Configuration Development of a Research Aircraft with Post-Stall Maneuverability

Stephen Ransom*
Messerschmitt-Bölkow-Blohm/Vereinigte Flugtechnische Werke, Bremen, Federal Republic of Germany

The configuration development of a small, highly maneuverable research aircraft is described. The aircraft, of delta-canard layout, is designed specifically to investigate the subsonic unconventional maneuver flight envelope, which includes direct-force and post-stall flight modes. Results from a low-speed wind tunnel investigation are presented, and their analysis shows that the inclusion in the layout of twin wing-mounted forward-swept vertical tail surfaces confers significant control and aerodynamic advantages.

Nomenclature

C_L = lift coefficient (stability axis)
C_D = drag coefficient (stability axis)
C_m = pitching moment coefficient (stability axis)
C_l = rolling moment coefficient (aircraft axis)
C_n = yawing moment coefficient (aircraft axis)
$C_{l\beta}$ = lateral stability (aircraft axis)
$C_{n\beta}$ = directional stability (aircraft axis)
$C_{n\beta\mathrm{dyn}}$ = dynamic directional stability parameter $C_{n\beta}\cdot\cos\alpha - I_z/I_x\cdot C_{l\beta}\cdot\sin\alpha$
I_z/I_x = yaw-to-roll moment of inertia ratio
α = angle of incidence
β = angle of yaw
ΔC_{lA} = rolling moment due to aileron deflection
ΔC_{mC} = pitching moment due to symmetrical canard deflection
ΔC_{lC} = rolling moment due to differential canard deflection
ΔC_{nC} = yawing moment due to differential canard deflection
ΔC_{mF} = pitching moment due to trailing-edge flap deflection
ΔC_{lR} = rolling moment due to rudder deflection
ΔC_{nR} = yawing moment due to rudder deflection
δ_A = aileron deflection
δ_C = canard symmetrical deflection
$\delta_{C\mathrm{Diff}}$ = canard differential deflection
δ_F = wing trailing-edge flap deflection
δ_{VF} = wing vent flap deflection
δ_R = rudder deflection
Λ = vertical tail sweep (positive—sweptback, negative—swept forward)

The center of gravity is at +30% of the mean aerodynamic chord

Introduction

FUTURE combat aircraft, especially those designed to fulfill the air-to-air role, are required to have an extremely high degree of maneuverability. This requirement demands improvements in known, and development of new, offensive and defensive maneuvers. With respect to the latter, recent investigations[1,2] have shown that direct-force mode and post-stall flight maneuvers offer additional operational advantages. There is little doubt that these extra capabilities are technically realizable, but it is not absolutely certain whether the system complexity incurred is financially justifiable, or that the maneuvers are acceptable to the pilot and can be performed in a fully controlled manner. A small research aircraft has therefore been considered specifically to evaluate the subsonic unconventional maneuver envelope.

This paper describes the development of the research aircraft as determined from the results of low-speed wind tunnel testing of a 1/7-scale model in MBB/VFW's facility in Bremen and of a 1/13-scale model of a twin-engined variant at the DFVLR, Braunschweig. The models were tested at a Mach number of approximately 0.2, a Reynolds number of approximately 1×10^6, over incidence ranges of from −5 to +70 deg (VFW) and from −5 to +40 deg (DFVLR), and at angles of yaw between −10 and +10 deg. The tests at Braunschweig compared wing-mounted forward-swept, straight, and sweptback vertical tail surfaces. In addition, flow characteristics were examined using oil and smoke visualization techniques. The models were unpowered.

Research Aircraft Program and Specification

The ultimate aim of the research program is the flight demonstration and evaluation of what are currently termed unconventional maneuvers. These include direct lift, direct side force, and fuselage aiming modes and post-stall modes (i.e., flight at angles of incidence greater than that at which maximum lift is obtained). The maneuvers are to be achieved using conventional control inputs and, if possible, conventional control surfaces acting in the accepted manner. Full control over the incidence range −10 through +70 deg and angles of yaw between −10 and +10 deg is required.

The aircraft is solely for subsonic research and has a speed limitation of Mach 0.8 at medium altitude. It has a low wing loading at a simulated combat mass and is powered by a reheated engine, which has the potential for modification to accept vectorable nozzles and provide sufficient thrust to give a thrust/weight ratio in excess of unity. The aircraft's takeoff mass is 3500-4000 kg. The configuration is aerodynamically unstable.

Configuration Development of Research Aircraft

The primary aim of the research aircraft feasibility study was the development of a configuration which fulfilled the stability and control criteria specified for the conventional and proposed for the post-stall flight envelopes (Fig. 1).[1,3] A corollary to this aim was that any special control features, which might be needed for post-stall maneuvers, should not degrade the effectiveness or change the expected characteristics of conventional control surfaces.

Previous extensive studies by MBB and VFW showed that careful consideration would have to be given to the design and integration of the flying controls to avoid undue complexity of the flight control system. These studies, however, also identified the need for engines with vectorable, reheated

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*Project/System Engineer, Research and Development, Marine and Special Products Division.

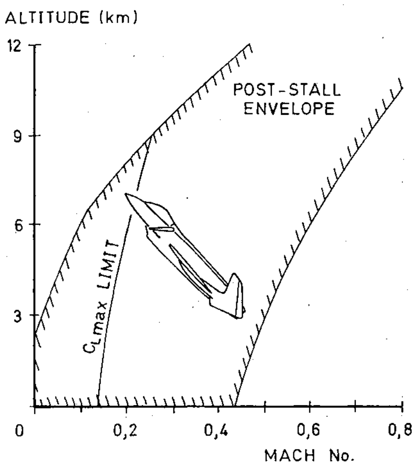

Fig. 1 Research aircraft flight envelope.

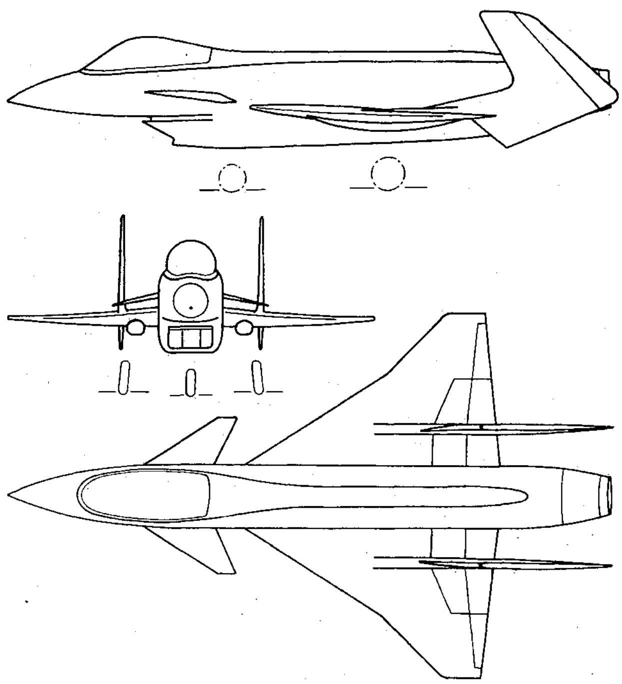

Fig. 2 Research aircraft configuration 1.

thrust, with which sustained post-stall maneuvers could be performed. In addition, they showed that control effectiveness would have to be improved substantially (the effectiveness of controls and high-lift devices tends to reduce to zero at very high incidences) and that lateral-directional stability needs to be enhanced to reduce maneuver departure effects and increase spin resistance.

Two approaches to the development of a suitable configuration were therefore adopted for the feasibility study. The first was to produce a design which relied solely on the aerodynamic characteristics of flying control surfaces and high-lift devices and then determine the minimum dynamic pressure at which the aircraft could be flown. The second was to supplement control surface effectiveness with thrust vectoring, so that the need for the latter could be assessed. The configurations selected are shown on Figs. 2 and 3. The basic canard-delta wing, chin intake layout of both aircraft was derived from configurations investigated by MBB and VFW[3,4] and by NASA.[5-7]

Each design is depicted with a vectorable nozzle. Configuration 1 is powered by a Rolls-Royce/Turbomeca Adour and incorporates a gimballed vector nozzle. Configuration 2 is powered by a variant of the Rolls-Royce/MTU RB 193-12 (originally the VAK 191B main engine), in which the forward pair of vector nozzles have been relocated in the vertical plane

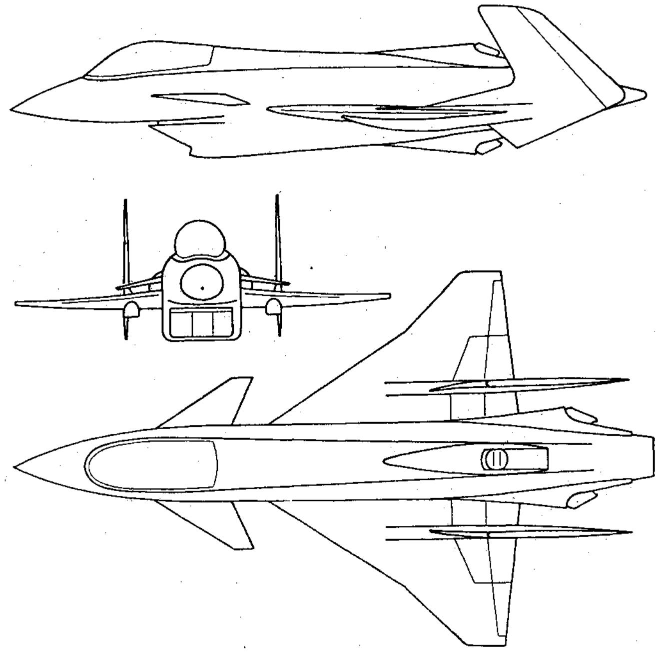

Fig. 3 Research aircraft configuration 2.

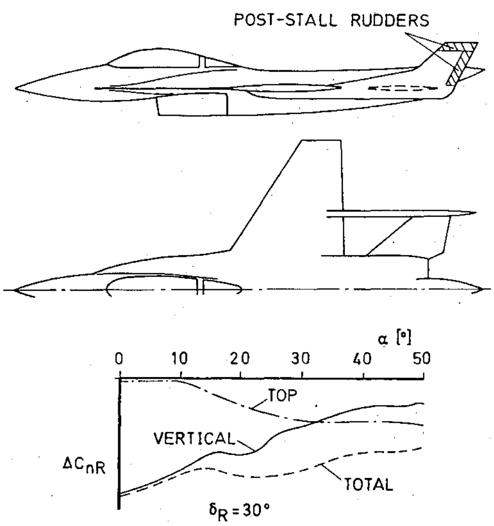

Fig. 4 Yawing moments produced by post-stall rudders of vented tail concept.

to provide a yawing moment when rotated, the rear horizontal pair of nozzles providing control in pitch. It is forseen that differential rotation of the nozzles can produce a rolling moment. The second design approach was viewed as a means of reducing the cost and development timescales of a vector nozzle for post-stall application by the adaptation of existing technology.

The choice of wing-mounted vertical tails and their spanwise location resulted from an amalgamation of ideas, which indicated large and worthwhile gains in rudder effectiveness:

1) The wind tunnel results were obtained with a straight wing/tailplane configuration (Fig. 4) in which twin vertical tails were located well aft of the wing's trailing edge and which, at high incidences, were fully exposed to the airstream. The vertical tails were fitted with post-stall rudders, i.e., a two-part rudder with mutually perpendicular hinge axes. It was proposed to operate the top rudder at incidences greater than 30 deg. The results show that the rudders provide a large increase in yawing moment up to very high incidences.

2) The wind tunnel results were obtained with a straked-delta wing configuration with wing-mounted vertical tails

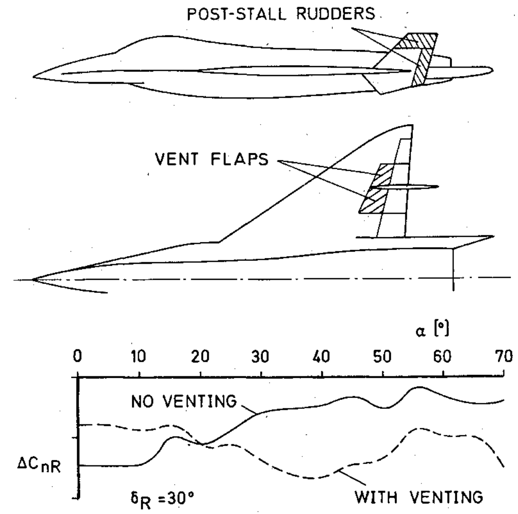

Fig. 5 Yawing moments produced by vented post-stall rudders of delta-strake concept.

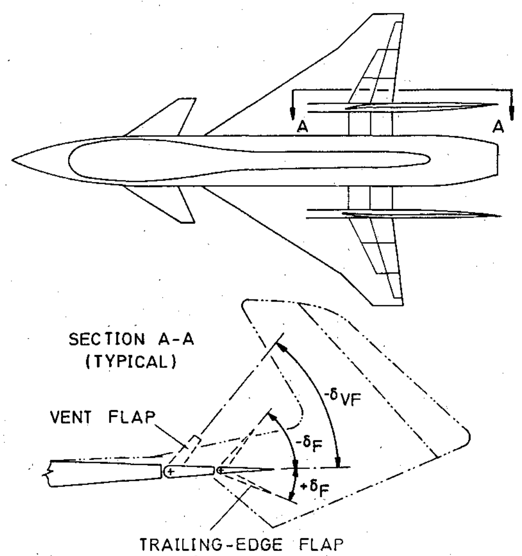

Fig. 6 Basic geometry of wind tunnel model tested at Bremen.

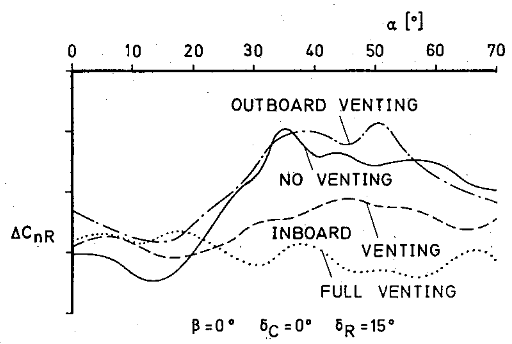

Fig. 7 The effects of various forms of venting on rudder effectiveness.

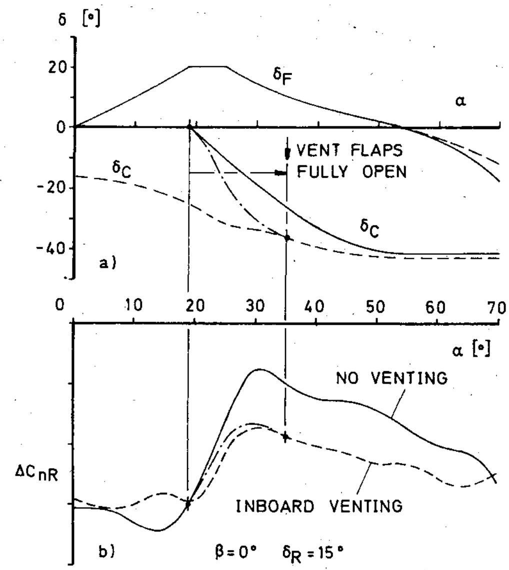

Fig. 8 a) Canard and wing trailing-edge flap deflections required to trim and b) the resultant trimmed aircraft rudder effectiveness.

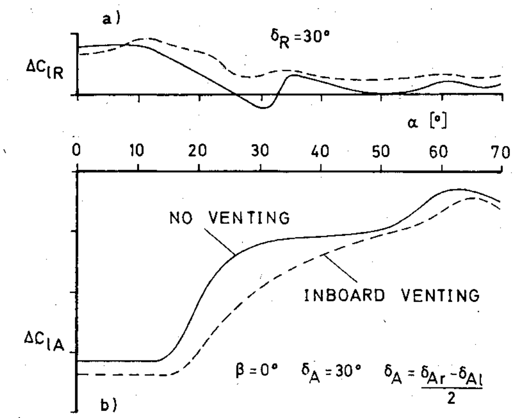

Fig. 9 Rolling moments produced by a) rudders and b) ailerons.

having post-stall rudders (Fig. 5). The configuration incorporates wing-mounted vent flaps, which were conceived as a means of controlling the aircraft in roll and yaw.[8] Opening of the vent flaps also fully exposed the wing-mounted vertical tails to the airstream at high incidences. Again, the results showed that exposing the rudders in this manner increased their effectiveness. These tests and others, in which vertical tails were located at and outboard of 50% exposed semispan, also revealed an unfavorable interaction between the wing leading-edge vortices and the vertical tails, leading to an unacceptably high interference drag.

3) Assessment of the results from flow visualization studies indicated that the effects of the wing's vortices could be minimized by placing the vertical tails at 25-30% exposed semispan. Information[9,10] obtained subsequent to the initial phase of the research aircraft study supported this conclusion and confirmed other aerodynamic effects observed during wind tunnel testing at Braunschweig.

The vertical tails of the research aircraft were therefore located at an inboard wing position and well aft of the wing's trailing-edge to minimize vortex interaction effects and fully expose them to the airstream at high incidences. The vent flap concept was retained only to maximize their exposure and not to provide means of roll and yaw control, which it was believed (and subsequently confirmed) could be achieved with the canard, ailerons, and rudders.

The selection of a forward-swept rather than a sweptback rudder was made with the knowledge that the loss of effectiveness of the latter was due to it becoming more parallel to the airstream as incidence was increased. The forward-swept rudder hinge line was selected to lie approximately normal to the airflow at high incidences and, at the same time, it provided a simpler solution than the two-part post-stall rudder proposal.

The more obvious combination of forward-swept rudder and rearward-swept vertical tail, although initially considered, was not chosen because it was believed that the unfavorable vortex interaction would still be present, the leading edge of the tail overlapping the wing's trailing edge. This combination also could not be relocated further rearwards to alleviate this problem, owing to constraints imposed by aircraft ground clearances required during takeoff and landing and by the need to keep the tail boom's length to a minimum to meet stiffness requirements. An acceptable compromise was found in the form of the forward-swept vertical tail. This arrangement was completed by the addition of strakes, introduced primarily to increase the stiffness of the tail booms but which, during the test phase at Braunschweig, were found to confer certain aerodynamic benefits on the complete configuration, and by extending the tail below the wing, to compensate the area of the upper part of it masked by the wing at high incidence.

Wind Tunnel Testing at Bremen

The research aircraft model configuration tested in the low-speed wind tunnel facilities at Bremen is shown on Fig. 6. Also shown is the relationship of the vent flaps to the vertical tails. The basic control surfaces comprise the canard, wing trailing-edge flaps, wing vent flaps and rudders. Wing leading-edge devices were not incorporated in the model.

The results from the preliminary investigation of rudder effectiveness with and without the vent flaps fully open are presented on Fig. 7. What can be clearly seen is, that above about 20 deg of incidence, rudder effectiveness is considerably improved by opening only the inboard or all of the vent flaps, the best results being achieved in the latter case. The general trends of the curves are valid for all angles of canard deflection. However, associated with the opening of the vent flaps there is a large nose-up pitching moment, which in the case of full venting, i.e., all flaps open, cannot be satisfactorily trimmed aerodynamically. Consequently, only the no venting and inboard venting concepts have been investigated in detail.

Initially, a simple concept using only canard deflection was considered for trimming the aircraft, but an investigation of the static and dynamic stability levels revealed that the aircraft would have unacceptable stall characteristics. This study also showed that directional stability was low and that the vertical tail surfaces needed to be increased in area by a small amount. The increase, incidentally, also slightly improved the aircraft's roll stability. Reexamination of the trim concept led to selection of one employing both canard and wing trailing-edge flap deflection. This method gave acceptable stability levels, reduced induced drag, and gave small but worthwhile improvements in rudder effectiveness. However, the use of the wing trailing-edge flaps for trimming was found to destabilize the aircraft slightly and, more importantly, considerably reduced their potential for producing a nose-down pitching moment. In addition, it was found in the case of no venting of the rudders that it was essential to reduce flap deflection from a positive to a negative setting to maximize rudder effectiveness (retention of a positive flap setting would have halved the rudder effectiveness). Clearly, careful optimization of the trim concept is required.

The canard and trailing-edge flap deflections required to trim the aircraft are shown on Fig. 8a, the maximum symmetrical deflection of the canard for trimming purposes being limited by practical considerations to about −40 deg. The canard may be deflected about the trim position symmetrically, or differentially, by 15 deg to provide elevator or roll/yaw control, in which case the maximum canard deflection is −65 deg. The inboard vent flaps are employed only above about 20 deg of incidence, the transition phase being completed at 35 deg of incidence. The flap angles are applicable to both the no venting and inboard venting studies. The resultant trimmed aircraft rudder effectiveness for a rudder deflection of 15 deg is shown on Fig. 8b. The dip in the yawing moment increments at about 30 deg of incidence is due to decoupling of the canard and wing vortices as the canard is rotated to trim the aircraft. The rudder yawing moment increment can be improved in this region by retaining zero canard deflection to a higher incidence, but means must be found to trim the additional canard pitching moment. Additional nose-down pitch control can be obtained with canard trailing-edge flaps set at a negative angle or with thrust vectoring. Associated with the rudder deflection, there is a small rolling moment (Fig. 9a) which can be readily trimmed by the ailerons (Fig. 9b). Note that inboard venting improves aileron effectiveness.

In accordance with a primary aim of the study, that control characteristics should not be changed by post-stall requirements, a check was made of the effects of inboard

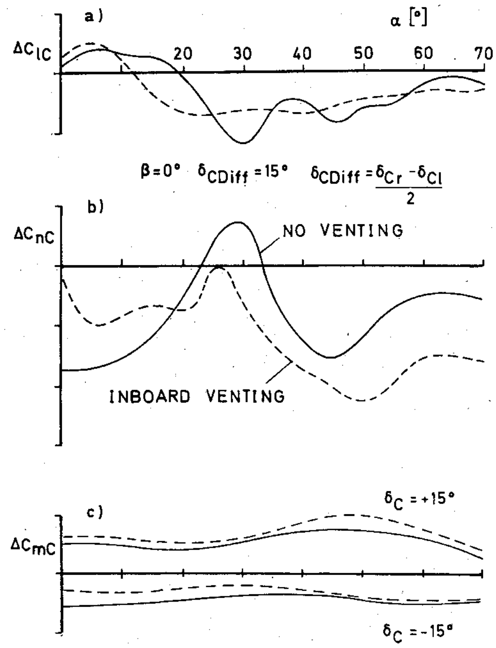

Fig. 10 Canard characteristics: a) rolling moment produced by differential deflection; b) yawing moment produced by differential deflection; and c) pitching moment produced by symmetrical deflection.

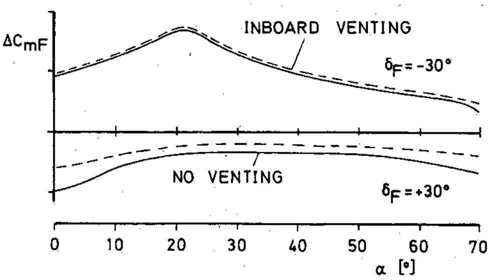

Fig. 11 Pitching moment increments produced by wing trailing-edge flap deflection after trim requirements have been taken into account.

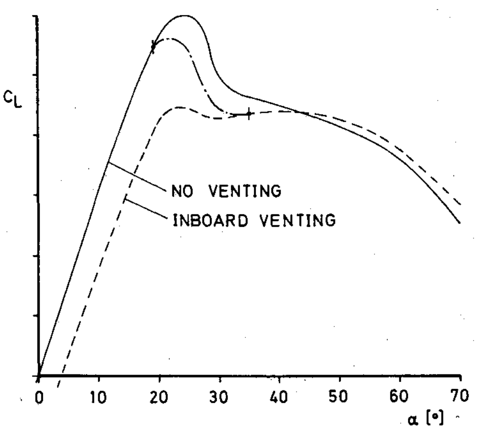

Fig. 12 Trimmed lift characteristic (no leading-edge devices).

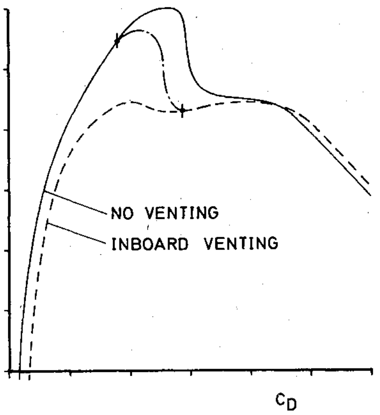

Fig. 13 Trimmed lift/drag polar (no leading-edge devices).

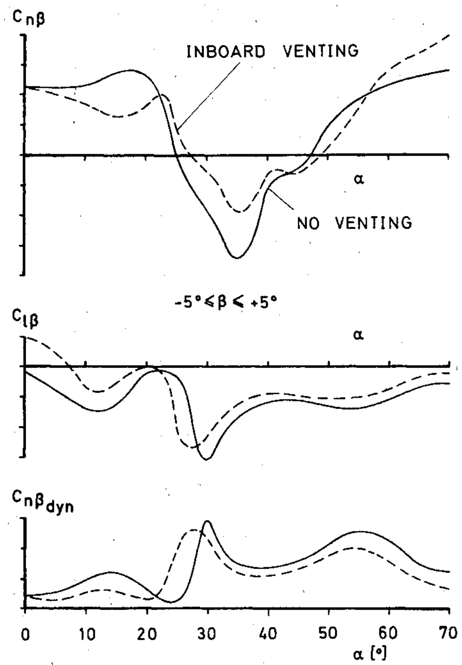

Fig. 14 Trimmed aircraft directional, lateral, and dynamic directional stability levels.

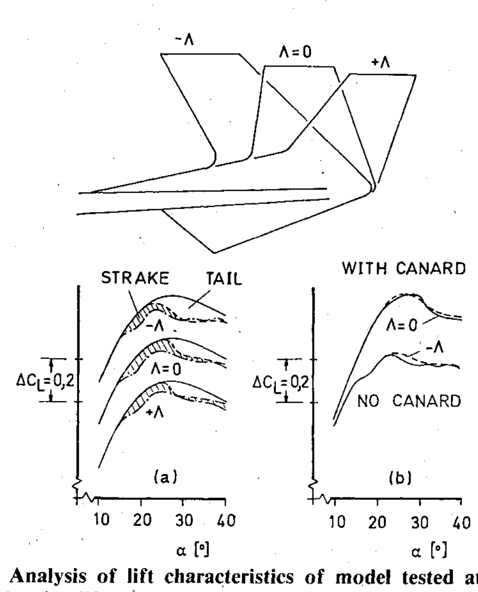

Fig. 15 Analysis of lift characteristics of model tested at Braunschweig showing lift losses due to the various components and forms of the vertical tails: a) canard off and b) the effect on lift of adding the canard.

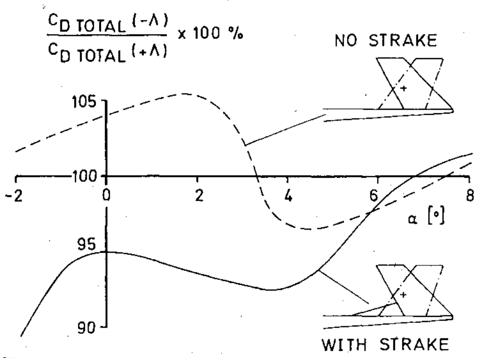

Fig. 16 Total drag comparison of configurations with forward- and aft-swept vertical tails (equal vertical tail volume ratio).

venting on the control function of the canard and wing trailing-edge flaps. In general, it was found that the shape of the characteristic was unaltered. However, venting was found to 1) reduce the rolling moments and increase the yawing moments generated by differential canard deflection at incidences higher than about 25 deg (Figs. 10a, and 10b); 2) slightly reduce the canard's effectiveness to produce a nose-down pitching moment (Fig. 10c); and 3) considerably reduce positive flap effectiveness (Fig. 11). In fact, positive flap deflection in the presence of venting was found to produce negligible nose-down moments at high incidences, the residual moment shown on the figure being due solely to flap deflection outboard of the vertical tails. This result also indicates that the inboard flap is an effective control.

The trimmed lift and drag polars are presented on Figs. 12 and 13 and show that inboard venting has only a small effect at high incidences. The research aircraft's lateral and directional stability levels are shown on Fig. 14, and, as can be seen, inboard venting has a beneficial effect on static directional stability over the incidence range 23-43 deg and on roll stability only between 23 and 28 deg. In general, inboard venting has a degrading influence on roll stability. The reader is reminded that the vent flaps, if employed, are open only above an incidence of about 20 deg. The dynamic directional stability characteristic is presented to give an indication of the susceptibility of the aircraft to directional departure. Based on published data,[11-13] it would seem that the aircraft could have acceptable stall characteristics with no yaw departure tendency, providing the stall is not prolonged in the critical region (at about 25 deg incidence). It should be noted that the model from which these results were obtained did not incorporate any wing leading-edge devices, which could improve the stall characteristic.

Wind Tunnel Testing at Braunschweig

The tests conducted at Braunschweig included a comparison between forward-swept, straight, and sweptback wing-mounted vertical tails of the same volume ratio. An analysis of the results obtained with no canard present showed clearly the contributions of the various components of the vertical tails to the lift losses known to result from mounting them on the wing (Fig. 15, lift curves staggered for clarity). The largest loss of lift was produced by the forward-swept tail without its strake, but the addition of the strakes brought the maximum lift generated to almost the same value in all cases, indicating that the strake had a more degrading effect on the straight and sweptback tails. The addition of the canard, however, produced a more favorable interference effect in the region of maximum lift with the forward-swept vertical tail configuration.

A comparison of the drag data obtained with the forward-swept and sweptback vertical tail configurations revealed that the former layout could give a reduction of about 5-6% in the total aircraft drag relative to a sweptback tail arrangement (Fig. 16). The gain is at the low incidences normally flown in

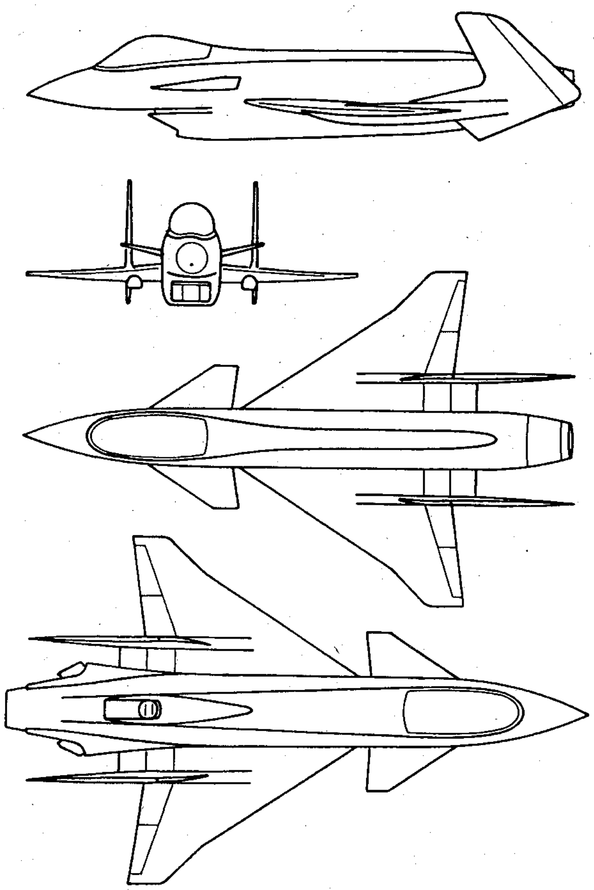

Fig. 17 Developed research aircraft configurations.

cruise conditions. Particularly noticeable is the beneficial effect of the strake.

Developed Research Aircraft Configuration

The developed forms of the research aircraft configurations incorporating the results of the Bremen and Braunschweig wind tunnel testing are shown on Fig. 17. The most noticeable differences between them and their original layouts (Figs. 2 and 3) are to be seen in the enlarged canard and the wing trailing-edge profile. Both of these features have been introduced to improve pitch-down control and, in the case of the stepped trailing edge, also to improve the wing's structure and lateral stiffness of the vertical tail booms. In addition, the canard's dihedral has been changed from a negative setting to a positive one, this alteration being found generally to improve the aircraft's aerodynamic characteristics as well as providing the aircraft with side force maneuver capability without having to resort to the use of a vertical canard installed below the intake.

The wind tunnel tests showed that the original vertical tail geometry could be retained, but that its area needed to be increased slightly. The revised inboard flap and vent flap geometry was found to have an insignificant influence on the rudder effectiveness. The wind tunnel results also indicated that, at high incidences, the canard's yaw and roll effectiveness could be coupled with those of the rudder and aileron, respectively, to provide even more effective control of the aircraft in this region and about those axes.

Conclusions

The feasibility study of the delta-canard research aircraft configuration with wing-mounted forward-swept vertical tail surfaces revealed the following:

1) The forward-swept vertical tail installation has lower interference drag at low incidences than a sweptback vertical tail layout. This drag component may be reduced further by the addition of strakes to the forward-swept tail.

2) The lift loss associated with the canard-off wing-mounted tail configurations is largest (by a small amount) for the forward-swept tail, but the addition of the canard has a more positive lift interference effect on this tail surface than on the configuration with straight or sweptback vertical tails.

3) Stability characteristics are dependent on the method of trimming the aircraft. The characteristics for the trim concept, presented here, which uses the canard and the wing trailing-edge flaps, are considered acceptable and capable of improvement by the addition of wing leading-edge devices. The introduction of inboard venting of the vertical tail has a beneficial influence in the region of the stall and a small but not seriously degrading influence at very high angles of incidence.

4) The twin forward-swept rudders provide good yaw control for conventional flight and for post-stall flight, particularly when they are more fully exposed to the airstream by opening the vent flaps at high angles of incidence. The rudder yawing moment characteristic is affected by both the canard and the wing trailing-edge flap deflections. The effects resulting from the canard may be minimized by retaining zero canard deflection to as high an incidence as practicable. Positive flap deflections degrade rudder effectiveness, but this is partly restored when vent flaps are deployed; negative flap deflections improve the rudder characteristic at high incidences.

5) The inboard venting concept (applicable only to incidences greater than about 20 deg) improves aileron effectiveness but has a very degrading effect on the trailing-edge flap nose-down pitch control function. The use of wing flaps for both trimming and elevator control functions limits their ability to generate nose-down moments. This capability is considerably reduced if the venting concept is employed and therefore is regarded as a critical design point in the consideration of how the aircraft may be controlled in pitch at very high incidences. Solutions to this problem may be found by increasing the canard area, adding trailing-edge flaps to the canard and/or reducing the stability margin to one less negative, or using thrust vectoring.

6) Differential canard deflection (primarily investigated in connection with side force maneuvers) could be used at high incidences to supplement aileron and rudder control functions. It should be noted that in these cases, the application of inboard venting slightly reduces the rolling moments and significantly increases the yawing moments generated by differential deflection of the canard surfaces.

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