TAIL VERSUS CANARD CONFIGURATION
AN AERODYNAMIC COMPARISON WITH REGARD TO THE SUITABILITY FOR FUTURE TACTICAL COMBAT AIRCRAFT

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Abstract

Extensive experimental and theoretical research work on tail and canard configurations has recently been done at Dornier, considering the requirements for a future tactical combat aircraft.

Tail and canard configurations, which were designed for the same tactical requirements, are compared. This comparison leads to the conclusion that the canard configuration cannot be regarded superior to the tail configuration, neither with regard to zero-lift drag at supersonic speeds nor with regard to lift-dependent drag at subsonic and supersonic speeds.

Furthermore, severe problems must be expected regarding lateral and directional stability at high angles-of-attack for a canard configuration.

It turns out that those problems do not occur or are easier to handle with tail configurations.

I. Introduction

Extensive experimental and theoretical research work on aft-tail and canard configurations has recently been done at Dornier, which allows a comparison of the suitability of both concepts for future combat aircraft. In this presentation the comparison of the two concepts being optimized to a certain extent for the same design goal is demonstrated, regarding mainly the aerodynamic point of view.

The comparison of the two concepts will be developed as follows (figure 1):

- Show basic requirements for a typical combat aircraft
- Show inherent aerodynamic qualities as:
  - o lift-dependent drag at subsonic speed
  - o lift-dependent drag at supersonic speed
  - o zero-lift drag as a function of Mach number
- Show behaviour at high angles-of-attack
- Show trimmable maximum lift
- Show consequences with respect to the suitability of the two tail concepts for a future combat aircraft

The comparison of lift-dependent drag and maximum lift is based mainly on wind-tunnel measurements. The zero-lift wave drag was calculated theoretically and increased by a correction factor derived from wind-tunnel tests.

II. Basic Requirements

To compare the two concepts basic requirements are defined, which are appropriate for a future combat aircraft. These requirements chosen for the aerodynamic comparison are shown in figure 2:

- High sustained turn-rate at subsonic speed. This demands in principal low lift-dependent drag coefficients and an appropriately large wing span.
- High instantaneous turn-rate at subsonic speed, for which a high trimmable maximum lift coefficient and a large wing area are needed.
- High SEP (specific excess power), which means low subsonic and especially low supersonic zero-lift drag.

  This demands:

  - o Small wetted surface (small wing, empennage, fuselage, etc.) to reduce skin friction drag.
  - o Low aspect ratio of the wing, slender configuration and well-designed cross-section distribution to reduce zero-lift wave drag at supersonic speed.
- High sustained turn-rate at low supersonic speed, which depends on low zero-lift wave drag, low lift-dependent drag coefficients and an appropriately large wing area.
- High acceleration potential around the axes: In this comparison the configurations are designed for the same pitch-down recovery acceleration at high angles-of-attack.

As may be seen from this list the design characteristics demanded for the different requirements are contradictory to each other, so that an optimum configuration will be a compromise.

III. Typical Features of the Two Concepts

When designing and optimizing a combat aircraft as a canard or an aft-tail configuration respectively typical features seem to be connected to the tail concept. Some of these are shown in figure 3:

- The size of the canard is smaller (about 5 to 8 % of the wing area) than that of an aft-tail, which will have an area of about 10 to 16 %.
- The fuselage length of a canard configuration seems to be somewhat shorter than that of an aft-tail configuration. The reason for this is that the needed tail efficiency is a function of the fuselage length when regarding

pitch acceleration. Therefore the larger and more effective aft-tail allows on one side a longer fuselage, but on the other side an aft-tail configuration needs a longer one. Because of the heavy engines in the aft-body and the wing shifted more forward due to the tail a longer forebody is demanded to get the center of gravity well positioned. A canard tends to have a shorter fuselage because of its lower tail efficiency.

- The distribution of the cross-section areas being one of the variables supersonic wave drag depends on shows a typically different form for the two concepts. For a canard configuration it is possible to get a more optimum area distribution. On the other hand the aft-tail is at a position, where the cross-section of the fuselage cannot be reduced because of the engines. Therefore an aft-tail configuration has an area distribution, which has too much cross-section area at the aft part to be optimum. But as already mentioned above the supersonic wave drag is a function of the slenderness too and further also a function of the type of engine, inlet, nozzle exit and many other factors. There seem to be two typical features of the two concepts whose influence on supersonic wave drag is contradictory:

  The aft-tail configuration having a longer fuselage and a smaller wing area, (as will be shown later) is more slender than the canard configuration, which has a better area distribution. Hence it is impossible to determine in advance, what concept will be better with respect to wave drag. More detailed design work has to be done to get an answer.

Other differences in the configurations shown in figure 3 as type of wing planform, single or twin vertical tail respectively, form of the inlet, etc. are thought to be not directly connected to the tail concept.

IV. Lift-Dependent Drag

Subsonic Speed

To get the best compromise between sustained and instantaneous turn-rate at subsonic speed on the one side and sustained turn-rate, specific excess power at supersonic speed on the other, it is advantageous to destabilize the configuration.

It cannot be shown here by what mechanism the coefficient of the lift-dependent drag C_{DL} is affected by the static margin, but one can state that a destabilisation improves this value in every case. The static margin however is not the only value which affects C_{DL}. The effectivity of the trim devices - especially the tail - has a large influence too.

To get the pure tail-effect for a direct comparison between canard and aft-tail, the measured increments in C_L, C_D, and C_m (as a function of α, δ_F, δ_T) due to both tails having a typical size (Canard area: 6,3 %; aft-tail area: 16 %) were added to the measured coefficients of one tailless configuration. In this manner the aerodynamic coefficients of an aft-tail and a canard configuration were constructed having only one different component: that is, the type of the tail. Figure 4 shows the results of this calculation in lift-dependent drag C_{DL} for subsonic speed. In this figure C_{DL} is reduced to the so-called "K-factor". This factor for both configurations and for the tail-off configuration is plotted as a function of static margin (SM) for a lift coefficient, which is essentially that at the sustained turn-rate.

The smaller the K-factor, the more efficient is the configuration and hence allows a smaller wing area.

Figure 4 shows the following:

- The K-factors of the canard configuration are worse than that of the aft-tail configuration.
- At high instability the difference in K-factors is quite small.
- The dependency of the K-factors on static margin is much smaller for the aft-tail than for the canard configuration.

The reason for this difference may be seen from the following facts:

- Firstly, for the aft-tail configuration the aerodynamic center is shifted aftward by the tail and by the canard configuration forward. This results in the effect, that for the same static margin the center of gravity of the aft-tail configuration is more aft relative to the wing than that of the canard configuration, so that the lever arm between center of gravity and aerodynamic center of the trailing-edge flaps is different. In consequence of a shorter lever arm the flap-down deflection for an unstable design and hence the lift due to flaps is larger. This has an advantage, because the main losses in lift-dependent drag of such wings come from the leading-edge and thus depend on angle of attack. Therefore it is better to reduce lift depending on angle-of-attack and get more lift from the flaps. That means, a center of gravity being more aft relative to the wing has some advantage.
- Secondly, tests have shown that the canard is a very poor trim device: Its optimum deflection is - independently of canard-size - essentially a zero deflection, which means that an optimum canard acts almost like a fixed wing strake. Consequently the K-factors are slightly worse than those of the tailless configuration because the lever arm of the trailing-edge flaps is increased by the canard. The same effect is shown also by large wing strakes. The conclusion is: the larger the canard the worse is the K-factor to be expected at one static margin.

The better K-factors of the aft-tail configuration permit a smaller wing when designing for the same maneuver performances (figure 5).

Supersonic Speed

To compare the lift-dependent drag at supersonic speed one has at first to look at the aerodynamic center $X_{a.c.}$ as a function of Mach number.

Figure 6 shows this dependency and, added to the curve for the wing-body combination the tested shifts due to canard or aft-tail respectively. The following remarks are important:

- Although the size of the canard is much smaller than that of the aft-tail, the shift in aerodynamic center due to the canard is much larger at low Mach number. The reason for this is that the canard is in the upwash and the aft-tail in the downwash of the wing.
- Near M = 1.0 the influence of both "tails" on aerodynamic center is much reduced. The influence of the aft-tail becomes practically zero (slender-body theory, applicable at M = 1.0!).
- At supersonic speeds the aerodynamic center of the canard configuration becomes essentially constant, and that of the aft-tail configuration, with tail fixed, goes very far aft so that the configuration becomes very stable. Sometimes it is believed that this high stability is a big disadvantage of the aft-tail concept at supersonic speeds. But that is not true, because as a first "optimization" it is possible to unload the aft-tail so that its "effective aerodynamic center" is that of the wing-body combination. Hence at supersonic speeds one has to expect essentially the same effective stability for both tail concepts.

The K-factors for a supersonic Mach number (here: M = 1.3) are shown in figure 7. Again the aft-tail configuration has a lower lift-dependent drag coefficient than the canard and the tailless configuration. The difference between them is larger for lower instability.

V. Zero-Lift Drag C_{Do}

As mentioned above the canard concept allows a somewhat shorter fuselage (this means less skin-friction drag) and a more optimum cross-section area distribution (less wave drag). The aft-tail configuration comparably needs a longer fuselage but allows smaller wing area, which reduces skin-friction drag and wave drag too.

So it is very difficult to show the superiority of one concept over the other one. The most realistic comparison, resulting from an optimisation of both concepts for one design goal, can be seen in figure 8. There are still differences between the two designs, which are not related to the tail concept (most important difference: type of the vertical tail). But their influence was thought to be not decisive for the comparison.

Figure 8 shows that there seem to be no principal advantages for one special tail concept. A superior overall zero-lift drag would rather be the result of an intelligent refinement, whichever configuration is adopted. It should be noted that the shorter and therefore blunter canard configuration shows an optimum drag at one distinct Mach number due to an optimum cross-section distribution, which is only valid for this one Mach number, whereas the more slender aft-tail configuration having a worse cross-section distribution shows better overall performance. This is observed for other canard and aft-tail configurations too.

VI. High Angle-of-Attack Behaviour

At high angles-of-attack one should distinguish four items of interest:

- Maximum possible instability due to recovery moment
- Pitch-behaviour
- Lateral and directional stability
- Maximum lift.

Maximum possible Instability

At high angles-of-attack there is a minimum pitch-down moment (called recovery-moment) for unstable configurations, which must not be too small (see figure 9), so that a certain minimum pitch-down acceleration at high α is guaranteed. Accepting the same acceleration for both concepts, the shorter fuselage of the canard configuration allows a smaller recovery moment than the aft-tail configuration. But because the canard is a very poor device to produce a pitch-down moment at high angles-of-attack, $C_{m\ rec}$ has to be provided mostly by the wing's trailing-edge flap alone. This results in an essential neutral stability of the wing-body combination. Therefore the device to destabilize the configuration is the canard: so instability is directly proportional to the canard size.

This may cause problems, because for high instability one needs relatively large canards, which may not be optimum with respect to other items, because canards show problems in lateral and directional stability due to bad interference effects.

For the aft-tail configuration maximum instability is of course a function of the tail size too. But at high α the tail doesn't cause problems related to lateral/directional motion so it's size is not critical. Furthermore the aft-tail is a good device for pitch-down moments, so that at very high angles-of-attack beyond α_{Cmrec} the pitch-down potential of this configuration is superior (see fig. 9). At low α both configurations have essentially the same pitch-down potential.

Pitch Behaviour

In the case of an unstable design pitch-up tendencies can cause severe problems[1]. An important variable to be looked for is the pitching moment derivative due to α, $\partial C_m/\partial\alpha$. This is one of the variables on which the needed reaction speed of the flight control system depends. One can show that there will be essentially the same problems at high speeds as at low speed. Hence one cannot allow a large increase of $C_{m\alpha}$ at higher angles-of-attack relative to that at low α, even for M = 0.

Concerning this problem the aft-tail configuration is superior, because when using a low tail, a pitch-down tendency is provided by the tail (figure 10). This is different when using a canard, which seems to cause a pitch-up slightly below C_{Lmax} (see figure 11) as long as the canard is not totally unloaded.

Lateral and Directional Stability

As long as angle-of-attack for maximum lift and the α-range above it is within the maneuver range of the aircraft, lateral and directional stability at high angle-of-attack is extremely important to the design. Time is too short to analyse the whole problem here. Hence only test-results will be shown.

There is no test of configurations having a close coupled canard known to the author that does not show a strong destabilisation due to the canard in rolling moment $C_{l\beta}$ within the critical α-region slightly above C_{Lmax} ($C_{l\beta}$ is the most important variable for stability at high α). This instability is definitely caused by the canard itself (figure 12). It seems to be a typical problem of too large vortex-augmentation systems that they destabilize in the α-region where vortex breakdown occurs. Too large wing strakes show quite a similar effect. Furthermore a canard can also cause strong nonlinearities in C_l over β as shown in figure 12. Without a canard the configuration shows a stable and essentially linear behaviour in C_l over β. With the canard on there is a strong instability (and possibility a hysteresis) at small β. At higher β the stability of the canard configuration is regained. Contrary to a canard an aft-tail does not affect the wing's vortex system, and therefore, it has no important influence on lateral stability at high α. Using an aft-tail it is possible to design the wing and the forebody of the fuselage in such a manner that excellent lateral stability is obtained (see figure 13).

Maximum Lift

Sometimes it is argued that all the problems at high α caused by a canard are irrelevant, because it is possible to avoid them by a total unloading of the canard. This is true: it is even possible to stabilize the configuration in lateral/directional motion by the canard, when deflecting it so far that it is downloaded.

But when doing so all the improvements due to a canard at high α are canceled too. Hence as long as the problems related to the canard at high angles-of-attack are not solved, the canard is a useless device at high angles-of-attack.

This has the most important consequences for maximum lift and hence for the instantaneous turnrate in comparison to an aft-tail configuration. Figure 14 shows the maximum trimmable lift coefficient of both configurations as a function of static margin. The tail off configuration ("aft-tail off" and "canard off" respectively) already differ in trimmable C_{Lmax}. This is due to the strake of the aft-tail configuration, a device which cannot be used on a canard configuration. The tail improves C_{Lmax} of both configurations. But on the one hand there are to be seen no essential problems related to stability in this α-region for the aft-tail concept so that this C_{Lmax} really can be used. On the other hand one cannot use the canard to improve C_{Lmax} due to stability problems so that for this configuration one has to expect usable C_{Lmax} in the order of those of the "canard off" configuration. As a consequence canard configurations need much more wing area to get a maximum lift comparable to that of an aft-tail configuration. But the increase of wing area is something one tries to avoid by destabilisation because of supersonic performance.

Even if the stability problems related to the canard could be solved there would to be expected no larger maximum lift inherent in a canard configuration than that of the aft-tail concept.

VII. Conclusions

It is not the intention here to pretend that a canard configuration is not feasible or an aft-tail configuration is necessarily the best compromise for a future combat aircraft. But from the standpoint of designing such an aircraft two things must be considered:

- There appear to be no advantages inherent in a canard configuration which make this concept more suitable for a design of a future combat aircraft than the "traditional" aft-tail concept.
- The aft-tail configuration is less critical with regard to high angle-of-attack problems as pitch-up problems or those related to lateral/directional stability. Therefore this concept shows less development risk.

VIII. Variables

AR	aspect ratio
$\bar{c}$	reference chord length
C_D	drag coefficient
C_{DL}	drag coefficient due to lift
C_{Do}	zero-lift drag coefficient
C_L	lift coefficient
C_l	rolling-moment coefficient
C_{Lmax}	maximum lift coefficient
$C_{l\beta}$	$\partial C_l/\partial\beta$
C_m	pitching-moment coefficient
$C_{m\ rec}$	recovery-moment coefficient
$C_{m\alpha}$	$\partial C_m/\partial\alpha$
C_n	yawing-moment coefficient
$C_{n\beta}$	$\partial C_n/\partial\beta$
D	drag
K	K-factor = $C_{DL}/C_L^2 \cdot \pi \cdot AR$
M	Mach number
q	dynamic pressure
S	wing area
SEP	specific excess power = (T-D)/W
SM	static margin = $(X_{a.c.}-X_{c.g.})/\bar{c}$
T	trust
W	weight
$X_{a.c.}$	X-position of aerodnyamic center
$X_{c.g.}$	X-position of center of gravity
α	angle-of-attack

α_{Cmrec}	α for C_{mrec}
β	side-slip angle
δ_c	canard deflection angle (positive: nose up)
δ_H	aft-tail deflection angle (positive: nose up)
$\delta_{N/F}$	deflection angle of leading- and trailing-edge flap (positive: flaps down)
ω	rotational velocity of sustained turn-rate

IX. References

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High Angle-of-Attack Aerodynamics

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Informal paper

CANARD VERSUS AFT-TAIL CONCEPT

development of analysis:

- basic requirements for a typical combat aircraft
- inherent aerodynamic qualities of the two concepts
- typical behaviour at high angles-of-attack
  trimmable maximum lift
- consequences with respect to the design of future combat aircraft

Fig. 1 Development analysis

CANARD VERSUS AFT-TAIL CONCEPT

Parameters for comparison:

- sustained turn-rate at subsonic speed
- instantaneous turn-rate at subsonic speed
- specific excess power (SEP)
- sustained turn-rate at supersonic speed
- acceleration around the pitch-axis

Fig. 2 Parameter for comparison

CANARD VESUS AFT-TAIL CONCEPT

Typical features:

	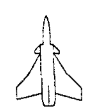	
• tail size	smaller (5÷8%)	larger (10÷16%)
• fuselage length	smaller	larger
• cross-sectional area distribution	more optimum	less optimum
• slenderness	less optimum	more optimum

Fig. 3 Typical features

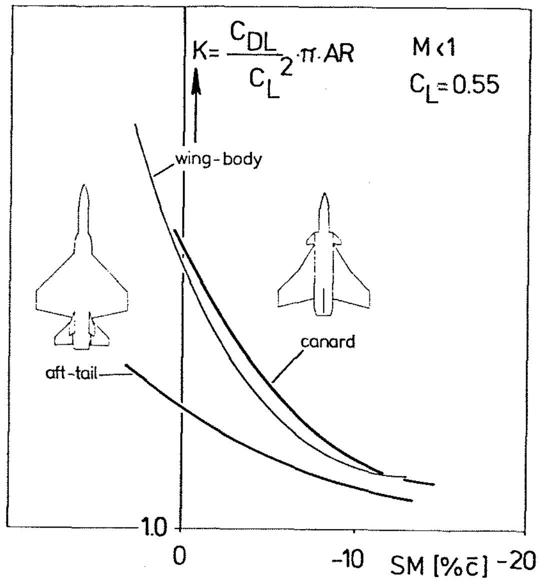

Fig. 4 K-factors at subsonic speed

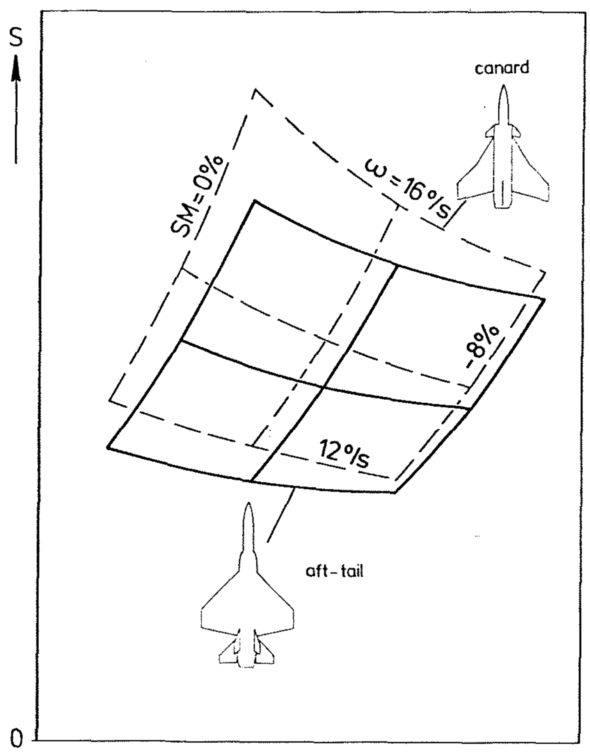

Fig. 5 Needed wing area

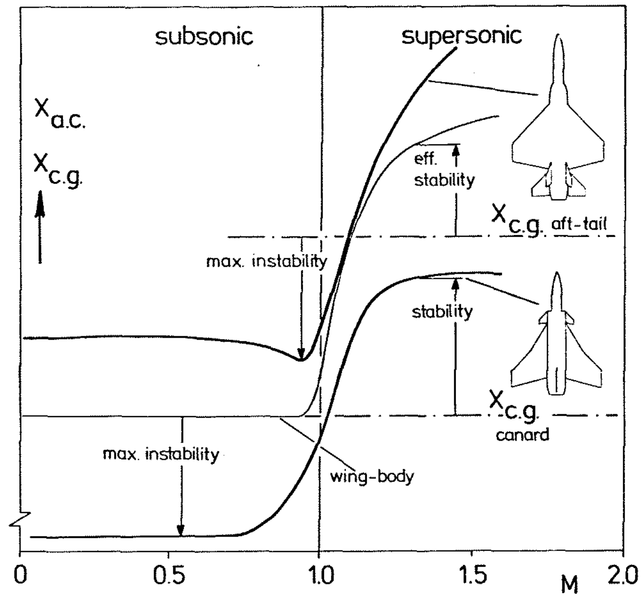

Fig. 6 $X_{a.c.}$ and $X_{c.g.}$

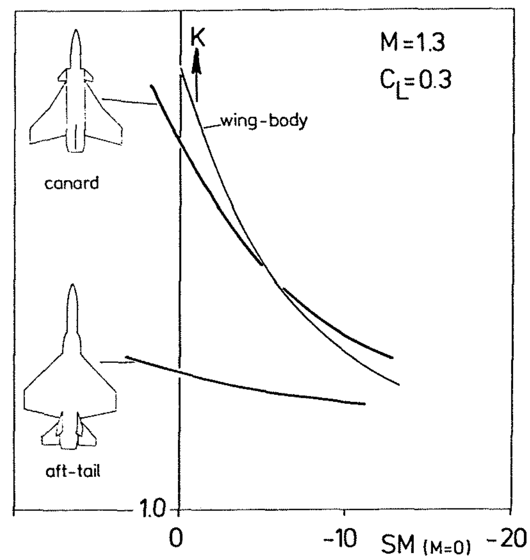

Fig. 7 K-factors at supersonic speed

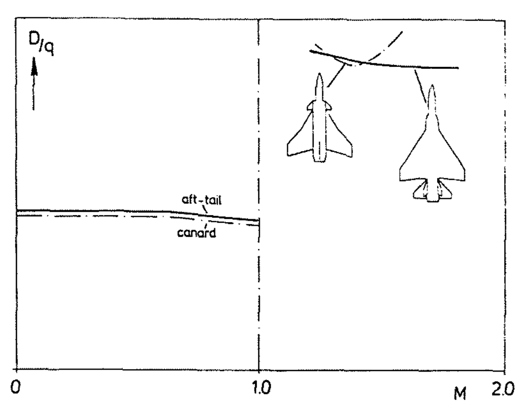

Fig. 8 Zero-lift drag

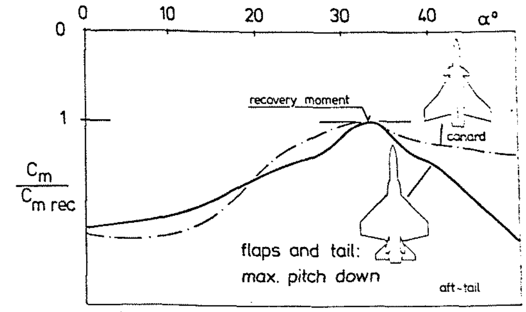

Fig. 9 Nose-down pitching moment

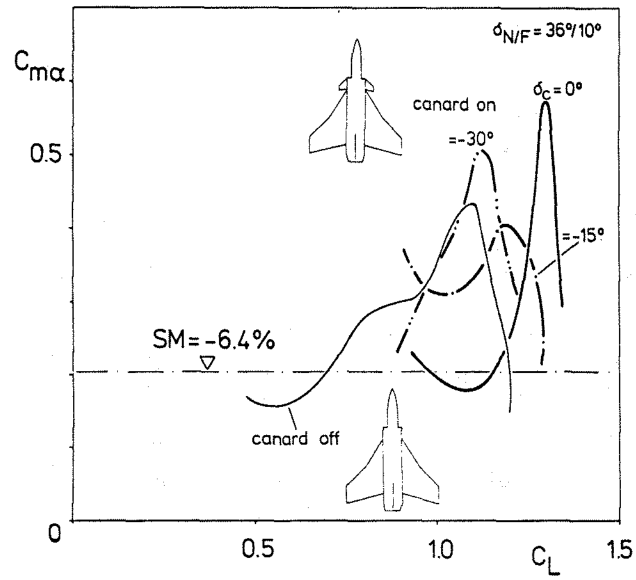

Fig. 11 Pitch behaviour; canard

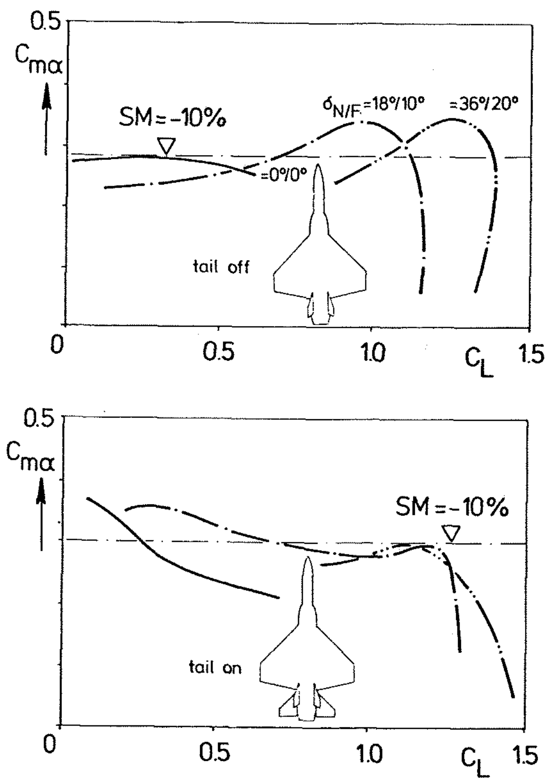

Fig. 10 Pitch behaviour; aft-tail

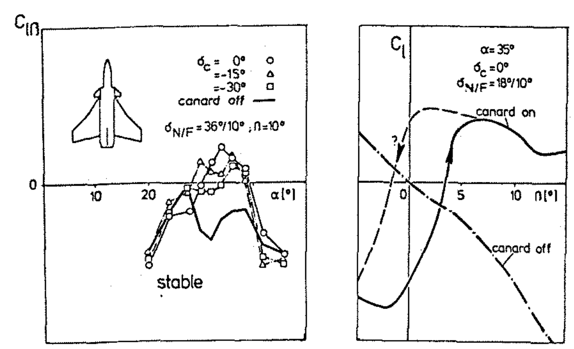

Fig. 12 Lateral stability; canard

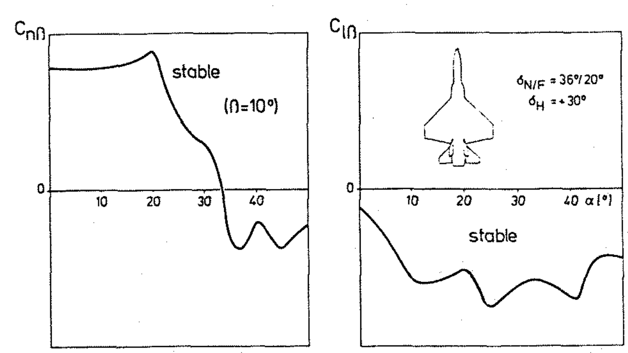

Fig. 13 Lateral/directional stability; aft-tail

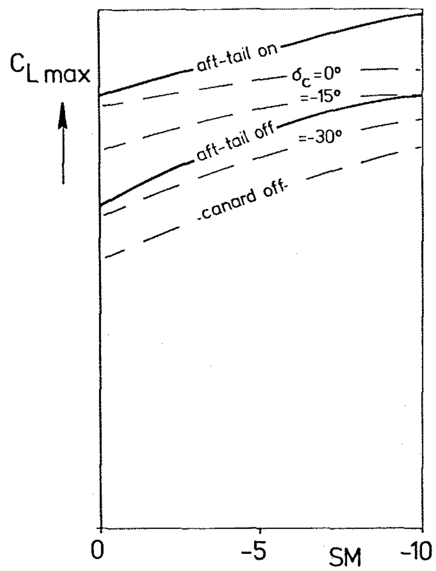

Fig. 14 Trimmable C_{Lmax}