Canard/Tail Comparison for an Advanced Variable-Sweep-Wing Fighter

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Equivalent canard and tail control surfaces are compared on an advanced, carrier-based fighter/attack aircraft featuring variable wing sweep and vectorable, two-dimensional nozzles. Evaluations of stability and control characteristics, trimmed drag due to lift, minimum takeoff rotation speeds, and carrier approach speeds are presented. The results show that the canard configuration has substantially less supersonic trim drag and a lower carrier approach speed, which can yield appreciable takeoff weight savings, but the tail configuration exhibits better stability and control characteristics with less development risk.

Nomenclature

AOA,α = angle of attack
AR = aspect ratio
$\bar{c}$ = mean aerodynamic chord
C_D = drag coefficient
C_L = lift coefficient
C_{L_δ} = lift due to surface deflection
C_{l_β} = rolling moment due to sideslip
C_m = pitching moment coefficient
C_{m_δ} = pitching moment due to surface deflection
C_{n_β} = yawing moment due to sideslip
M = Mach number
P_s = specific excess power
Re = Reynolds number (based on fuselage length)
S = planform area
SM = subsonic static margin
β = angle of sideslip
δ = surface deflection angle
λ = taper ratio
Λ = leading-edge sweep angle

Introduction

PREVIOUS investigations[1-5] have differed on the best choice between tail and canard for future tactical aircraft employing fixed, low-aspect-ratio wings. A previous Grumman/USAF study[1] of an advanced strike fighter emphasizing supersonic persistence showed the superior trim drag characteristics of a canard. Northrop[2] argued that a tail design has lower subsonic maneuver trim drag and greater stability/center-of-gravity (c.g.) location flexibility and is, therefore, the preferred configuration for an air-combat fighter. Studies by General Dynamics[3] and Dornier[4] concluded that a canard-equipped fighter introduces stability and control problems without offering significant performance improvements. The next generation of European tactical designs (Rafale, Gripen, European Fighter Aircraft) employ canards for gust alleviation, direct force maneuvering, and trimmed lift enhancement, as discussed by Burns.[5] The message seems to be clear: The selection of a canard vs a tail is both configuration- and mission-dependent.

Variable-sweep aircraft typically exhibit a greater rearward shift in aerodynamic center from subsonic to supersonic speeds than fixed-wing planforms. Over the years, aircraft designers have tried several schemes to circumvent this phenomenon. The first variable-sweep design, the X-5 research vehicle, minimized aerodynamic center travel by employing a rail carriage system to provide forward translation to the wing at the swept-back position. The XF10F-1 aircraft, the second variable-sweep design, had a forward translation capability that was somewhat less complex and bulky, but it could not independently vary sweep and translation like the X-5. The F-111 wing sweep system incorporated an inboard pivot location without the translation feature of the earlier experimental aircraft. It suffered from excessive longitudinal stability and large attendant tail downloading during supersonic flight. Subsequent research efforts[6,7] found that an outboard pivot location minimized the stability increase due to wing sweep, which was a prime design consideration in the case of the F-14. A glove vane was also provided for deployment at higher Mach numbers to further reduce trim drag and relieve tail loads.[8]

A canard configuration offers today's designer the potential advantages of less rearward aerodynamic center travel than a tail arrangement and wing/canard load sharing. The objective of the present effort was to determine the extent to which these benefits can be realized on a swing-wing fighter, within the bounds set by critical stability and control requirements. An additional goal was to examine pitch-axis thrust-vectoring technology, and to identify any synergistic payoffs.

The canard/tail evaluation baseline was a multirole, supersonic, Navy tactical-aircraft concept, as illustrated in Fig. 1. Variable wing sweep was employed to meet the diverse mission requirements of a carrier-based fighter/attack design for the late 1990s. All-movable canard and tail surfaces of equal area (17% wing area) and coplanar with the wing were positioned for comparable pitch control effectiveness (Fig. 2) at low angles of attack (AOA). It was assumed that both canard and tail surfaces had a throw range of +30 (trailing edge down) to −90 deg. The canard planform location was limited by pilot visibility considerations. The tail was nested within the aft wing sweep position of 60 deg. In both cases the wing employed variable camber through scheduled leading- and trailing-edge deflection. The camber schedule optimized wing-body lift-to-drag ratio at lift coefficients up to maximum sustained maneuver levels. Beyond that, wing flaps were deflected to meet stability and control demands. Thrust vectoring was considered to provide direct powered lift and to augment pitch control authority at low airspeeds. A single expansion ramp nozzle was utilized with an effective thrust deflection range of −12 (jet exhaust upward) to +20 deg.

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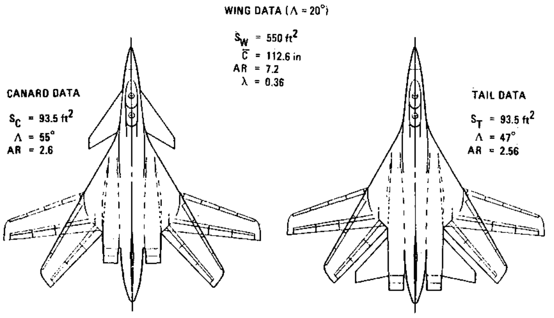


Fig. 1 Aircraft geometric characteristics.

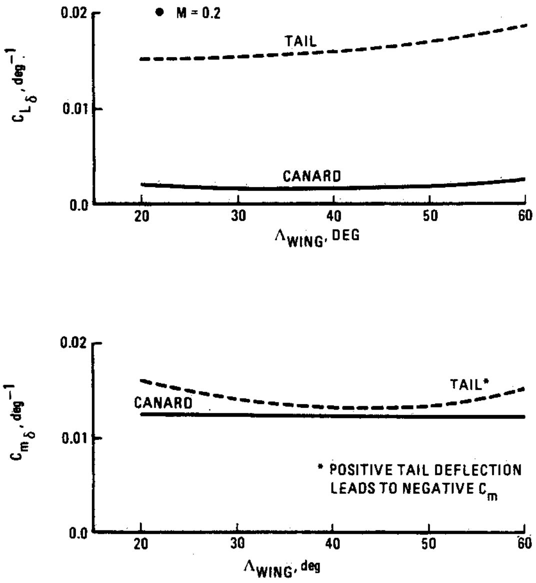


Fig. 2 Longitudinal control derivatives.

Static Longitudinal Characteristics

Figure 2 depicts the lift and pitching-moment effectiveness (within the low-AOA linear regime) of the two control surfaces. Comparable pitch authority is available across the range of wing sweep settings. A comparison of the C_{L_δ} values illustrates the coupled interaction of the canard/wing configuration. While tail lift is essentially isolated from the wing, the downwash from canard lift generates substantial wing downloading at subsonic speeds. This downwash acts well forward on the wing glove, reducing canard control effectiveness. For comparable pitch authority, the canard arm (c.g. to surface $\bar{c}/4$) is greater than the tail arm by a factor of 1.36. Figure 3 shows the estimated location of the configurations' aerodynamic center with wing sweep set at the 20-deg low-speed position. A point worth noting is that the destabilizing effect of the "control equivalent" canard is greater than the tail's stability increment.

Figure 4 presents the aerodynamic pitch control envelope of the wing/body/canard configuration balanced 6% unstable. The incremental effects of full canard authority and 30-deg wing trailing-edge flap deflection are shown in the figure, based on wind-tunnel data acquired at the University of Maryland's low-speed test facility. A design margin of -0.3 rad/s² was selected as representative of the minimum amount of nose-down pitch acceleration required to prevent AOA departure. This can occur in an air-combat fighter from either large commanded nose-up pitch rates or kinematic/inertial coupling from maximum sustained rolls at low airspeed.

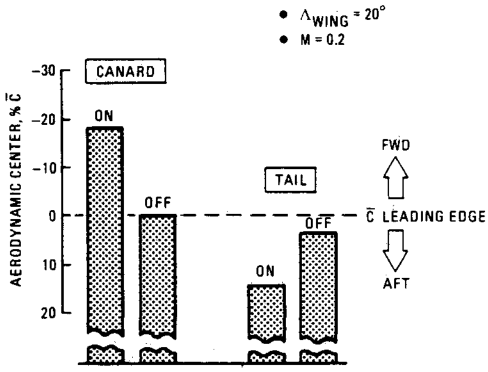


Fig. 3 Longitudinal stability contributions.

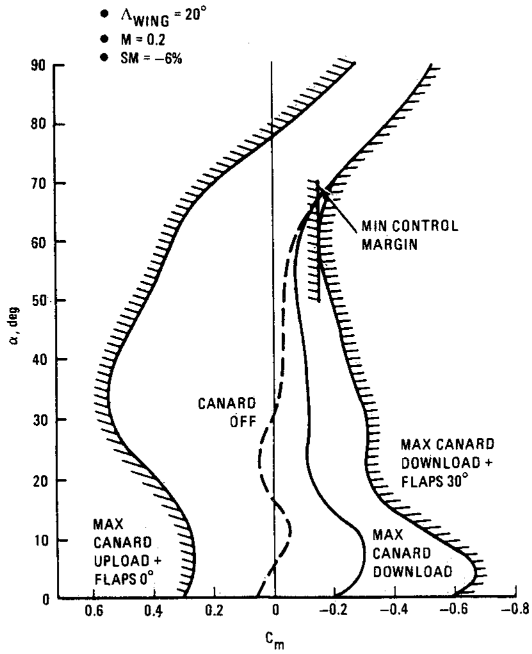


Fig. 4 Aerodynamic pitch control envelope of canard configuration.

Maintaining this control margin at a mimimum level of freestream dynamic pressure (70 psf), translated into pitching-moment coefficient ($C_{m_{min}} = -0.17$), becomes the design limitation of the aft c.g. position.

A similar analysis was performed on the tail design utilizing the aforementioned test data (canard off) in conjunction with F-14 tail increments[9,10] corrected for differences in planform and body/tail carryover. Figure 5 presents the aerodynamic pitch control envelope of the wing/body/tail configuration. The aircraft is balanced 2% stable at low AOA in order to satisfy the high-AOA control criterion by purely aerodynamic means. Introducing thrust vectoring (TV) as a pitch effector to each configuration enables a relaxation of $C_{m_{min}}$ from -0.17 to 0. Although TV control is quite potent at high power settings during low-speed maneuvering, a minimum level of aerodynamic control must be maintained to avoid a "hung stall" condition in the unlikely event of a twin-engine failure. This criterion allows each configuration to be destabilized by an extra 9% $\bar{c}$. Figure 6 summarizes the design static margins of the aircraft as constrained by the requirement for an adequate high-AOA recovery margin. Subsequent discussions in this paper will refer to the TV control configurations as a baseline.

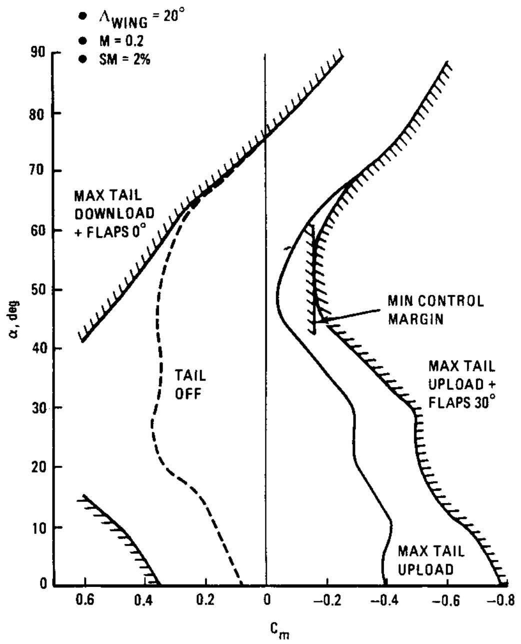


Fig. 5 Aerodynamic pitch control envelope of tail configuration.

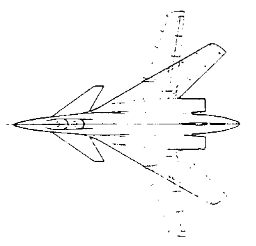
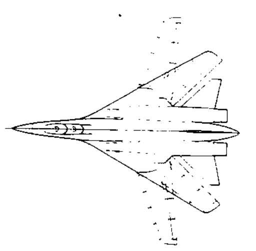
	PITCH CONTROL EFFECTORS	MAX RSS LEVEL (%$\bar{C}$)
	CANARD	−6%
	CANARD + TV	−15%
	TAIL	+2%
	TAIL + TV	−7%

Fig. 6 Maximum level of relaxed static stability for high-angle-of-attack control.

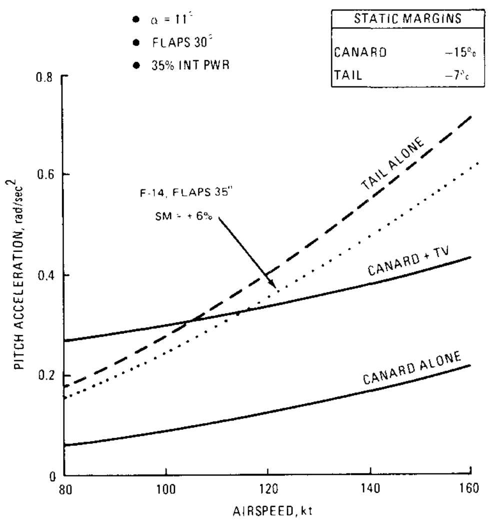


Fig. 7 Available nose-up pitch control, approach configuration.

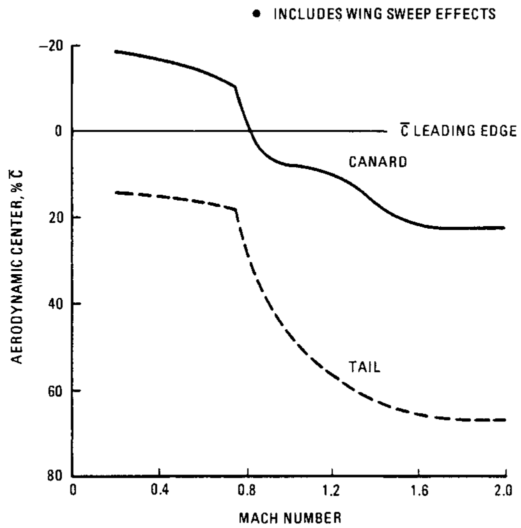


Fig. 8 Comparison of aerodynamic center travel.

Figure 7 examines the availability of nose-up control in the flaps-down carrier takeoff and approach configuration. The F-14's control authority is included as a representative design target. The tail configuration has a similar pitch control margin even though its tail area is significantly less than the F-14 (17% vs 25% wing area). This is due to differences in stability level, wing flap deflection, and surface throw range. The canard configuration requires control augmentation from thrust vectoring to meet the F-14 capability. Canard deflection alone cannot provide the rotation rates necessary for dynamic maneuvering during catapult launch or landing waveoff, particularly with c.g. positions forward of the baseline location.

Figure 8 shows that the tail configuration has a greater rearward shift in aerodynamic center with Mach number than the canard. The effects of both compressibility and wing pivoting are included. Figure 9 shows the simple Mach-sweep schedule used in the analyses, along with the baseline c.g. locations. The kink in each curve is the shift in c.g. location with wing sweep.

Dynamic Longitudinal Characteristics

A check of the open-loop dynamic stability characteristics was made to assure that high-AOA control was the more restrictive static margin criterion for these configurations. Dynamic instability was quantified by time to diverge to double amplitude in pitch, based on the classic two-degree-of-freedom short-period approximation. Figure 10 depicts the effect of Mach number on time to double amplitude during a sea-level dash. The tail configuration possesses a lower rate of divergence compared to the more statically unstable canard configuration. At equal levels of static instability (Fig. 11), the tail aircraft is more dynamically unstable due to an 8% higher lift-curve slope. When balanced at their baseline static margins, the minimum time to double of the canard and tail aircraft (0.45 and 1.15 s, respectively) were deemed to be well within the capabilities of a modern flight control system.

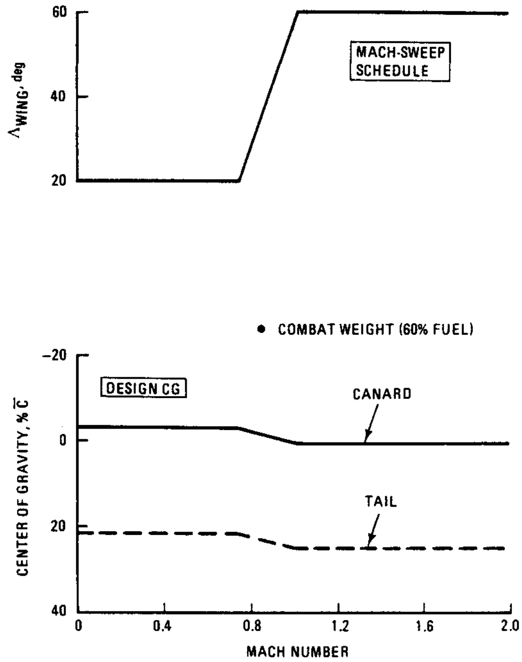


Fig. 9 Effect of wing sweep on center-of-gravity location.

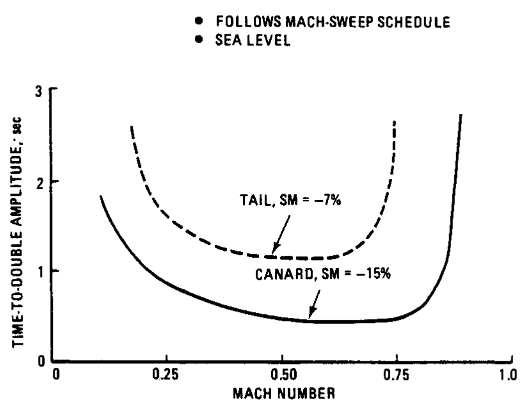


Fig. 10 Effect of Mach number on time to double amplitude.

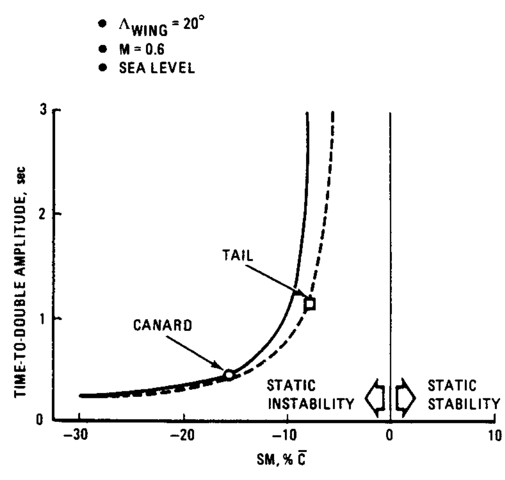


Fig. 11 Comparison of dynamic instability characteristics.

Trim Drag Characteristics

The compromise in relaxed static stability for high-AOA control introduces trim drag peanalties throughout the flight envelope. Figures 12 and 13 illustrate the trim drag increment vs static margin at transonic maneuver and supersonic cruise, respectively, based on an empirical drag synthesis method. At the maneuver condition, the tail configuration has slightly less trim drag than the canard configuration when balanced at their optimum static margins. However, with the c.g. at the aft-most position allowed by high-AOA control, the canard configuration has less trim drag. While both designs achieve minimum trim drag with a surface upload (corresponding to a lift coefficient of 0.3), the load-sharing nature of the canard produces less sensitivity to increased static margin. At a 1.6 Mach cruise condition (Fig. 13), neither aircraft displays a trim drag penalty if balanced neutrally stable. Minimum drag occurs when the surface lift coefficient equals the total configuration lift coefficient. The canard aircraft has significantly lower drag when balanced at its baseline c.g., again due to load sharing with the wing and a smaller stability increase from compressibility. Note that at both flight conditions the 9% aft shift in c.g. position permitted by TV control augmentation relieved canard/tail trim loads substantially. In addition to a hefty drag reduction, benefits in structural weight are anticipated.

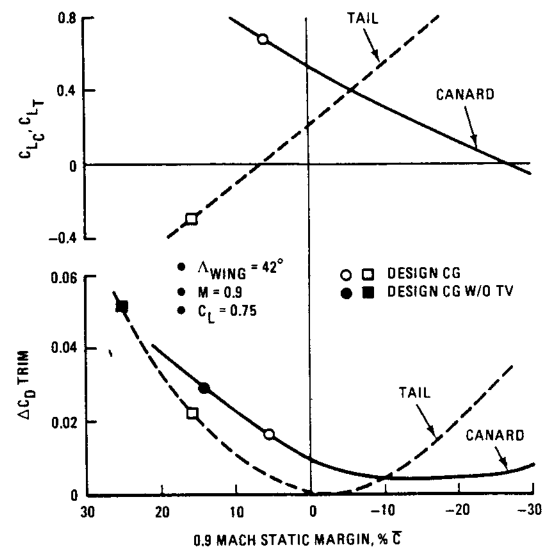


Fig. 12 Transonic maneuver trim characteristics.

Lateral-Directional Characteristics

Figures 14 and 15 provide an indication of canard/tail deflection effects on lateral-directional characteristics for two representative configurations.[11,12] The greater sensitivity to canard deflection is due to the interaction with the forebody flowfield, which dominates the lateral-directional characteristics at mid-to-high AOA. The position of the canard influences the windward and leeward forebody vortices and the resultant pressure distribution across the forebody and wing. For the representative canard configuration (Fig. 14), the effect is directionally destabilizing in the low-AOA region and directionally stabilizing in the mid-to-high AOA region. A similar, although less severe, impact is observed on lateral stability. For the study aircraft, a limited test data base is available which shows comparable trends. Although lateral-directional characteristics are very configuration-dependent, it is clear that a canard must be carefully integrated with the forebody and wing to prevent susceptibility to spin departure during poststall maneuvering. One means of tailoring lateral-

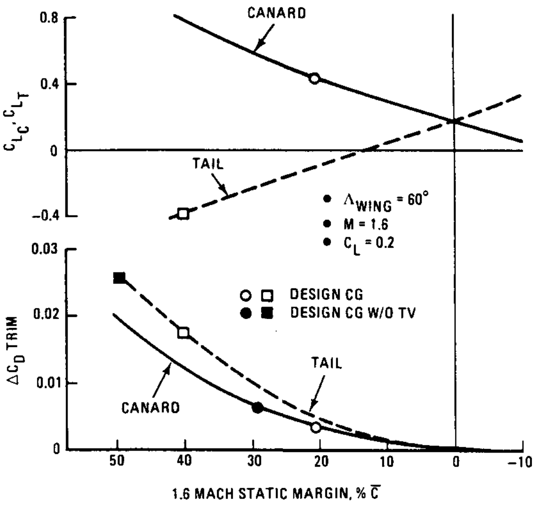


Fig. 13 Supersonic cruise trim characteristics.

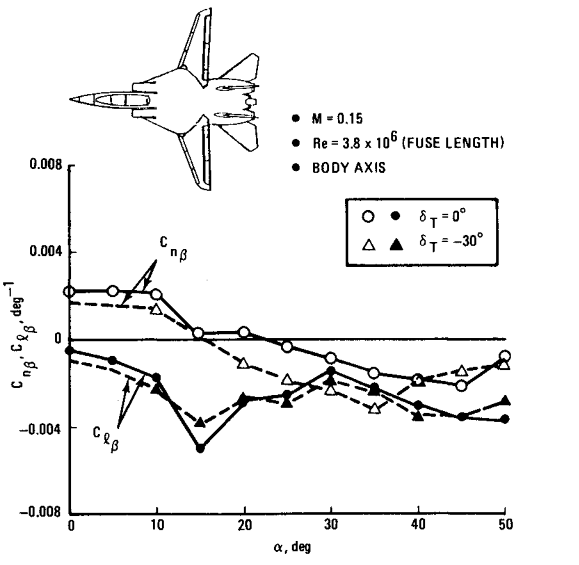


Fig. 15 Effect of tail deflection on lateral-directional characteristics.

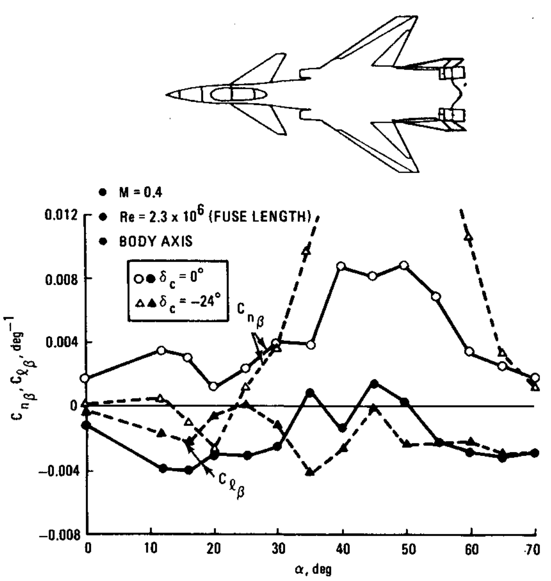


Fig. 14 Effect of canard deflection on lateral-directional characteristics.

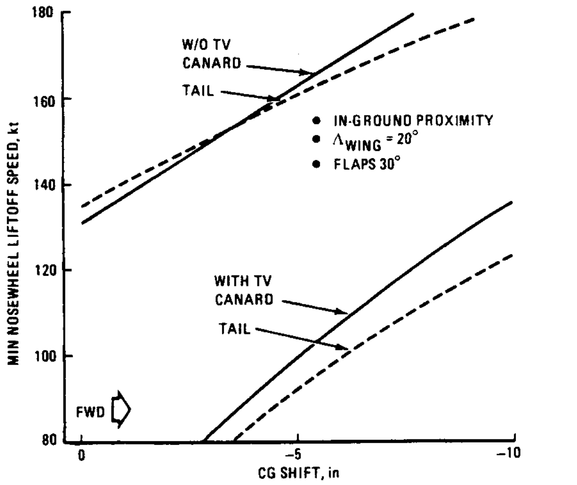


Fig. 16 Effect of forward center-of-gravity shift on minimum nosewheel liftoff speed.

directional stability is through canard scheduling with TV pitch control augmentation. The canard also offers additional yaw control at high AOA through differential deflection.

Figure 15 shows that the effect of tail deflection on the F-14 is less influential on lateral-directional stability. Desirable lateral-directional characteristics are achievable at high AOA through optimization of the dominant forebody. The tail can be used for additional roll control through differential deflection.

Takeoff/Landing Performance

The takeoff performance of fighter aircraft often tends to be limited by high requisite airspeeds to unstick the nose gear and begin rotation. Figure 16 compares the minimum nosewheel liftoff speeds of the canard and tail configurations. Both vehicles have high rotation speeds with the c.g. located forward of the baseline position, the canard design showing the least tolerance. Thrust vectoring provides a substantial improvement to minimum rotation speed. Commanding slight upward thrust deflection at a predetermined ground speed was investigated during the Grumman X-29/ADEN[13] feasibility study. Dynamic time histories indicated that only modest nozzle deflection rates were necessary to initiate rotation at less than 115 knots.

Figure 17 compares the carrier landing speeds of the aircraft at an approach AOA of 11 deg. The tail design has a lower trimmed lift coefficient with wing flaps down due to tail downloading. In contrast, the canard upload to trim yields a small increase in net lift coefficient. The difference in trimmed lift leads to a 4.5-knot increment in favor of the canard aircraft. Some extra lift enhancement is afforded the canard design by implementing vectored thrust. A thrust deflection of 8 deg is possible without completely saturating the canard, which is worth an additional improvement of 2 knots. The tail design does not realize any benefit from vectored thrust since tail download to trim negates nozzle deflection for lift.

This seemingly small difference in approach lift coefficient can lead to a dramatic savings in iterated vehicle weight when the wing area is sized by carrier landing speed. Figure 18 il-

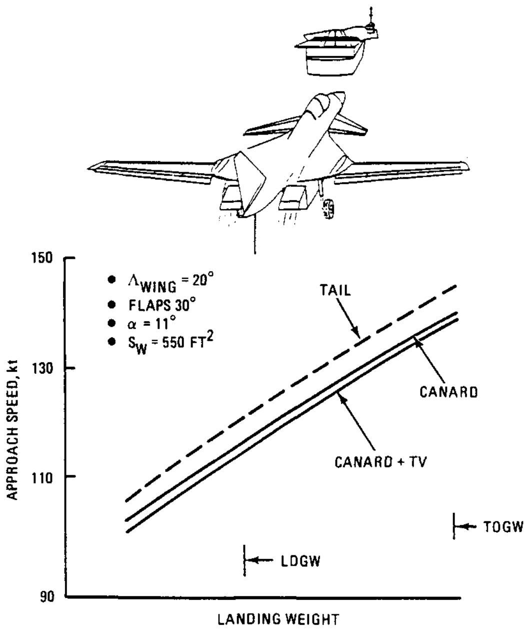


Fig. 17 Comparison of carrier approach speeds.

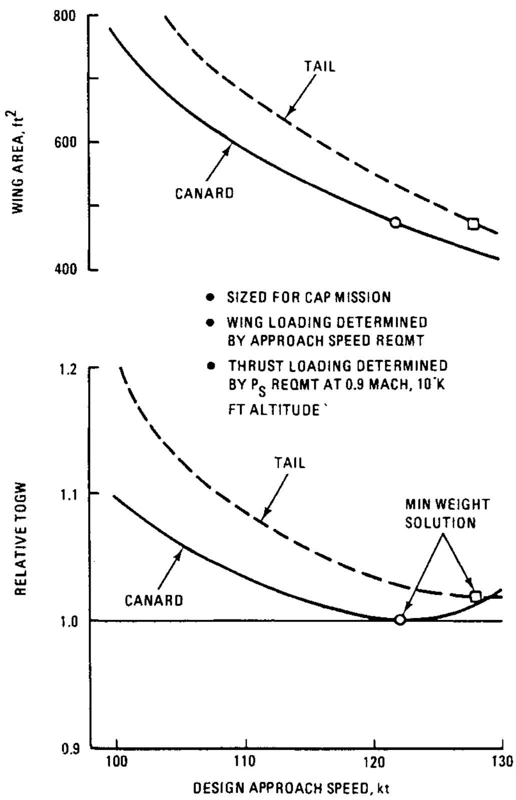


Fig. 18 Vehicle sizing impact of design approach speed.

lustrates the effect of design approach velocity on aircraft takeoff gross weight based on a mission sizing analysis. The aircraft were sized to a combat air patrol (CAP) role, comprised of a diverse set of mission elements (subsonic cruise, loiter, supersonic dash). Sustained maneuver requirements were not specified. A minimum weight solution was obtained for both designs with a wing area of 475 ft^2. The resulting approach speed performance of the canard configuration is 6 knots less than the tail configuration. A comparison at equal design approach speeds shows the canard aircraft is appreciably lighter as the landing speed requirement becomes more stringent. This analysis indicates that, when approach speed performance is the primary driver of design wing loadings, a canard configuration may be an attractive option to consider. The canard design was also found to be the lighter vehicle when sized to high levels of transonic maneuver (Fig. 12) or supersonic persistence (Fig. 13).

Conclusions

An attempt was made to bring to light the advantages of a canard-configured variable-sweep-wing aircraft. In this particular application, a canard arrangement provided substantial trim drag reductions relative to a conventional tail design, with up to a 30% improvement in supersonic lift-to-drag ratio. Canard upload-to-trim provided higher useable lift for carrier landings, including a powered-lift contribution from vectored thrust. Unconventional flight modes such as direct lift (canard plus wing flaps) and direct side force (differential canard plus rudder) are also possible.

These benefits are not without an attendant increase in technical risk, however. With wing flaps extended, the canard aircraft required longitudinal control augmentation via thrust vectoring to meet minimum nose-up control levels. Lateral-directional stability at moderate-to-high angles of attack was adversely influenced by the presence of the canard surface. Design solutions such as variable canard camber, expanded wing-sweep schedules, yaw thrust vectoring, and control system limiters would help to alleviate these stability and control concerns. The technological dichotomy between performance and risk is not new to aircraft designers: The marriage of a canard with a variable-sweep wing is a classic case of increased complexity to achieve greater capability.

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