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Benefits of Aerodynamic Interaction to the Three-Surface Configuration

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Recent wind tunnel data for a contemporary fighter with a close-coupled horizontal canard added are presented with emphasis on demonstrating the beneficial aerodynamic interaction of the canard with the wing, empennage, and other aircraft control surfaces. These data show that a properly configured three-surface configuration can provide significantly increased performance and an effective six-degree-of-freedom maneuvering capability.

Nomenclature

$\bar{c}$ = wing mean aerodynamic chord
C_D = drag coefficient, D/qS_W
C_L = lift coefficient, L/qS_W
C_l = rolling moment coefficient, $L_{c.g.}/qS_W b$
C_{l_β} = rolling moment derivative with respect to sideslip angle (per degree)
$C_{l_{\delta_A}}$ ‡ = rolling moment derivative with respect to aileron deflection (per degree)
C_m = pitching moment coefficient, $M_{c.g.}/qS_W\bar{c}$
C_n = yawing moment coefficient, $N_{c.g.}/qS_W b$
C_{n_β} = yawing moment derivative with respect to sideslip angle (per degree)
C_Y = side force coefficient, Y/qS_W
l_C = horizontal canard moment arm (distance from center of gravity to quarter-chord of canard mean aerodynamic chord)
M = Mach number
N_Y = lateral acceleration, g
N_Z = normal load factor, g
NP = control-fixed neutral point, % $\bar{c}$
P_S = specific excess power, ft/s
S_C = exposed area of horizontal canard, ft^2
S_H = horizontal stabilator reference area, ft^2
S_W = wing reference area, ft^2
V = airplane velocity
$\bar{V}_C$ = horizontal canard volume coefficient, $\bar{V}_C = S_C l_C / S_W \bar{c}$
α = airplane angle of attack, deg
β = airplane angle of sideslip, deg
Δ = increment
δ_A = differential aileron deflection, positive for right roll, deg
δ_C = horizontal canard deflection, positive leading edge up, deg
δ_{DC} = differential horizontal canard deflection, $\delta_{DC} = \delta_{C_L} - \delta_{C_R}$, deg
δ_F = wing trailing edge flap deflection, positive trailing edge down, deg
δ_H = horizontal stabilator deflection, positive leading edge up, deg
δ_R = rudder deflection, positive trailing edge left, deg
Γ_C = horizontal canard dihedral angle, positive up, deg

Introduction

SINCE the introduction of the SAAB AJ-37 Viggen aircraft[1] in the mid-1960s, private industry and various government agencies have conducted numerous studies to evaluate the aerodynamic characteristics of configurations that incorporate a horizontal canard in close proximity to the wing. These studies have shown that substantial performance benefits result from the vortex interaction of the horizontal canard with the wing and many reports have been published to this effect. For the last ten years, McDonnell Aircraft Company (MCAIR) has been examining the effect of integrating close-coupled horizontal canards with conventional wing-horizontal tail configurations in a three-surface arrangement. To date, more than 2600 h of low speed and high speed wind tunnel testing have been invested in the study of this concept. In addition, the Precision Aircraft Control Technology (PACT) program[2] provided full scale flight data on an F-4 airplane which was modified by the addition of a horizontal canard. These studies have shown that the performance benefits resulting from the canard-wing interaction are retained with the three-surface concept and that significant maneuvering capability is added without resorting to extreme relaxation of static stability.

The data presented in Fig. 1 from the PACT program and from the recent Advanced Fighter Technology Integration (AFTI-15) competition[3] are indicative of the performance gains that may be achieved when a canard is added to an existing aircraft. Other studies have shown that a new three-surface design can capitalize on these benefits and, for equal capability, will be smaller and lighter than a comparable aircraft having a wing-tail or canard-wing arrangement.

Part of this size reduction is directly attributable to the maneuvering load distribution which is illustrated in Fig. 2. With the more efficient distribution illustrated, structural weight savings may be realized in both the wing and the fuselage of aircraft designed for equal maneuvering capability.

The three-surface approach also adds a dimension of controllability which is either not available, or available only in reduced amounts, in a more conventional two-surface configuration. Direct lift control is provided by symmetrical deflection of the canard in conjunction with the wing trailing edge flaps and horizontal tail. Differential deflection of the canard surfaces in conjunction with the rudder provides substantial levels of direct side force.

This paper presents aerodynamic data for a three-surface configuration with primary emphasis on the beneficial in-

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‡The control effectiveness derivatives $C_{m_{\delta_H}}$, $C_{n_{\delta_R}}$ and $C_{Y_{\delta_R}}$ are similarly defined.

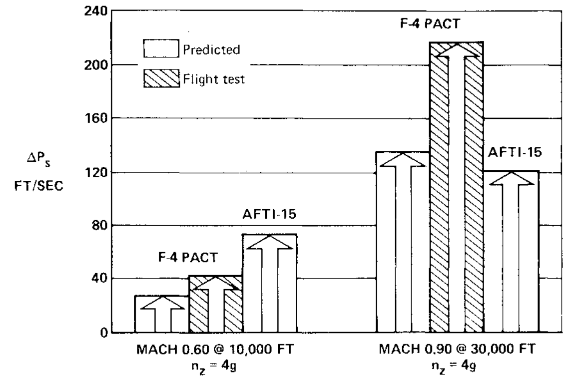


Fig. 1 Horizontal canard improves maneuvering performance.

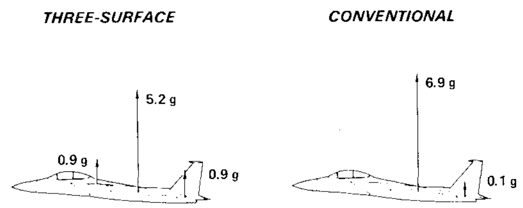


Fig. 2 Lifting surface loading comparison, $n_z = 7\ g$.

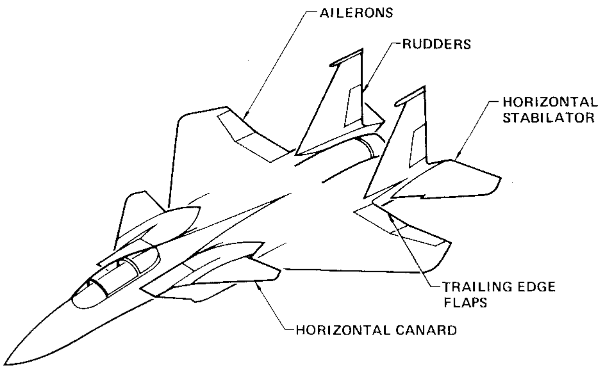


Fig. 3 Three surface AFTI-15 configuration.

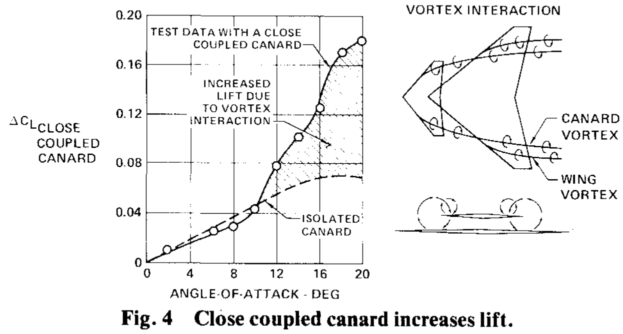


Fig. 4 Close coupled canard increases lift.

teraction of the canard with the wing and other aircraft control surfaces. The data presented, for the most part, represent the aerodynamic characteristics of the three-surface AFTI-15 configuration developed during the recent AFTI competition. This configuration, shown in Fig. 3, was derived by adding a close-coupled horizontal canard to the F-15. The aerodynamic characteristics were documented in a series of wind tunnel tests using a 13% scale low speed model and a 4.7% scale high speed model. The test program involved more than 500 h of testing from which approximately 700 aerodynamic force and moment runs were obtained. During this program, the effects of canard planform, size, location and dihedral angle were investigated.

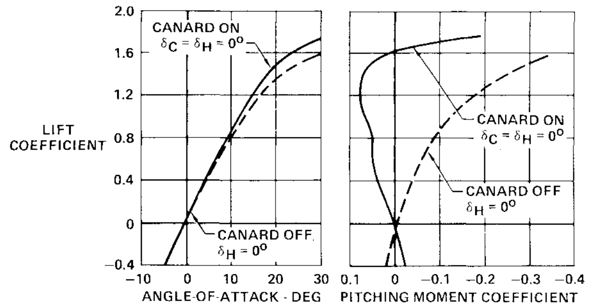


Fig. 5 Effect of horizontal canard on lift and pitching moment, Mach 0.90.

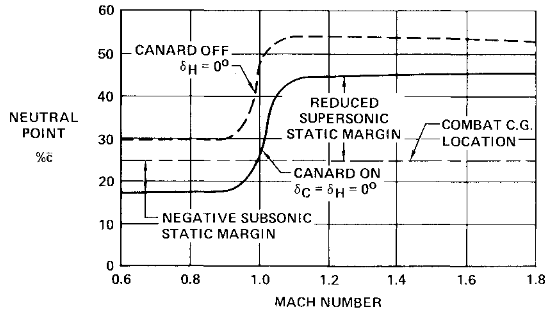


Fig. 6 Horizontal canard reduces longitudinal stability.

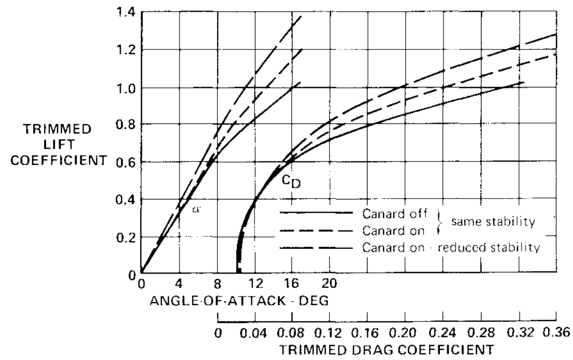


Fig. 7 Trimmed lift and drag characteristics; wing tunnel data comparison, Mach 0.90.

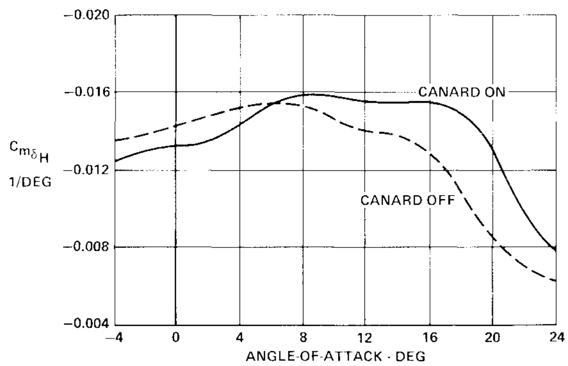


Fig. 8 Horizontal canard interaction increases stabilator effectiveness, Mach 0.9.

Longitudinal Aerodynamic Characteristics

One of the more obvious effects of the interaction of the canard and the wing is a significant increase in lift, particularly at maneuvering angles of attack. This effect is illustrated by the F-4 PACT data of Fig. 4 in which the incremental lift due to adding the canard in close proximity to the wing is compared to the lift of the isolated canard. This

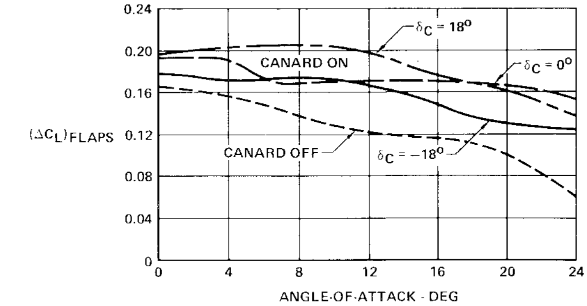


Fig. 9 Wing trailing edge flap effectiveness; Mach 0.20, $\delta_F = 30$ deg.

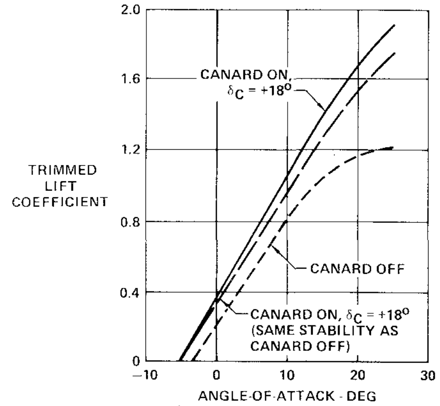


Fig. 10 Horizontal canard increases high lift capability; Mach 0.20, $\delta_F = 30$ deg.

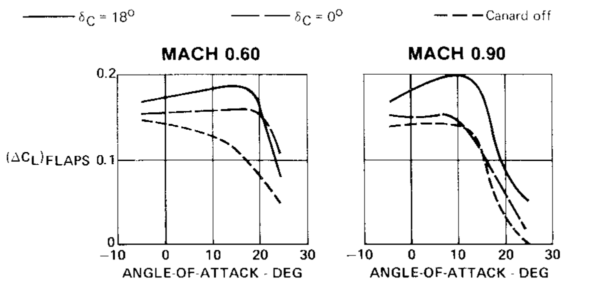


Fig. 11 Horizontal canard increases maneuvering trailing edge flap effectiveness, $\delta_F = 20$ deg.

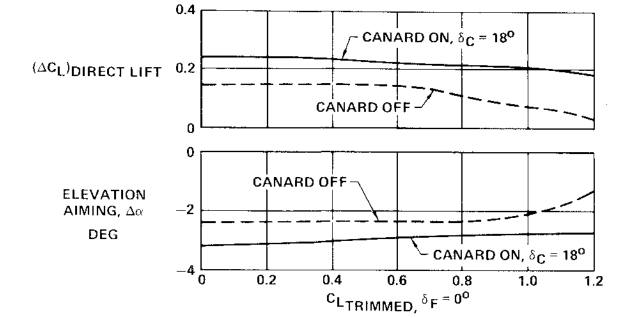


Fig. 12 Horizontal canard increases direct lift and elevation aiming capability; Mach 0.60, $\delta_F = 0$ deg.

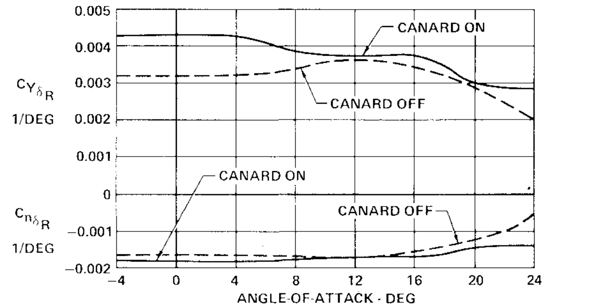
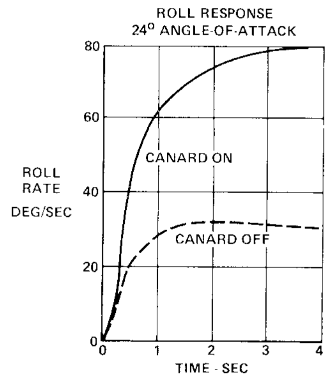


Fig. 13 Effect of horizontal canard on rudder effectiveness, Mach 0.60.

Fig. 14 Rudder effectiveness improves high alpha roll control.



comparison illustrates the increase in lift resulting from the beneficial interaction of the canard in delaying the flow separation on the inner portion of the wing. This same phenomenon is also apparent in the untrimmed AFTI-15 data shown in Fig. 5. Again, the increment in lift due to adding the canard is relatively small at angles of attack up to the point where the flow on the wing begins to separate (approximately 10 deg). Examination of the canard-on lift curve shows that the canard-wing interaction is responsible for extending the linear portion of the curve approximately 5 deg in angle of attack. These characteristics at 0.9 Mach number are typical of the trends displayed at all subsonic Mach numbers. Supersonically, the increase in lift is primarily a result of the added lifting surface area of the canard.

Another important aspect of the three-surface concept is also illustrated in Fig. 7. The stable break in the pitching moment curve at high angle of attack is a common characteristic of properly designed wing-tail configurations. This characteristic is not usually present with a canard-wing arrangement. Thus, the three-surface configuration combines the desirable features of the wing-canard and wing-tail configurations, i.e., relaxed tail-off stability for low trim drag and high stability at high angles of attack for resistance to departure from controlled flight.

The low angle of attack longitudinal static stability of the three-surface AFTI-15 configuration in terms of surface fixed neutral point is shown in Fig. 6 as a function of Mach number. The forward shift of the neutral point due to the addition of the canard resulted in an unstable static margin at subsonic conditions and greatly reduced stability at supersonic speeds. The reduction in stability, coupled with the increased lift due to canard-wing interaction, results in increased maneuvering performance for the three-surface AFTI-15 configuration. Figure 7 shows that, for canards added to the F-15, the two components are of almost equal benefit.

Analysis of the wind tunnel data for the AFTI-15 configuration has also revealed significant beneficial interaction effects with the other aircraft control surfaces. As shown in Fig. 8, the addition of the canard significantly enhances the effectiveness of the stabilator, and consequently, the controllability, particularly in the moderate angle-of-attack region.

The aerodynamic interaction phenomena are also responsible for the sizable increase in wing trailing edge flap effectiveness illustrated in Fig. 9. This figure shows that, at low speeds, the presence of the canard increases the incremental lift due to flap deflection even when the canard is deflected to large leading edge down angles. This increased flap effectiveness results in a greatly increased trimmed high lift capability at low speeds. This is illustrated in Fig. 10, which also shows the effect of the reduced longitudinal stability. To put this improvement into perspective, the increased lift at approach angle of attack would result in a reduction in landing ground roll of approximately 25%.

The high speed test data presented in Fig. 11 show that the improvement in flap effectiveness is present throughout the subsonic speed range. This was important for this configuration because the flaps were to be used (in conjunction with the canard and stabilator) for direct lift control throughout the subsonic maneuvering envelope of the aircraft. It is also important to note that the increase in lift for positive (trailing edge down) flap deflection is greatest when the canard is also deflected in the positive direction. This is important because, in the direct lift application, positive canard deflection also requires positive stabilator deflection, thus all of the lift increments are maximized. The magnitude of the total direct lift improvement attributable to the addition of the horizontal canard is illustrated in Fig. 12. Data are also presented which illustrate the alternate application of changing aircraft attitude while holding lift constant (fuselage elevation aiming).

Lateral-Directional Aerodynamic Characteristics

When the horizontal canard panels are differentially deflected, sizable forces and moments are generated which, when combined with the capabilities of the rudders, make possible the application of direct side force to provide independent control of the airplane attitude and velocity vector. The aerodynamic interaction between the canard and the other control surfaces plays an important part in this unique control capability. This interaction can also provide significant improvements in the controllability of the aircraft motions in more conventional maneuvering.

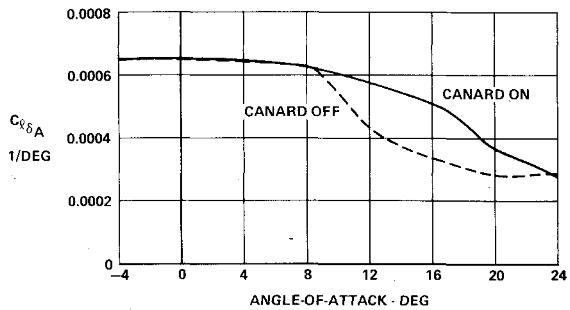


Fig. 15 Horizontal canard interaction increases aileron effectiveness, Mach 0.60.

Conventional Controls

One of the more important examples of beneficial aerodynamic interaction between the canard and conventional control surfaces is illustrated in Fig. 13, which shows the effect of the canard on rudder effectiveness at 0.6 Mach number as a function of angle of attack. The increase in rudder effectiveness at the higher angles of attack at this Mach number is typical of that seen in the test data at all subsonic speeds. This increase is a direct result of the increased dynamic pressure at the vertical tails caused by the canard-wing interaction previously discussed. The significance of this improvement in rudder effectiveness is shown in Fig. 14. The ability to generate larger levels of yawing moment to coordinate roll maneuvers at the higher angles of attack permits increased deflection of the roll control surfaces and consequently, greatly increased roll performance.

Another benefit of the aerodynamic interaction with conventional control surfaces in the three-surface configuration is illustrated by the aileron effectiveness data shown in Fig. 15. The vortex interaction of the canard with the wing which, as discussed previously, provides increased trailing edge flap effectiveness is also responsible for similar beneficial effect on the ailerons. Aileron effectiveness data at all subsonic speeds tested display characteristics similar to those shown at 0.6 Mach number. Supersonically, the canard was found to have very little effect. Similar characteristics have also been found in the data from other three-surface configurations tested.

Direct Force Controls

The three-surface configuration has the capability to generate substantial levels of direct side force. Differential deflection of the horizontal canard creates a nonsymmetrical pressure distribution on the sides of the fuselage that generates a side force in the direction of the side with the negative canard deflection. Since the canard is located forward of the aircraft center of gravity, a substantial yawing moment is generated along with this side force. This is shown in Fig. 16 which presents the differential canard control capability of the three-surface AFTI-15 configuration at 0.20 Mach number. The left hand canard is deflected to 12 deg and the right hand canard is deflected to −24 deg for a total differential deflection of 36 deg.

It is also apparent from the data in Fig. 16 that a significant sidewash angle is induced at the vertical tails by differential canard deflection. Comparison of the data with vertical tails on and off shows that the vertical tail contribution essentially doubles the yawing moment generated, but reduces the untrimmed side force. This interaction effect is not detrimental

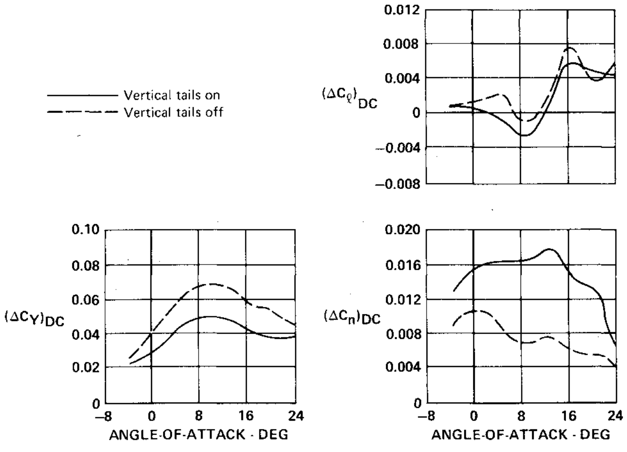


Fig. 16 Differential canard effectiveness; Mach 0.20 δ_{C_L} = 12 deg, δ_{C_R} = −24 deg, Γ_C = 20 deg, and δ_H = 0 deg.

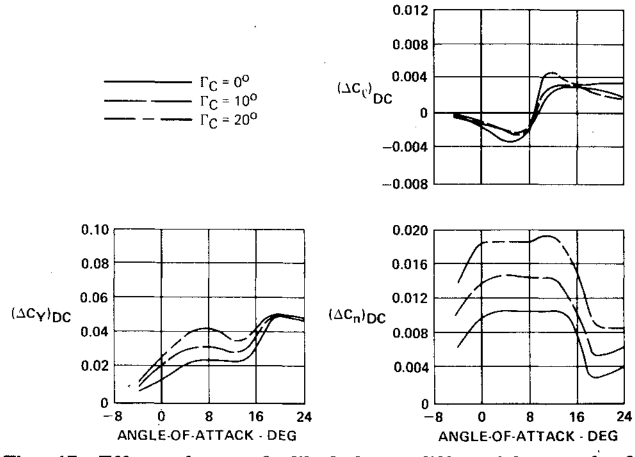


Fig. 17 Effect of canard dihedral on differential canard effectiveness; Mach 0.60, $\delta_{DC} = \delta_{C_L} - \delta_{C_R}$ = 40 deg.

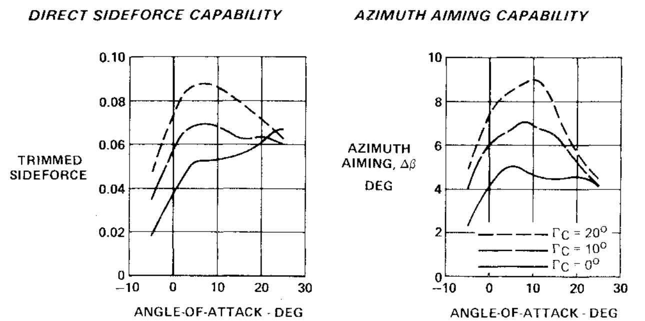


Fig. 18 Direct sideforce and azimuth aiming capability from differential canard deflection; Mach 0.60, $\delta_{DC} = \delta_{C_L} - \delta_{C_R} = 40$ deg.

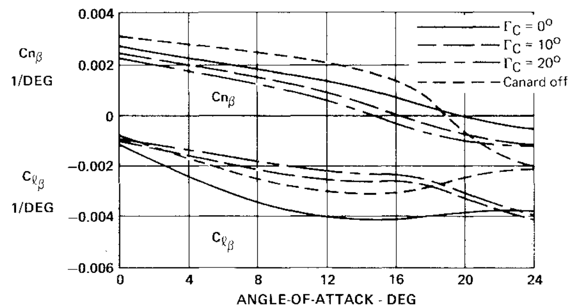


Fig. 19 Effect of canard dihedral on lateral-directional stability; Mach 0.60, body axes.

to the trimmed side force capability because the side force is regained when the rudders are deflected to trim the additional yawing moment.

It is interesting to note that the rolling moment generated by differential canard deflection is generally quite small. This is because the rolling moment due to the loads on the individual canard panels is essentially nullified by a rolling moment of opposite sign resulting from the effect of the canard downwash on each wing. This is especially true at low angles of attack where wing flow separation phenomena are not involved. As the angle of attack is increased to the point where the canard is influencing the flow separation patterns on the wing, some rolling moment is observed. This is, however, less than would be computed from the individual canard panel loads. At all conditions, the differential canard rolling moment is small compared to that available from the roll control surfaces.

In terms of differential canard effectiveness, one of the more significant parameters evaluated in the AFTI-15 test program was canard dihedral angle. As shown in Fig. 17, major increases in yawing moment and side force were demonstrated with positive canard dihedral. Positive dihedral results in a component of the lift of each canard surface being projected in the same direction as the side force generated by nonsymmetrical fuselage pressure distribution. This side force component is directly additive to that resulting from fuselage pressures. Also, judging from the test results shown, the fuselage pressures are relatively unaffected by canard dihedral angles of at least 20 deg.

As previously stated, the ability to generate direct side force adds a new dimension in controllability through the independent control of the fuselage attitude and the velocity vector. This allows (in one application) aiming of the fuselage without changing the flight path or conversely changing the flight path while maintaining a constant heading. The direct side force and azimuth aiming capabilities of the three-surface AFTI-15 configuration are shown for three canard dihedral angles in Fig. 18 to illustrate the magnitude of these parameters that can be generated with a typical three-surface configuration.

For the AFTI-15 configuration, the horizontal canard with no dihedral increased subsonic lateral stability at all angles of attack tested. Directional stability was somewhat decreased at low angles of attack, but was increased at high angle of attack; demonstrating again the favorable influence of the horizontal canard on the vertical tails. These characteristics are illustrated in Fig. 19. It is also illustrated, however, that introducing canard dihedral to increase direct side force capability resulted in some degradation in both lateral and directional stability. Therefore, a penalty is indicated for increasing differential canard effectiveness with canard dihedral. Differential canard deflection does not affect the three-surface configuration lateral-directional stability. The stability penalties indicated for this configuration are not considered to be limiting factors in the design of new three-surface airplanes.

Conclusions

MCAIR studies have shown that the three-surface configuration offers a great potential for the development of advanced aircraft with six-degree-of-freedom maneuvering capability while maintaining a high degree of aerodynamic efficiency. There are a number of important aerodynamic interaction effects that must be considered in the design of such aircraft. It has been shown that these interaction phenomena can be of significant benefit in terms of performance and maneuverability. A detailed understanding of these phenomena is of paramount importance in order to use them to full advantage in the design of new aircraft.

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