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Water Tunnel Flow Visualization: Insight into Complex Three-Dimensional Flowfields

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Water tunnel facilities and flow visualization techniques have been developed at Northrop to provide high quality visualization of vortex interactions at high angles of attack. Results have provided considerable insight into highly complex three-dimensional flowfields generated by contemporary fighter aircraft. Studies have been made of the leading edge vortex systems generated by wing leading edge extensions (LEXs) typical of current subsonic-transonic fighter aircraft, high angle of attack aerodynamic asymmetries associated with the vortex system developed on long slender forebodies, and forebody and wing/LEX vortex interactions characteristic of highly maneuverable aircraft with hybrid wing planforms and slender forebodies. Qualitative results are in excellent agreement with existing subsonic wind tunnel data. The water-to-air analogy has been verified, that is, aircraft forebody and wing/LEX vortex systems, vortex system interactions, and the downstream influence on flow characteristics exhibited in air at high Reynolds numbers can be simulated at low Reynolds numbers in the water tunnel.

Nomenclature

C_L	= lift coefficient
$C_{L_{max}}$	= maximum lift coefficient
c_0	= wing centerline chord, in.
M_∞	= freestream Mach number
R_a	= ratio of exposed LEX area and wing reference area
V_∞	= freestream velocity, ft/s
x	= vortex burst location measured from wing trailing edge, in.
α	= angle of attack, deg
β	= angle of sideslip, deg
Λ_{LE}	= leading edge sweep angle, deg

Introduction

THE leading edge vortex formed by flow separation from a wing leading edge extension (LEX) or wing-body strake favorably interacts with the flow over a higher aspect ratio main wing surface typical of current fighter aircraft, enhances the maneuvering lift capability of the aircraft, and strongly affects the stability characteristics. The fluid mechanic phenomenon of leading edge vortex breakdown limits, however, the maneuver performance improvement that can be obtained. Vortex breakdown forward of the wing trailing edge results in a reduction in induced lift. In a sideslip condition, vortex bursting becomes asymmetric which can lead to lateral instabilities and when the vortex burst points are in close proximity to the vertical or horizontal tails, abrupt loss of directional or longitudinal stability is often experienced. The location of the vortex burst points over the wing panels is highly dependent upon factors such as LEX planform shape, wing leading edge sweep angle, and deflection of leading and trailing edge flaps.

The phenomenon of aerodynamic asymmetries at high angles of attack, historically associated with missile aerodynamics, has received considerable interest in recent years due to trends in fighter aircraft design which feature long, slender fuselages of high fineness ratio. The strong vortex system emanating from the forebody, which is influenced by nose fineness ratio, bluntness, and cross-sectional shape, may assume an asymmetric orientation with subsequent large yawing moments at zero sideslip. The degree of directional stability which the aircraft will exhibit can also be determined by the forebody vortex system. Furthermore, current generation, highly maneuverable aircraft with hybrid wing planforms and slender forebodies are characterized by strong interactions between the forebody and the wing/LEX vortex systems.

Clearly, accurate visualization of the flowfield about an aircraft is a valuable aid to the aerodynamicist and can provide insight into highly complex three-dimensional flowfields generated by contemporary fighter aircraft. An understanding of the details of leading edge vortex systems generated by leading edge extensions (Fig. 1), closely coupled canard and wing, highly swept planforms typical of supercruise fighter designs (Fig. 2), and slender forebodies at high angles of attack (Fig. 3) can be developed.

Water tunnels have been used with great success in the past, particularly in the development of the Anglo-French Concorde supersonic transport (SST).[1-4] Studies made at ONERA have perhaps exemplified the high quality results obtainable in the water tunnel and have proved the utility of hydrodynamic facilities in the analysis of vortex flows about ogee and delta wings and slender forebodies. Northrop has developed water tunnel facilities and flow visualization techniques to provide convenient, vivid, and easily controlled flow visualization studies of vortex interactions at high angles of attack. In addition to providing information on existing aircraft flow details, water tunnel flow visualization can provide diagnostic analysis in parallel with wind tunnel tests, flowfield studies of new configurations and subcomponents, and exploratory investigation of new aerodynamic concepts. The light-reflecting characteristics of dyes or other tracers injected into the flowfield are orders of magnitude better than in air due to the density of water being 800 times that of air. In addition, at the same unit Reynolds number and model scale, the velocity in water is 1/15th of that in air and, thus, the aerodynamic phenomena can be observed at slow speed.

For present day fighter aircraft operating at high angles of attack, flow separation occurs at wing leading edges at all Reynolds numbers, provided the Reynolds number is above a critical value. The water tunnel is operated above the critical

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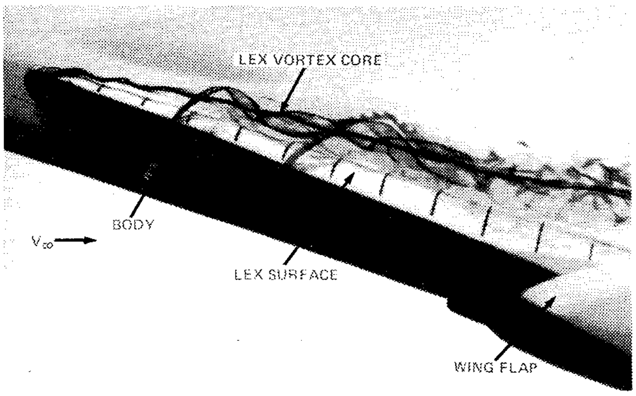


Fig. 1 Wing LEX vortex on an advanced fighter aircraft.

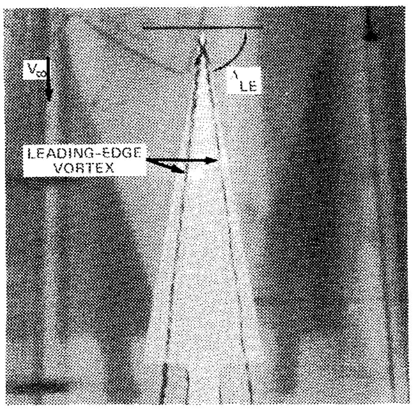


Fig. 2 Leading edge vortices on a slender wing.

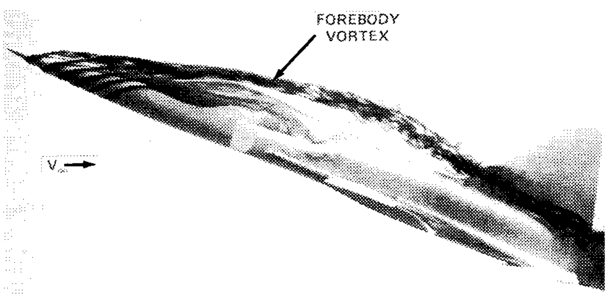
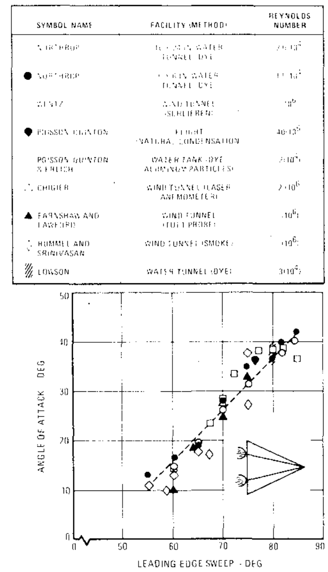


Fig. 3 Vortex system on a long slender forebody.


Fig. 4 Northrop Diagnostic Water Tunnel Facility.

value corresponding to leading edge separation, despite the practical limitations in speed and model scale which necessitate running the water tunnel at Reynolds numbers generally well below those of wind tunnels. Therefore, the water-to-air analogy is valid, that is, aircraft leading edge

Fig. 5 Effect of delta wing sweep angle on angle of attack for vortex breakdown at the trailing edge (from Ref. 5). (Note: Reynolds number based on model centerline chord.)



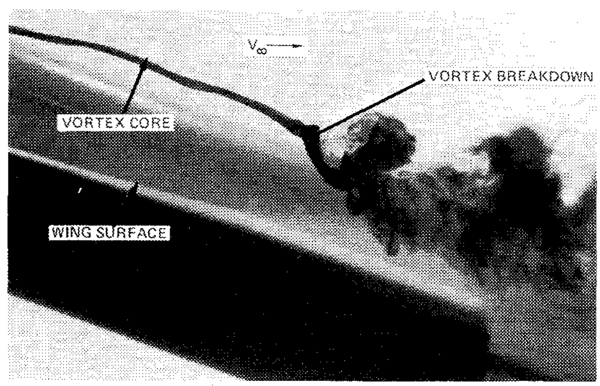


Fig. 6 Vortex breakdown phenomenon.

separation phenomena, including the downstream influence on the flowfield, can be simulated in the water tunnel.

Studies made at Northrop have consisted of extensive research into LEX contouring and leading edge modifications to delay vortex breakdown, configuration studies to aid in the location of wings, inlets, tails, and control surfaces to take maximum advantage of vortex-induced lift and to minimize adverse interactions, propulsive lift concepts to enhance vortex flows, studies of forward-swept wing configurations, and forebody shaping to augment stability at high angles of attack. The current paper will summarize many of the water tunnel research highlights and, where feasible, will compare vortex breakdown trends with available subsonic wind tunnel data.

Experimental Investigation

Diagnostic Water Tunnel

The Northrop Diagnostic Water Tunnel is a closed return tunnel used for high quality flow visualization of complex three-dimensional flowfields. The tunnel is nominally operated at a test section velocity of 0.25-0.35 ft/s which corresponds to a Reynolds number of approximately 3.0 (10^4)/ft. Figure 4 shows the layout of the water tunnel. The test section, sized for a 1/40 scale F – 18, is 16 in. by 24 in. by 6 ft long and is oriented in the vertical direction. The model is accessed through the top of the tunnel by means of cables connected to the model support system.

The model support system consists of a sting and yaw arc which is capable of pitch angles from – 10 to 70 deg, concurrent with a sideslip range of – 20 to 20 deg. The pitch angle can be manually adjusted from the side of the test section while the sideslip angle is preset prior to the model installation.

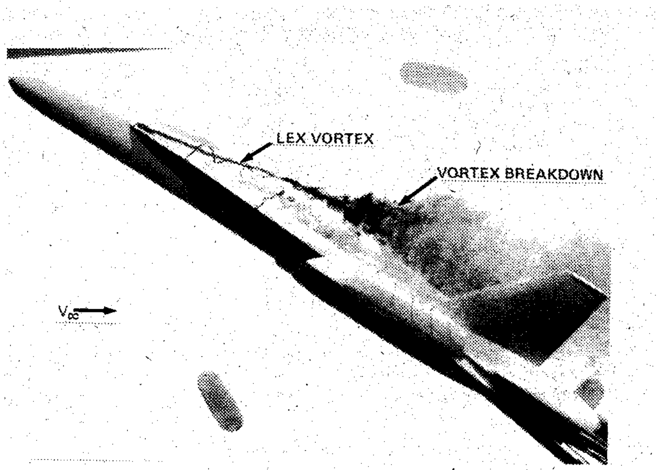


Fig. 7 Vortex burst over the wing of an advanced fighter aircraft.

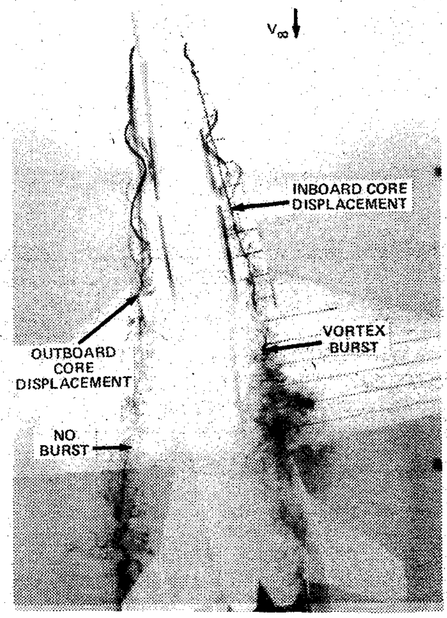


Fig. 8 Asymmetric LEX vortex breakdown in sideslip.

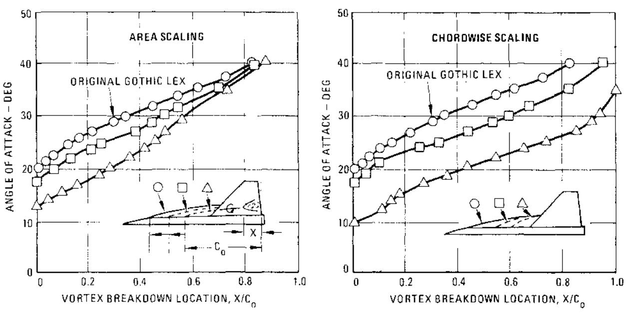


Fig. 9 Effect of area and chordwise scaling on the vortex breakdown characteristics of a large gothic LEX.

Dye injection into the flowfield is accomplished through a remotely controlled dye probe and through dye tubes internally or externally mounted to the test models. Inlet flows and exhaust jets can be simulated in the water tunnel through the use of water flow meters which can accurately provide a suction or blowing rate.

The models used in the current tests were flat-plate delta and delta-related planforms with sharp leading edges (thickness ≈ 0.05 in.), 1/72 scale model of the Northrop YF-17, 1/40 scale models of the Northrop F-5F/Production Nose and Shark Nose configurations and the Northrop F-18L, and

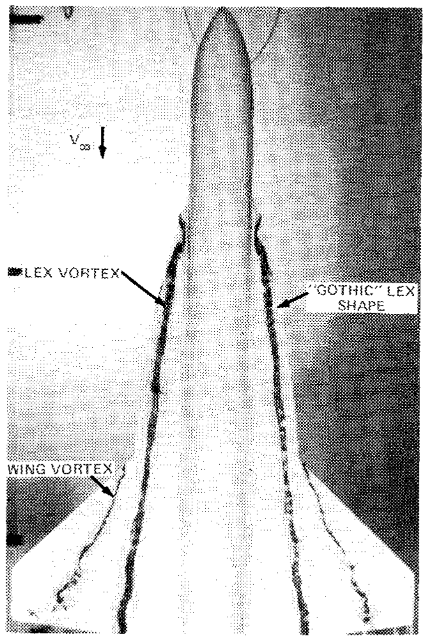


Fig. 10 Typical result from LEX contouring studies.

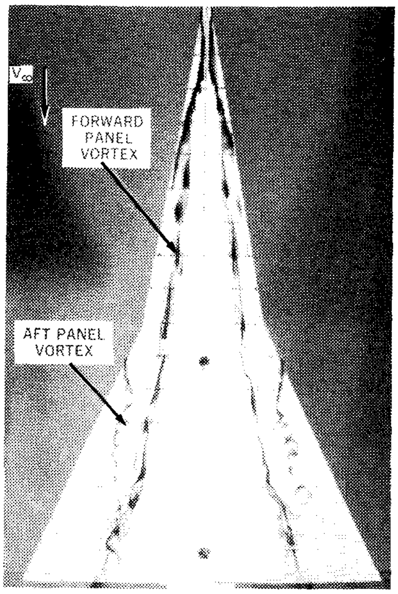


Fig. 11 Vortex patterns on an 80/65 deg double-delta planform at low angle of attack.

a 1/2 scale model of a NASA Langley Research Center general research wing/body configuration.

Discussion of Results

Vortex Breakdown Characteristics of Slender Wings and Wing/LEX Combinations

Slender Wings

Figure 5 presents the effect of delta wing leading edge sweep angle on angle of attack for vortex breakdown at the trailing edge. The Northrop water tunnel data are presented along with existing water tunnel/wind tunnel data obtained at Reynolds numbers ranging from 2.0 (10^4) to 2.0 (10^6) using widely varying methods to visualize vortex burst.[5] All the data exhibit the same trend, namely, as leading edge sweep angle is increased the angle of attack for vortex breakdown at the trailing edge is correspondingly increased. No effect of Reynolds number on vortex burst is discernable.

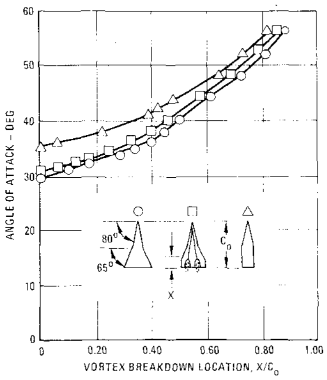


Fig. 12 Effect of wing tip cropping on vortex breakdown.

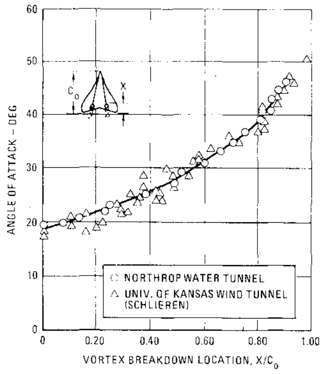


Fig. 13 Vortex breakdown characteristics of ogee wing.

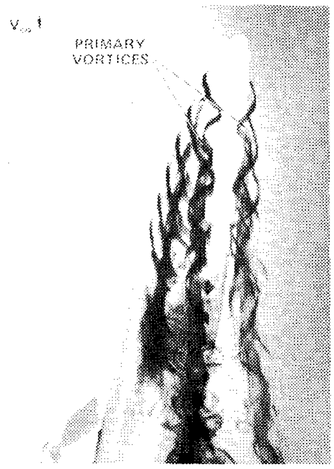


Fig. 14 Vortex pattern on a long slender forebody.

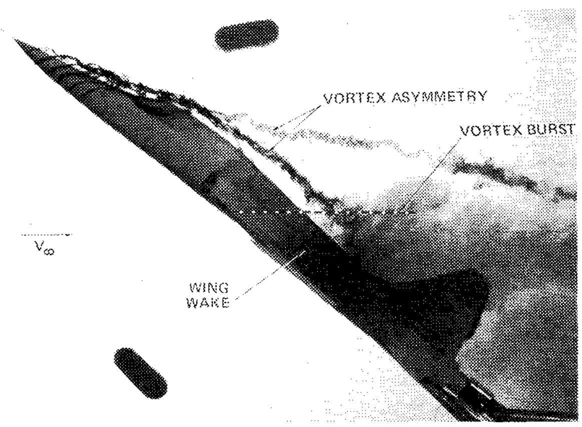


Fig. 15 F-5F forebody vortex pattern at zero sideslip.

The phenomenon of vortex bursting is illustrated in the water tunnel photograph in Fig. 6. Vortex breakdown is characterized by a flaring of the vortex core into a trumpet-like shape which is associated with a sudden flow deceleration along the vortex axis, expansion of the vortex about a stagnant core, and turbulent flow thereafter.

The progression of vortex burst over a highly swept planform is quite rapid in the region of the trailing edge due to large adverse pressure gradients. Similar effects are present on hybrid wings (wing/LEX combinations). When vortex burst location progresses forward of the wing trailing edge, as shown in Figure 7, a reduction in induced lift is observed. Asymmetric vortex breakdown occurs in a sideslip condition, illustrated in Fig. 8, which can lead to lateral instabilities and, for wing/body/tail configurations, an abrupt loss of directional or longitudinal stability when the vortex burst points are in the vicinity of vertical or horizontal tails.

Wing Leading-Edge Extensions

A mutual research interest in the development of new LEX shapes stimulated an informal, cooperative water tunnel research effort between Northrop and NASA Langley Research Center. LEX shapes developed by a Langley LEX (or strake) design code[6] were integrated with a half-scale version of a Langley 44 deg trapezoidal wing/body research model configuration. Some results from this study are shown in Figs. 9 and 10 which illustrate the sensitivity of the curved or gothic LEX vortex burst characteristics to area and chordwise scaling. Reference 6 has presented results obtained previously in the Northrop water tunnel facility which indicate the superior vortex burst (and hence lift) characteristics of a gothic LEX relative to a straight or delta-shaped LEX of the same slenderness ratio. The lift dependence on LEX area has been well documented in Ref. 7 in the development of the Northrop F-5 E/F and YF-17 LEX shapes and also in Ref. 8 for a reflexive LEX shape in conjunction with the 44 deg trapezoidal wing/body configuration.

Double-Delta Planforms

Two distinct vortex flows are evident on a double-delta planform at low angles of attack (Fig. 11) whereas at higher angles of attack only one vortex system is of consequence, the separated flow from the aft wing panel coalescing with the vortex system developed on the forward wing panel. These results are in good agreement with wind tunnel oil flow studies of similar planforms.[6] A similar flow situation is observed on wing/LEX configurations.

Cropping the tips of a double-delta planform has been observed to increase the stability of the forward panel vortex system, as illustrated in Fig. 12. This beneficial effect on vortex stability can be attributed to the vortex feeding mechanism associated with the side edge separated flow.

Ogee Wing

The vortex breakdown characteristics of an ogee wing are shown in Fig. 13 where the Northrop water tunnel results are presented along with wind tunnel results obtained in Ref. 9 at a Reynolds number of approximately 1.0 (10^6) using a schlieren system to visualize vortex burst. The results indicate a gradual forward progression of vortex burst location over the wing with increased angle of attack. In addition, excellent agreement is evident between the present studies and the data of Ref. 9, which have been shown to correlate well with existing NASA flight test data obtained at a Reynolds number of about 20.0 (10^6) on a modified Douglas F-5D aircraft featuring the same ogee wing planform.[10]

Vortex Patterns on Long, Slender Forebodies at High Angles of Attack

Asymmetric Shedding of Forebody Vortices

An understanding of details of the vortex systems generated by forebodies at high angles of attack can be developed from

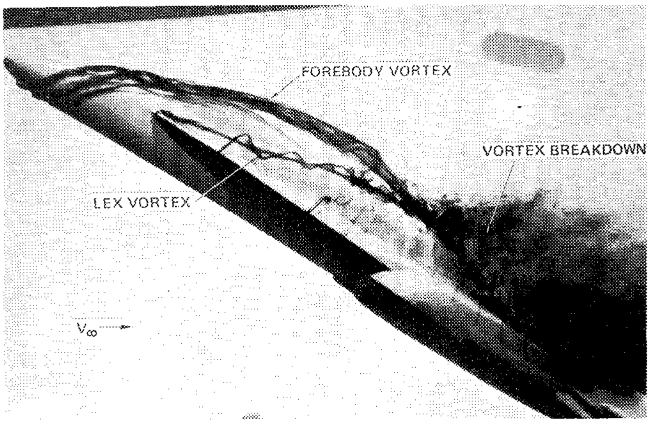


Fig. 16 Forebody/wing vortex interactions.

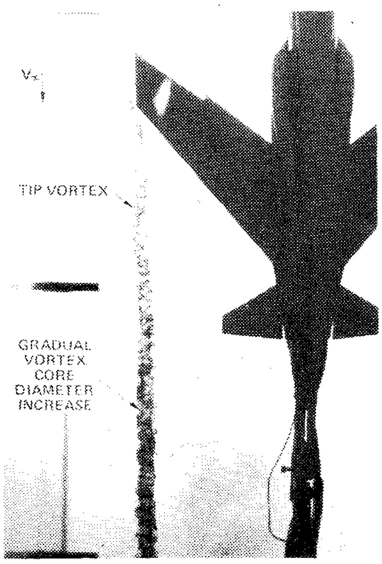


Fig. 17 Swept-forward wing tip vortex.

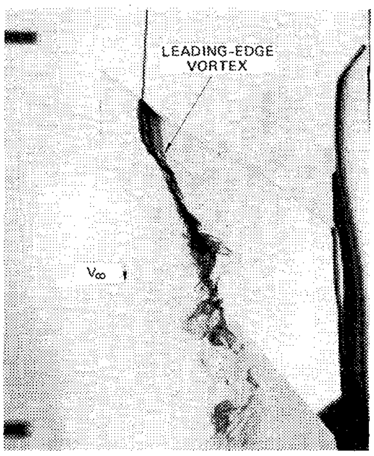


Fig. 18 Swept-forward wing leading edge vortex.

results of tests made in the water tunnel. A typical result obtained on long, slender forebodies is shown in Fig. 14 which illustrates the pair of apex vortices emanating from the tip of the nose in addition to the tertiary vortex pair arising from the separated flow along the fuselage side.

Water tunnel observations of the F-5F/Production Nose configuration have clearly shown an asymmetric forebody vortex pattern at high angles of attack and zero sideslip as illustrated in Fig. 15 which is in qualitative agreement with the

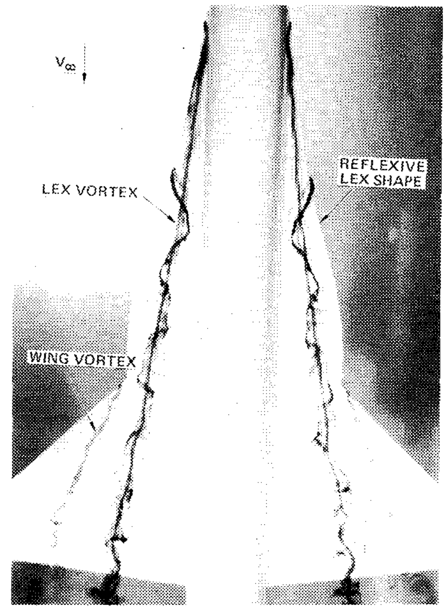


Fig. 19 Reflexive LEX/wing vortex patterns, $\alpha = 10$ deg.

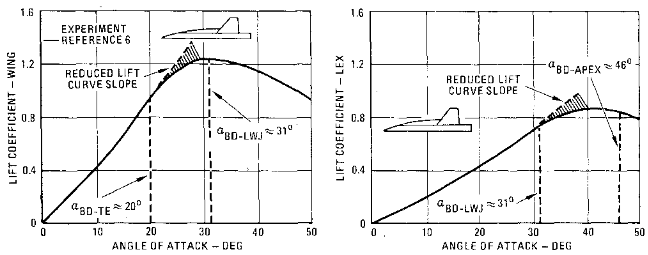


Fig. 20 Lift characteristics of gothic LEX/wing configuration, $R_a = 0.325$, $M_\infty = 0.20$.

asymmetric yawing moments experienced in wind tunnel and flight tests obtained at Reynolds numbers of 2.0 (10^6) and 5.5-6.5 (10^6), respectively.[11] A nose planform and cross-sectional shape were designed to attenuate the asymmetric vortex formations while enhancing the favorable directional stability effects at nonzero sideslip. The resulting forebody geometry, referred to as the "Shark Nose," results in an order of magnitude reduction in high angle of attack asymmetric yawing moment and water tunnel studies have verified that the Shark Nose develops a strong symmetric forebody vortex pattern at zero sideslip up to high angles of attack.

Forebody/Wing Vortex Interactions

Aircraft configurations featuring hybrid wings with LEX's in close proximity to the forebody are characterized by strong interactions between the forebody and wing/LEX vortex systems. Figure 16 illustrates these strong interactions, depicting the interaction of the forebody primary vortices with the wing/LEX flowfield. This phenomenon can have a profound influence on the lateral/directional stability exhibited by the configuration.

Swept-Forward Wing Flow Characteristics

A solution to the weight penalty associated with attenuation of aeroelastic divergence of swept-forward wings has been provided with the advent of advanced composite materials.[12] As a result, a resurgence of research activity has occurred to investigate the potential benefits of forward sweep. Preliminary flow visualization studies made at Northrop confirmed the low angle of attack root stall problem encountered on wings with forward sweep, trailing edge vortex, and the characteristic "never-stalling" wing tip (Figs. 17 and

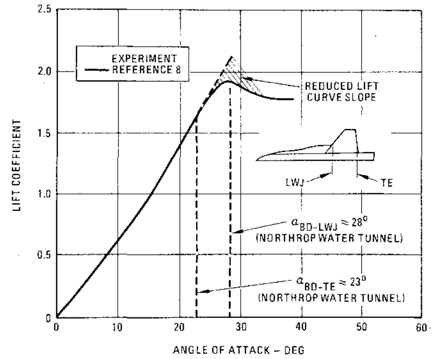


Fig. 21 Lift characteristics of reflexive LEX/wing configuration, $R_a = 0.27, M_\infty = 0.30$.

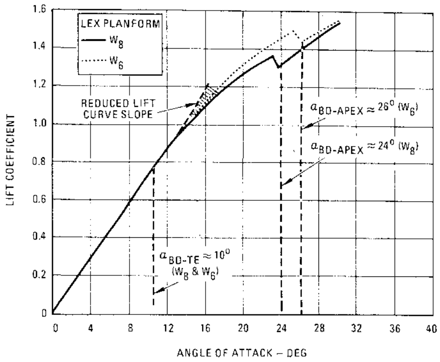


Fig. 24 F-5F lift characteristics with W_8 and W_6 LEX planforms, $M_\infty = 0.26$ (from Ref. 13).

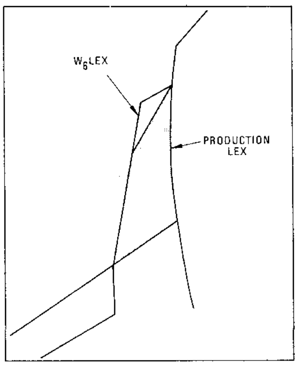


Fig. 22 F-5F W_6 and W_8 (production) LEX planforms.

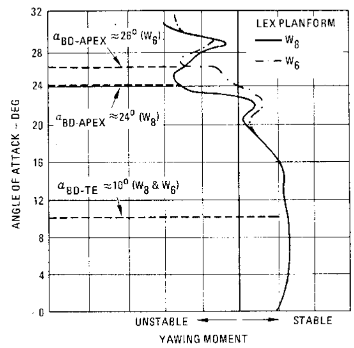


Fig. 25 F-5F yawing moment characteristics with W_8 and W_6 LEX planforms, $\beta = 10$ deg (from Ref. 13).

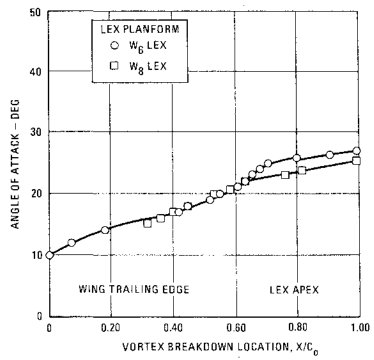


Fig. 23 F-5F W_6 and W_8 LEX vortex breakdown characteristics.

18). Variable geometry concepts are now being developed to improve the inboard wing flow characteristics and studies are being made to optimize the vortex flow interactions between close-coupled forward-swept canards and wings. Preliminary results also indicate that the stall characteristics peculiar to forward-swept wings promote early breakdown of the LEX and forebody vortex systems at much lower angles of attack relative to an aft-swept wing configuration.

Correlation of Water Tunnel Vortex Breakdown Observations with Wind Tunnel Data

Large Gothic and Reflexive LEX/Wing Configurations

A typical result of water tunnel studies made of large gothic and reflexive LEX shapes developed in Refs. 6 and 8, respectively, is shown in Fig. 19. Lift characteristics obtained in Refs. 6 and 8 are presented in Figs. 20 and 21 along with LEX vortex breakdown characteristics observed in the water tunnel. Here, α_{BD-TE}, α_{BD-LWJ}, and $\alpha_{BD-APEX}$ are defined as the angles of attack for vortex breakdown at the wing trailing edge, LEX-wing junction, and LEX apex, respectively. Wing and gothic LEX lift characteristics obtained by means of a dual-balance arrangement are shown in Fig. 20. Good agreement is obtained between $\alpha_{BD-TE} \approx 20$ deg and $\alpha_{BD-LWJ} \approx 31$ deg and the angles of attack at which the wing lift curve slope is reduced and Wing $C_{L_{max}}$ occurs, respectively. Furthermore, $\alpha_{BD-LWJ} \approx 31$ deg and $\alpha_{BD-APEX} \approx 46$ deg agree well with reduced LEX lift curve slope and LEX maximum lift, respectively. Similar correlation between water and wind tunnel results are shown in Fig. 21 for the reflexive LEX/wing configuration.

F-5F LEX Optimization

Wind tunnel tests have shown that optimization of F-5 LEX geometry can result in an increase in lift and directional stability.[13] Water tunnel studies have shown the F-5 W_6 LEX (W_6 denotes wind tunnel part number) to exhibit delayed vortex burst progression with increasing angle of attack relative to the production, or W_8, LEX, as illustrated in Figs. 22 and 23. The angle of attack for vortex breakdown at the trailing edge corresponds to the angle at which a lift curve slope reduction occurs in Fig. 24. The angles of attack for complete breakdown ($\alpha_{BD-APEX}$) of the production and W_6 LEXs correlate well with the corresponding lift curve breaks shown in Fig. 24. The local increase in the slope of the W_6 LEX vortex breakdown curve (Fig. 22) at $\alpha \approx 22$ deg, which reflects a more gradual progression of LEX vortex burst, is in good agreement with the improved directional stability characteristics in the stall region, as shown in Fig. 25.

Summary

Water tunnel facilities and flow visualization techniques have been developed at Northrop to provide high quality visualization of vortex interactions at high angles of attack. Results have provided considerable insight into highly complex three-dimensional flowfields generated by contemporary fighter aircraft. Studies have been made of leading edge extensions (LEX's) typical of current subsonic-transonic fighter aircraft, high angle of attack aerodynamic asymmetries associated with the vortex system developed on long, slender forebodies, and forebody and wing/LEX vortex interactions characteristic of highly maneuverable aircraft with hybrid wing planforms and slender forebodies. Qualitative results are in excellent agreement with existing subsonic wind tunnel data. The water-to-air analogy has been verified, that is, aircraft forebody and wing/LEX vortex systems, vortex system interactions, and the downstream influence on flow characteristics exhibited in air at high Reynolds numbers can be simulated at low Reynolds numbers in the water tunnel.

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