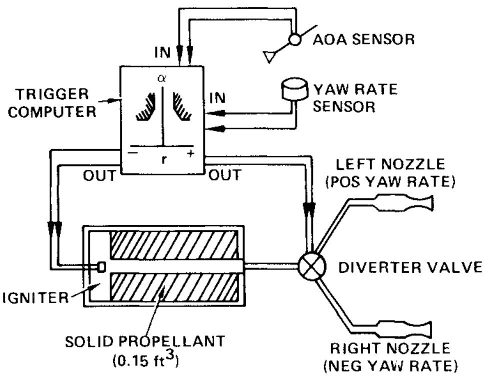

Fig. 11 Schematic diagram of proposed solid propellant blowing system.

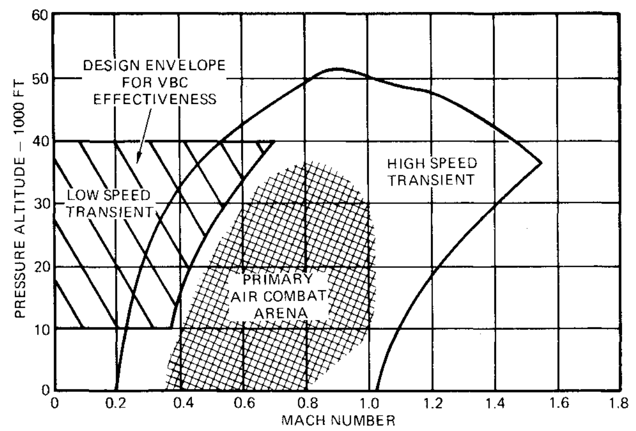

Fig. 12 Region of effectiveness of vortex blowing control device.

could be achieved at blowing coefficients of $C_\mu = 0.015\text{-}0.025$. The required duration of blowing was found to be between 3 and 5 s. In order to maximize the reliability of the system, engine bleed air was not considered as a potential source for the blowing jet, inasmuch as engine flame-outs at high angles of attack and yaw rate are to be expected. A solid propellant system was chosen as the most attractive source of blowing. Figure 11 shows a schematic diagram of the proposed blowing system.

The solid propellant blowing system is estimated to require approximately 4.25×10^{-3} m^3 of propellent. The total system weight is estimated to be less than 9.1 kg.

Figure 12 illustrates the region of the flight envelope over which the system is designed to produce the required blowing momentum coefficients. This region encompasses the low-speed transient area in order to provide maximum departure recovery enhancement, and is well outside of the primary ACM arena so that the maneuvering capability of the aircraft is not impacted adversely.

Conclusions and Recommendations

Based on small scale water and wind tunnel experience, it has been shown that asymmetric tangential blowing along the surface of the forebody of an aircraft can be used to control the orientation of the leeside vortex system at high angles of attack. Further, it has been shown that the forces and moments produced by these vortices can be used, in a controlled manner, to greatly enhance the predicted departure recovery characteristics of an existing fighter aircraft configuration. Blowing rates required to produce these forces and moments were shown to be small, owing to the fluid amplification afforded by the vortex growth. Volume requirements are reasonable and indicate that such a concept could be applied to a new aircraft or retrofitted to an existing aircraft with minimum impact on other aircraft systems.

Further experiments must be conducted on a large scale free-flight model to substantiate the predictions. Further analysis should be done to determine whether this concept could be used not only as a departure recovery enhancement device but also as a departure inhibitor.

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