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Linear and Nonlinear Aerodynamics of Three-Surface Aircraft Concepts

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Most modern fighter aircraft rely on vortex interaction to provide lift enhancement at maneuvering angles of attack. The close-coupled horizontal canard in a three-surface (canard-wing-tail) configuration provides a surface which, in addition to its control functions, can be used to optimize this vortex interaction. McDonnell Aircraft Company, in cooperation with NASA, is currently conducting a study designed to provide a detailed understanding of the aerodynamics of this type of configuration. The results of this investigation are discussed and hypotheses are presented to explain the linear and nonlinear aerodynamic phenomena observed. Parallels are drawn to the characteristics observed in the data from other configurations exhibiting significant amounts of vortex lift.

Nomenclature

b	= wing span
C_L	= lift coefficient = L/qS_W
C_{l_β}	= lateral stability parameter—derivative of rolling moment coefficient with respect to sideslip angle (β)
$C_{l_{\delta_A}}$	= aileron effectiveness—derivative of rolling moment coefficient (C_l) with respect to aileron deflection (δ_A)
$C_{M_{\delta_H}}$	= stabilator effectiveness—derivative of pitching moment coefficient (C_M) with respect to stabilator deflection (δ_H)
C_{n_β}	= directional stability parameter—derivative of yawing moment coefficient with respect to sideslip angle
$C_{n_{\delta_R}}$	= rudder effectiveness—derivative of yawing moment coefficient (C_n) with respect to rudder deflection (δ_R)
n_L	= vertical load factor = $C_L qS_W/W$
n_Y	= lateral load factor = $C_Y qS_W/W$
n_Z	= normal load factor = $C_N qS_W/W$
S_W	= wing reference area
α	= angle of attack
Δ	= increment
δ_C	= canard deflection

Introduction

MOST modern-day fighter airplanes rely to some extent on the interaction of a highly complex system of vortices to provide a significant enhancement of the lifting capability at maneuvering angles of attack. The major portion of this lift enhancement is due to the interaction of the wing flow with a vortex generated by a lifting surface placed ahead of the wing. With this lift enhancement comes an attendant potential for drag reduction from two sources. First, owing to the higher lift, there is a reduction in the angle of attack required for a given maneuver. In addition, the vortex interaction tends to inhibit flow separation from the wing, thereby reducing the separation drag at a given angle of attack.

The surface used to generate the interacting vortex may take any one of several forms. The fuselage forebody strake on the F-16, the leading-edge glove on the F-14 and F-111, the leading-edge extension (LEX) on the F-5 and F-18, and the overhead ramp inlets plus the fairings which house the gun and aerial refueling receptacle on the F-15 are all examples of vortex generating surfaces. Close-coupled horizontal canards are a way of modulating this vortex interaction in an optimum fashion while also providing an additional control surface.

Numerous studies have been conducted over the past several years to evaluate the aerodynamic characteristics of configurations incorporating close-coupled canards. These studies have substantiated the fact that significant performance benefits accrue from the interaction of the canard and the wing. Studies conducted at McDonnell Aircraft Company (MCAIR) have shown that these performance benefits can be retained and significant maneuvering capability added by integrating the horizontal canard with a wing and horizontal tail in a three-surface arrangement. Data from one such study, the AFTI-15, are discussed in Ref. 1 with emphasis on the beneficial interaction of the canard with the wing and other aircraft control surfaces.

The great majority of the studies of close-coupled canard integration (canard-wing or three-surface) which have been conducted to date have concentrated on the performance aspects at low to moderate angles of attack. Relatively little data exists concerning the stability and control aspects, particularly at moderate and high angles of attack where aerodynamic asymmetries and nonlinearities and interaction of the control surfaces determine the stall, departure, spin, and recovery characteristics. Understanding of these characteristics is essential if fighter aircraft are to be developed which take full advantage of the substantial performance and maneuverability benefits offered by the three-surface concept. MCAIR, in cooperation with NASA, is currently conducting a program of test and analysis designed to provide this understanding. The test portion of this program has, to date, utilized appropriately modified F-15 models, primarily because of the availability of a number of models of various sizes and an extensive data base by which to judge the effectiveness of this modification. As such, this program could be considered an extension of the development

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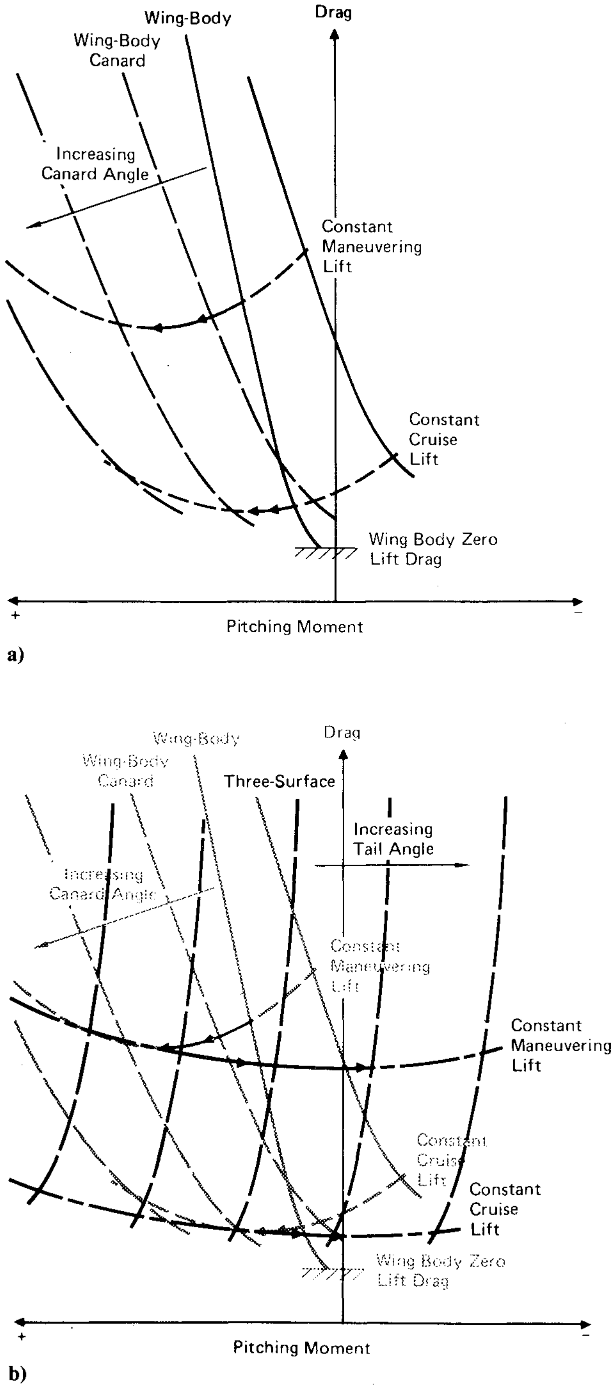


Fig. 1 Three-surface configuration buildup: a) wing-body and wing-body canard, b) wing-body and wing-body canard plus tail.

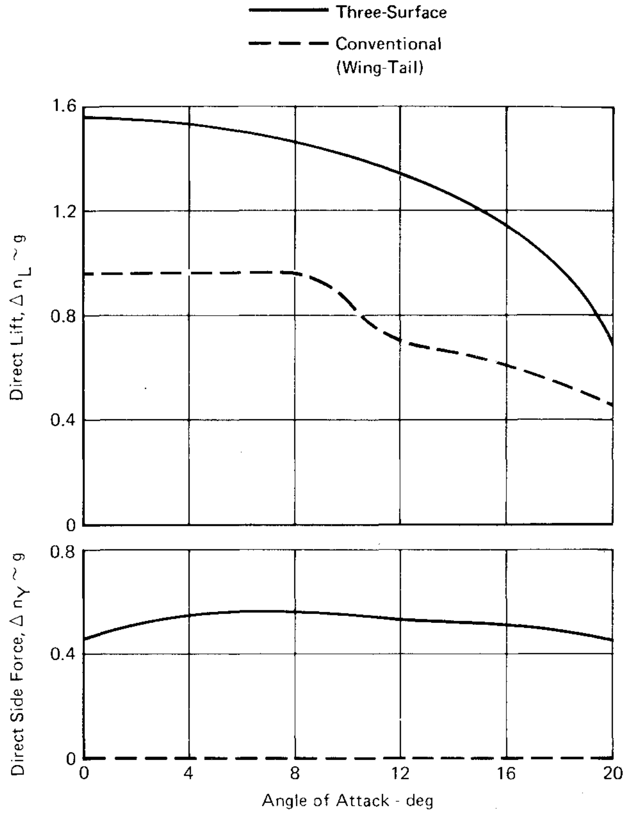


Fig. 2 Direct force control, Mach 0.6 at 10,000 ft, typical combat weight.

discussed in Ref. 1. The results discussed herein, however, are considered to be of a generic nature and, therefore, applicable to a wide variety of three-surface fighter configurations.

Three-Surface Advantages

A major advantage of the three-surface concept is that the configuration design can be tailored to provide minimum drag without resorting to extreme relaxation of the static longitudinal stability. Figure 1, which presents drag as a function of pitching moment, illustrates conceptually how this is achieved. Note that, since drag is directly related to lift, the slope of the lines on this presentation is a measure of the static longitudinal stability. The characteristics shown on this figure, while not derived for a specific configuration, are representative of the process by which minimum drag is achieved for three-surface configurations in general.

As illustrated in Fig. 1a, the process begins with proper design of the wing-body combination. In general, experience has shown that the characteristics illustrated (i.e., slightly unstable with a small positive pitching moment at $C_{D_{min}}$) will yield the desired result when the control surfaces are added.

Figure 1a also illustrates the addition of the horizontal canard and points up a major advantage of this concept. Since the canard is a moveable control surface, the angle may be adjusted to provide the optimum canard-wing vortex interaction and thus minimum drag, for any given lift coefficient. The addition of the canard also results in a substantial forward shift of the neutral point. The resulting instability combined with the lift carried by the canard to optimize the interaction effects creates a sizable nose up pitching moment which must be trimmed by the horizontal tail. As shown in Fig. 1b, adding the horizontal tail and trimming out this moment can result in a further drag reduction. In addition, a much more stable configuration is provided.

As with any other concept, each configuration must be tailored to a particular set of design requirements. The final design is, of necessity, a compromise which considers the complete operating envelope. Other concepts can certainly be designed which are superior at a particular design condition (e.g., high-*g* maneuvering, supersonic cruise, etc.). The advantage of the properly designed three-surface aircraft is the ability to operate at near minimum drag over a wide range of trimmed conditions. This ability means that less fuel will be required for a given mission, particularly if that mission consists of several diverse elements, which is usually the case. This, coupled with the structural weight savings attributable to the more efficient maneuvering load distribution discussed in Ref. 1 results in a substantially smaller and lighter aircraft than comparable two-surface (canard-wing or wing-tail) configurations designed for equal mission capability.

An additional benefit is offered by the three-surface concept which is either not available, or available only in reduced amounts, in a more conventional two-surface configuration (particularly wing-tail). Proper combinations of

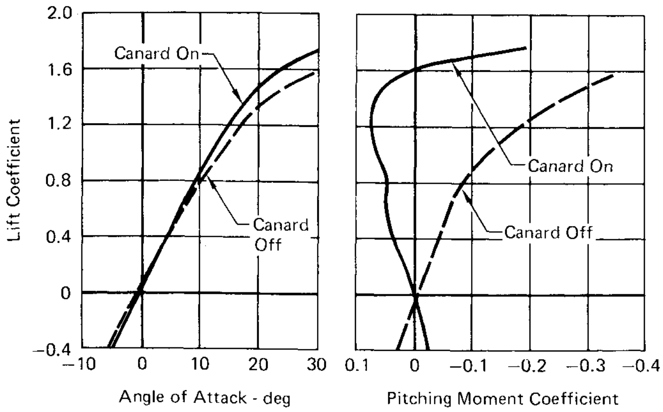


Fig. 3 Effect of horizontal canard on lift and pitching moment, Mach 0.90.

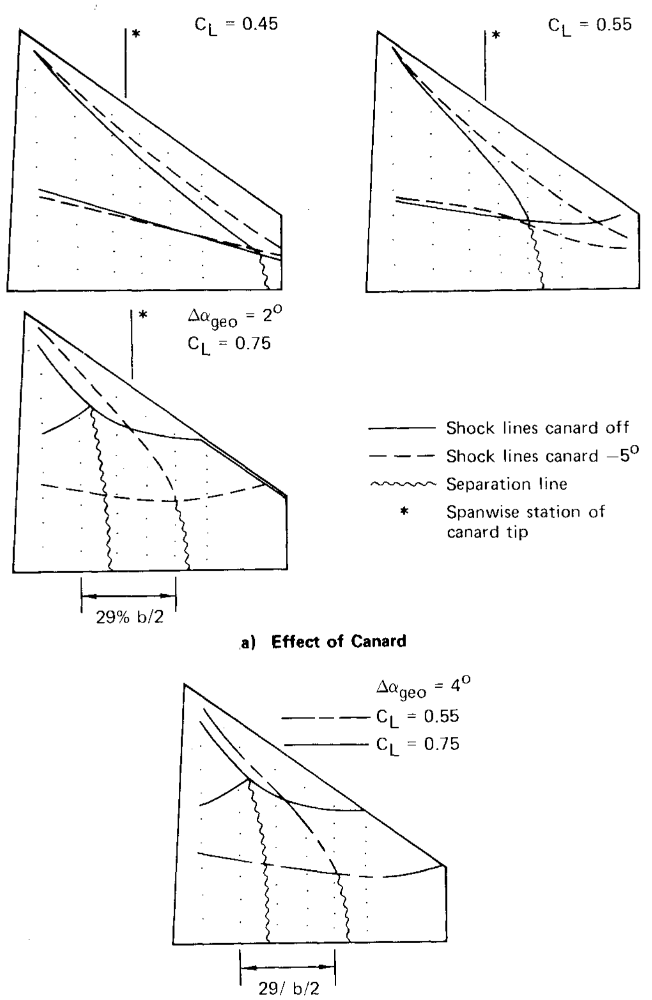


Fig. 4 Canard interactions improve wing shock patterns, Mach 0.9.

control surface deflections provide substantial levels of direct force control to enhance the controllability of this concept. Direct lift is provided by symmetrical deflection of the canard surfaces in combination with the wing trailing-edge flaps and horizontal tail. Differential canard deflection in combination with the rudder provides direct side force. Figure 2 illustrates the magnitude of these forces achieved in the current investigation. Achievement of these levels by alternate methods which do not provide the favorable interaction attainable with the three-surface concept would result in significant weight and drag penalties. It should be noted that some direct lift is available using only the flaps and the tail, but this is greatly enhanced by the addition of the canard. For this configuration, very little direct side force is available without the canard.

Linear Aerodynamics

As previously stated, the current investigation is concerned primarily with the moderate to high angles of attack where aerodynamic nonlinearities are expected. During the course of this investigation, however, certain trends have been observed in the linear aerodynamic characteristics which are worthy of note. Consider, for example, the untrimmed lift curves presented in Fig. 3. These data, which are reproduced from Ref. 1, show that the canard has very little effect on the lift at angles of attack up to the point where the flow on the wing begins to separate (indicated by the change in slope of the canard-off lift curve at approximately 8-deg angle of attack). The influence of the canard is seen to extend the linear portion of the lift curve approximately 8-10 deg in angle of attack. This effect is also apparent in the pitching moment curve which also maintains approximate linearity to a higher angle of attack with the canard installed.

It was stated in Ref. 1 that this extension of the linear characteristics was due to a delay of the wing flow separation on the inner portion of the wing. This was an incomplete conclusion. Subsequently, data have been obtained from two sources which show that flow separation is delayed by the presence of the canard over the entire span of the wing.

The first source of data illustrating this characteristic was a MCAIR Polysonic Wind Tunnel (PSWT) test of a model with a pressure instrumented wing which was conducted to investigate canard-wing interactions at high subsonic speeds. The pressure distributions obtained from this test were used to define the shock and separation patterns shown in Fig. 4 at 0.9 Mach number. It is shown in Fig. 4a that, without the influence of the canards, the wing used in this test provides recompression through two relatively weak shocks with no separation at low lift coefficients. As the lift is increased above approximately $C_L = 0.45$, the two shocks merge near the wing tip forming one stronger shock which is of sufficient strength to induce separation. Further increase in C_L causes the point of merger of the two shocks to move inboard resulting in a larger area of separated flow. The influence of the canard is seen to maintain the desirable two shock system at spanwise stations well outboard of the tip of the canard to substantially higher lift coefficients. A portion of this improvement is because the lift added by the canard allows a reduction in the angle of attack required to attain a given total lift. As indicated, at $C_L = 0.75$, this reduction is approximately 2 deg for the test configuration. Figure 4b shows that to achieve an equivalent change in the shock pattern with the canard removed requires a reduction in angle of attack of 4 deg. Thus the interaction of the canard with the wing flow is responsible for an improvement in the separation characteristics equivalent to 2 deg of angle of attack.

The second source of data illustrating the beneficial effect of the canard on wing flow separation was a flow visualization study conducted in the MCAIR Low Speed Wind Tunnel (LSWT). The surface tuft photographs shown in Fig. 5 at 15-deg angle of attack again illustrate the delayed flow separation at spanwise stations well outboard of the canard. It appears from these photographs that the canard vortex serves to strengthen the wing leading-edge vortex and increase the angle of attack at which it leaves the leading edge and bursts over the surface of the wing.

An additional benefit of this canard induced delay in the wing flow separation is apparent in the effectiveness of the aft located control surfaces. As discussed in Ref. 1, the aileron, stabilator, and rudder all exhibit improved effectiveness at the higher angles of attack. Further examination of the Ref. 1 data shows that the angle of attack at which the improvement in aileron and stabilator effectiveness first becomes apparent approximately coincides with that at which wing flow separation is first indicated by the canard-off lift curve slope.

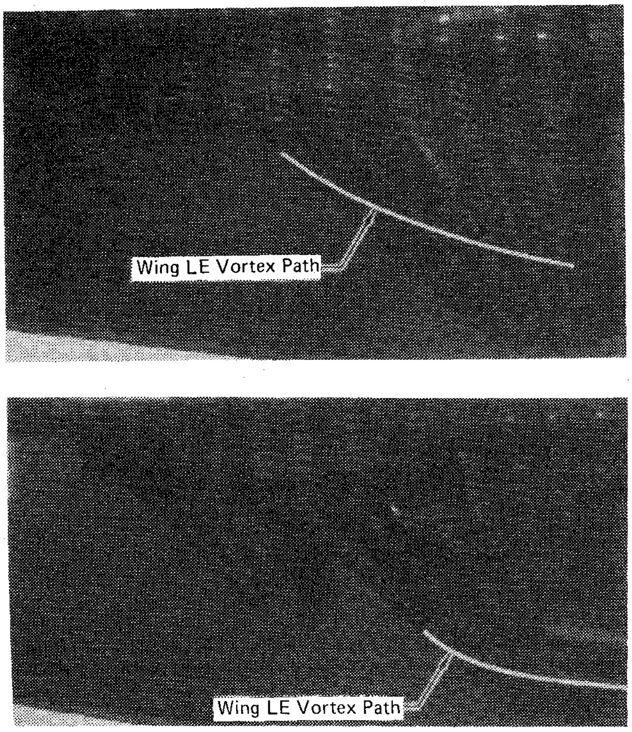


Fig. 5 Canard effect on wing flow separation, $\alpha = 15$ deg.

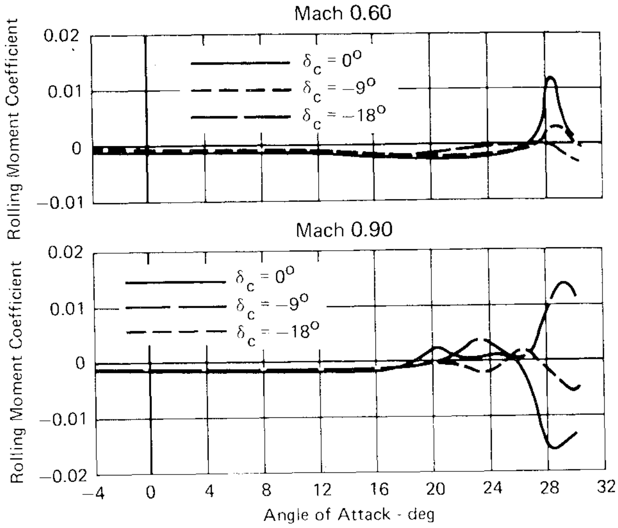


Fig. 6 Rolling moment asymmetry at zero sideslip, three-surface fighter configuration.

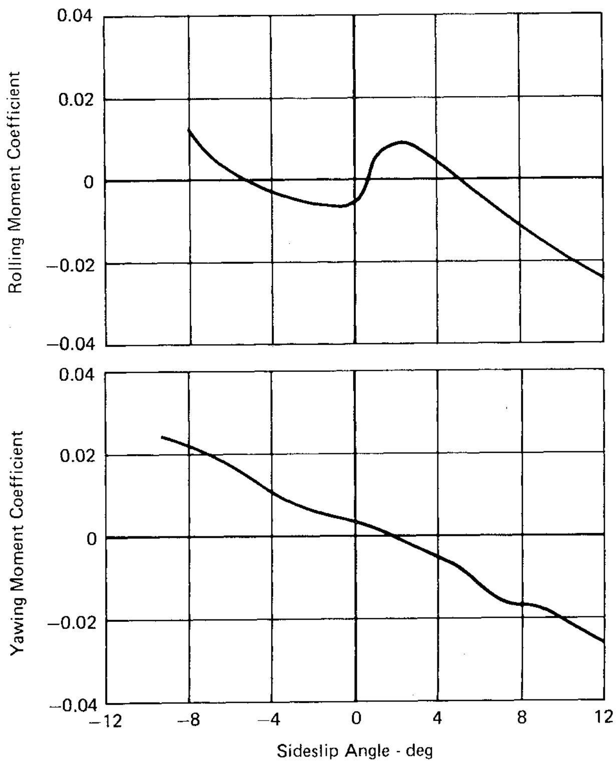


Fig. 7 Lateral-directional stability characteristics of a three-surface fighter configuration, MCAIR LSWT data, $\alpha = 31.5$ deg.

The rudder effectiveness, however, does not show the improvement until a considerably higher angle of attack is reached. This is because the rudder effectiveness is most influenced by the flow over the inboard wing and fuselage, which is the last portion of the aircraft to stall with the canards either on or off. The improvement at the higher angles of attack again reflects the influence of the canard in delaying the stall.

Nonlinear Effects

The vortex interaction phenomenon which is responsible for extending the angle of attack range for aerodynamic linearity also creates a situation which can result in large asymmetries and nonlinearities. Since this interaction maintains attached flow over large areas that would normally be separated, the changes which occur when the vortex system breaks down are likely to be quite abrupt, with large changes in forces and moments occurring over a very small angle of attack range. This characteristic is quite apparent in the canard-on pitching moment curve shown in Fig. 3, which displays an abrupt change from somewhat unstable to very stable over an angle of attack range of less than 5 deg.

From the longitudinal maneuvering standpoint, this abrupt change is considered a highly desirable characteristic, provided the break is toward increased stability. By proper tailoring of the configuration design, the basic maneuvering stability level can be maintained over almost the entire range of maneuvering angles of attack, and the abrupt stable break forms an effective barrier to protect against undesirable excursions which could lead to departures and spins. The data obtained to date in the current investigation, as well as in previous three-surface configuration studies, show that the canard has almost no effect on the longitudinal stability level at the high angles of attack which would be encountered in post stall gyrations and spins. After the initial abrupt change when the vortex system breaks down, the three-surface configuration assumes the same level of longitudinal stability as that displayed with the canard removed.

The abrupt nature of the vortex breakdown also becomes apparent in the lateral-directional characteristics, but in this case the effect is adverse. The first evidence of this was observed in the rolling moment characteristics obtained from a test in the MCAIR PSWT. These data, which are presented in Fig. 6, exhibit a marked asymmetry for a small range of angle of attack approximately coincident with maximum lift. Subsequent tests in the MCAIR LSWT confirmed the existence of this asymmetry and also revealed a rather substantial loss of lateral stability for small sideslip angles. These data are shown in Fig. 7. The loss in stability is of sufficient magnitude that the departure resistance of this configuration could be seriously degraded. Consequently, considerable effort has been expended to understand the underlying cause

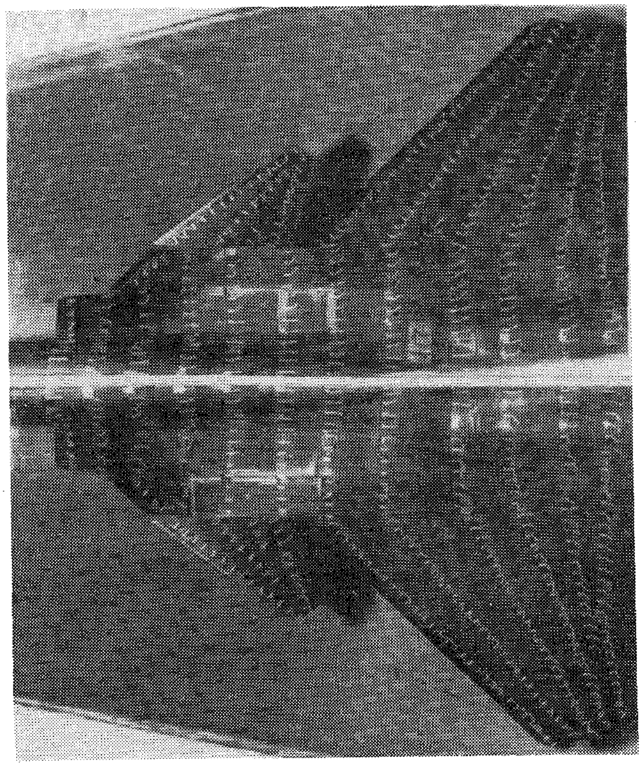
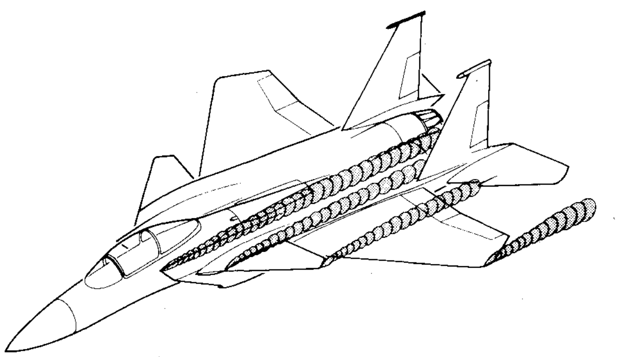
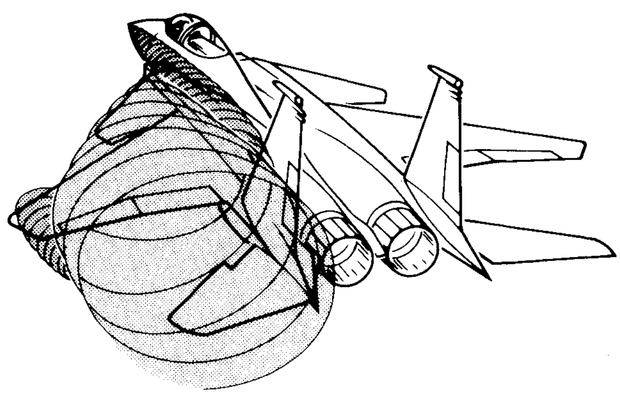


Fig. 8 Example of asymmetric flow separation, $\alpha = 26$ deg, $\delta_c = 18$ deg.



a) Vortex Formation at Low Angles of Attack



b) Vortex Interactions at High Angle of Attack

Fig. 9 Three-surface vortex flow characteristics.

of this adverse characteristic and define configuration modifications or control surface variations to reduce or eliminate it. It is interesting to note that the directional stability remains relatively linear at this angle of attack, which indicates that the cause of the lateral stability reversal is associated with a flow separation on the lifting surfaces only.

Surface tuft studies were conducted in the LSWT in an attempt to determine the source of the asymmetry/nonlinearity. While these studies helped to understand the vortex interaction phenomenon at lower angles of attack (see Fig. 5), at the angle of attack where the adverse characteristics were observed in the force data, the tuft patterns showed very little that could help to explain the forces. With the canards at the most adverse deflection (determined from the force data to be +18 deg), the tuft pictures shown in Fig. 8 do show decidedly more separation on the left side of the fuselage than on the right. Fuselage separation alone, however, because of the small moment arm involved, could not explain rolling moments of the magnitude observed. In addition, these studies did not provide the desired insight as to the cause of the asymmetry.

A second flow visualization study was conducted in the LSWT using a tuft grid above the model. By observing the vortex patterns in this grid at various fuselage stations and varying angle of attack and sideslip angle, a reasonably complete understanding of the vortex formation and interaction was obtained. As illustrated in Fig. 9a, the vortices begin forming at fairly low angles of attack at several different locations on the model. Each is influenced by those adjacent to it, but they are readily identifiable as separate and distinct vortices. At low angles of attack, the systems of vortices are reasonably symmetrical on both sides of the aircraft. As the angle of attack is increased, the strong canard vortex merges with the wing leading-edge vortex to form a stronger vortex at the wing leading edge. As angle of attack is increased further the combined canard-wing vortex in turn encompasses the wing tip vortex and the vortices emanating from the inlet and canard actuator fairing (which may already be combined). At this point the tufts indicate one large system as hypothesized in Fig. 9b. While this system (actually two systems—one on each side of the aircraft) does not have a well defined core, it does exhibit a rotational flow which serves to maintain attached flow over the fuselage and at least orderly flow, albeit mostly spanwise, over much of the wing. As angle of attack is increased through the range where the rolling moment asymmetry at zero sideslip is observed, this large system is seen to deteriorate abruptly, first on one side and then the other. When this vortical system breaks down on one side, the flow on that side of the model separates almost all at once. As the sideslip angle is varied at the critical angle of attack, the breakdown is seen to shift from one side to the other which causes the reversal in lateral stability noted earlier.

The reason for the breakdown on one side earlier than the other at zero sideslip is not entirely clear. One theory is that when the vortical flow reaches a point where breakdown is imminent on both sides, the two systems cannot coexist and the system on one side becomes dominant. In this theory, the fact that one system is removed allows the other to exist for a few more degrees of angle of attack before it, too, breaks down and symmetry is restored.

What determines which is the dominant side is also unclear. It may be due to small irregularities in the model, slight asymmetries in the canard deflection angles, or perhaps a small flow angularity in the tunnel. It is also possible that the forebody vortices feeding into the larger system have begun to assume an asymmetric orientation and this causes the total system to be slightly stronger on one side.

Additional insight into the causes of these asymmetries and nonlinearities has been provided by a test conducted in the NASA Langley 12-ft low speed wind tunnel. A number of configuration modifications were evaluated in this test for the purpose of defining their effects on these characteristics.

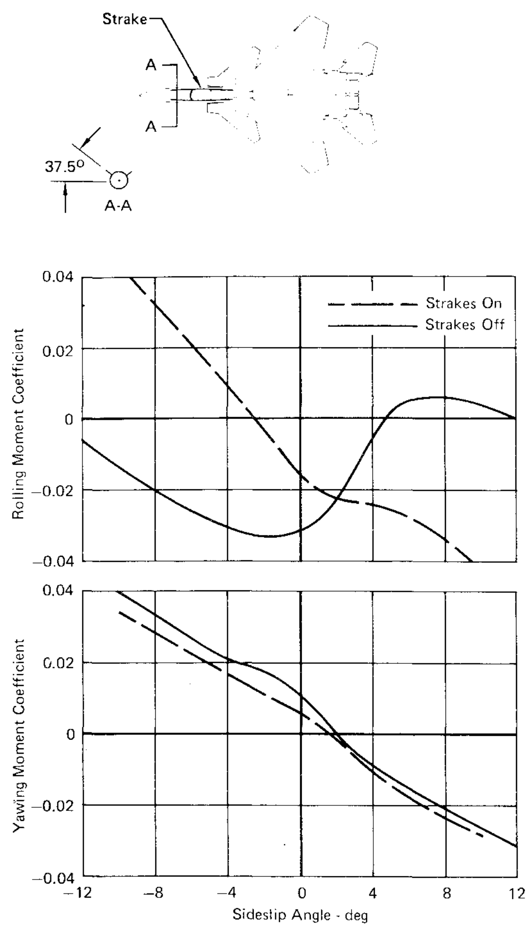


Fig. 10 Effect of fuselage strakes on lateral-directional stability, NASA-LaRC low speed data, $\alpha = 30$ deg.

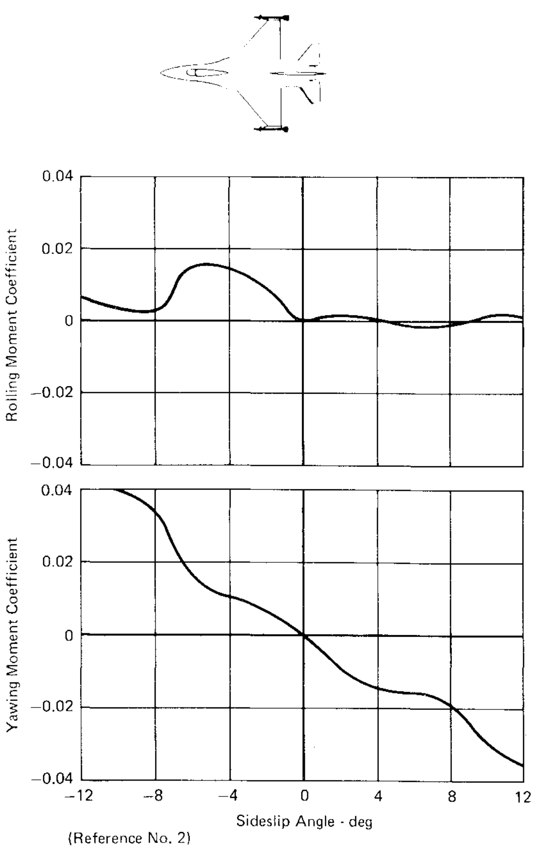


Fig. 11 Lateral-directional stability characteristics of a fighter configuration with fuselage forebody strakes, $\alpha = 35$ deg.

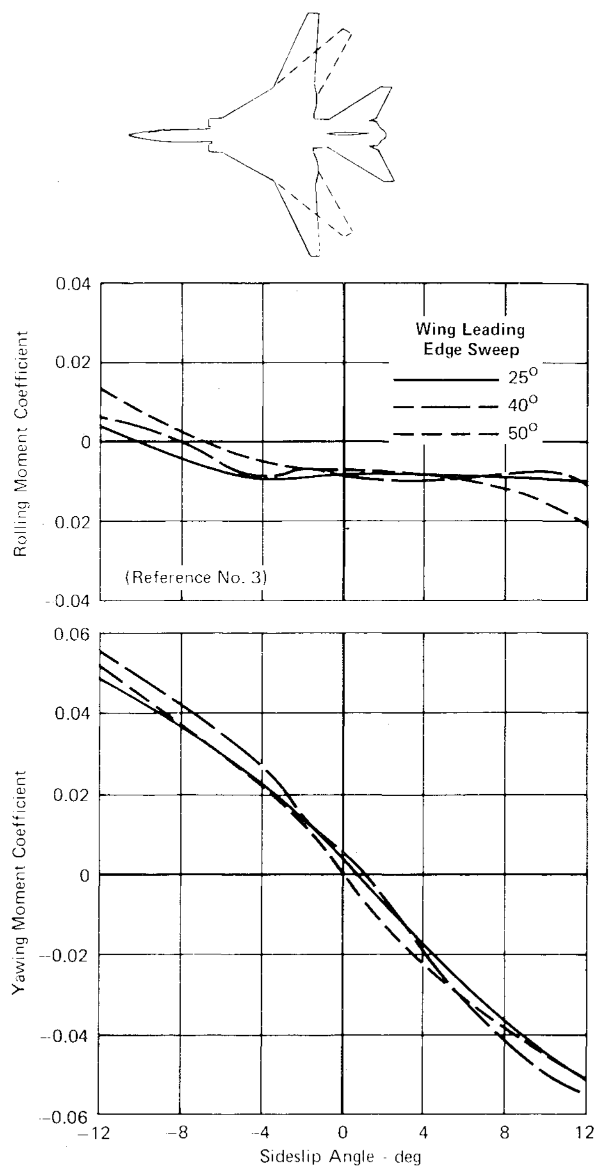


Fig. 12 Lateral-directional stability characteristics of a fighter configuration with leading-edge glove, $\alpha = 25$ deg.

These modifications consisted of: fences located at various places on the canard, wing, and fuselage; strakes at various locations on the forebody; and leading edge modifications on the wing and canard. While a number of these modifications influenced the adverse characteristics, the largest effect was obtained with fuselage forebody strakes located 37.5 deg above the point of maximum fuselage width. This effect is illustrated in Fig. 10. These data lend credence to the hypothesis that the forebody vortices are a major contributing factor. Fixing the point at which these vortices leave the surface of the fuselage and thereby assuring their symmetry eliminates most of the problem. It is also gratifying to note that the linearity of the yawing moment is relatively unaffected by these strakes.

Part of the effort to understand the nonlinearities observed in this investigation included a review of the research on vortex flow phenomena. This led to examination of the characteristics of a number of aircraft which incorporate configuration features conducive to the generation of a significant amount of vortex lift. The conclusion reached as a result of this examination is that the asymmetries and nonlinearities described herein are not exclusive properties of three-surface configurations. In fact, the data presented in Refs. 2-7 indicate that this is a common problem to all aircraft which obtain significant lift enhancement through vortex

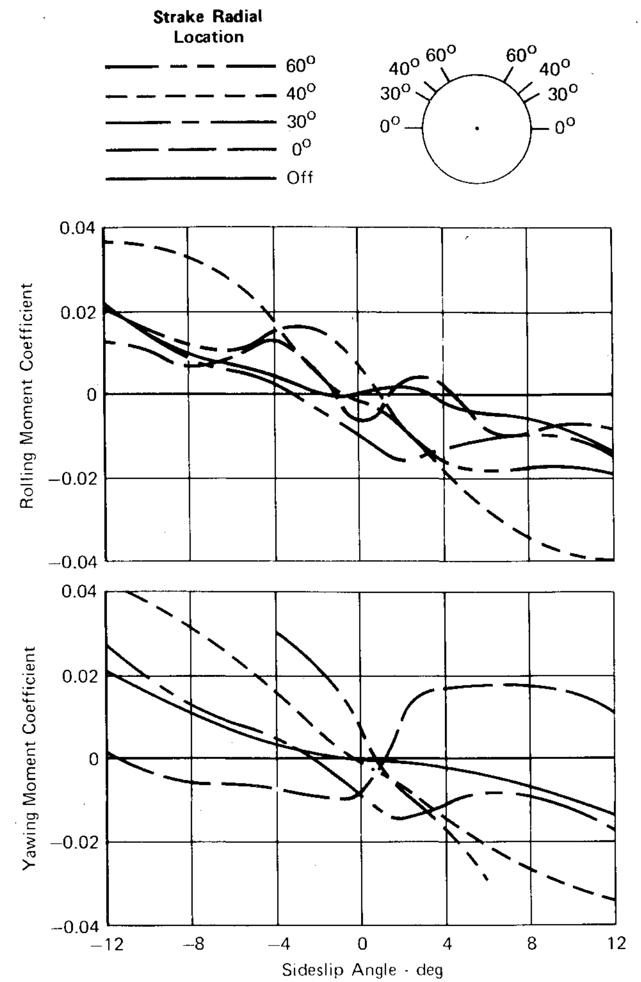


Fig. 13 Effect of fuselage nose strakes on lateral-directional stability characteristics, wing/LEX configuration, $\alpha = 35$ deg.

interactions. Figures 11 and 12 are typical examples of the nonlinearities observed in these data. The data of Ref. 8 show that this problem also extends to the subsonic operation of the highly swept arrow or delta wings being considered for advanced fighters designed for efficient supersonic cruise. It is interesting to note that the rolling moment nonlinearity indicated for the wing/LEX configuration of Fig. 13 was essentially eliminated by the addition of forebody strakes very similar to those which worked for the three-surface configuration (see Fig. 10). It is also apparent from Fig. 13 that the radial location of these strakes is very important to directional stability as well as lateral stability. In both cases the linearity is much improved with the strakes located 40 deg above the horizontal.

Conclusions

It has been shown that, by careful attention to the wing-body characteristics and proper sizing of the canard and horizontal tail during the design process, three-surface configurations can be developed which operate at minimum drag over a wide range of lift coefficients while maintaining stability levels consistent with relatively simple control system concepts. With this capability and the structural advantages realized with a more efficient load distribution, this concept offers the potential for application to a wide range of missions. A major portion of the aerodynamic improvement obtainable with this concept stems from the favorable interaction of the canard vortex with the wing flow. Another advantage of this concept is that the same surfaces that provide the aerodynamic improvements can also be used to provide direct force control.

The data presented herein show that a complex vortex system is created by the interaction of the canard vortex with the flow from other configuration components. This system is responsible for a significant extension of the angle of attack range for approximate aerodynamic linearity. It is also shown that, when this vortex system breaks down at high angles of attack, substantial nonlinearities and asymmetries may occur. These characteristics (extended linear range followed by substantial nonlinearities) are not, however, exclusive properties of three-surface configurations. Examination of data from a number of configurations with features conducive to the generation of significant amounts of vortex lift (e.g., LEX's, fuselage strakes, leading-edge gloves, etc.) leads to the conclusion that all such configurations exhibit these characteristics to some degree. The three-surface configuration may have a distinct advantage in this respect because the canard can be controlled to maximize the beneficial effects and minimize the adverse.

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