9. High Angle of Attack Aerodynamics

9.1 Introduction

High angle of attack aerodynamics is inherently associated with:

- separated flows, and thus nonlinear aerodynamics
  - > one of the key aspects is the interaction of components, and in particular, vortex flows (vortex bursting is also an important effect)
- heavily dependent on wind tunnel testing
- connected with flight simulation to ensure good handling qualities
  - > this means that large amounts of data have to be acquired to construct the aero math model.

The key tutorials and surveys on high angle of attack aerodynamics were written by Chambers and Grafton,[1] and Chambers.[2] Typical high angle of attack concerns are:

General Aviation aircraft

- prevention/recovery from spins

  To improve spin resistance, consider the drooped outer panel (NASA LaRC) or the interrupted leading edge (NASA Ames)

  Do consider placing the vertical tail where it can get "good" flow during a spin, including inclining the rudder hinge line forward rather than aft. It will make it more effective. Also, placing a ventral strake ahead of the rudder, as seen on many GA airplanes, not only adds side area, but also produces a vortex at sideslip that helps maintain the entire surface effectiveness. Finally, **do not** use the Tail Damping Power Factor (TDPF) available in the old NACA literature. It is known not to work.

  Folklore has it that T-tail configurations may have a benefit: the vertical tail and rudder may not be blocked by the wake of the horizontal tail. This may or may not be true.

Fighters:

- resistance to departure from controlled flight
- ability to control aircraft at hi-α air combat maneuvering[3]
- allowance for unlimited α range (the F-16 requires an angle of attack limiter)
- requirement to be able to perform velocity vector rolls[4] (through inertial coupling, this adds additional nose down pitching moment requirement)
- perform the so-called Herbst maneuver (rapid change of heading, but also loses a lot of energy, so in a multiple engagement you may become a sitting duck for someone else).
- do fuselage pointing to allow missile lock-on and fire
- use of the control system to enhance maneuver capability
- enhance controls using thrust vectoring (possibly especially important for stealth a/c)

  Recent high angle of attach research aircraft: F-18 HARV (TV with vanes), X-31 (TV with vanes), X-29 (no. 2 had nose blowing)

- Supermaneuverability and aircraft agility are of current interest. This requires the use of dynamic measures to assess performance. Supermaneuverability seeks to exploit an unsteady flow effect, the fact that you can get higher C_{lmax}'s by so-called dynamic overshoot.

Transports:

As discussed previously in terms of basic transport configuration aerodynamics, the primary high angle of attack problem is the suppression and control of pitchup and avoidance of deep stall. The case study of the DC-9 development provides an excellent overview of the issues with the T-tail configuration and the stall issues in general.

9.2 Basic Aerodynamics of Hi-α

9.2.1 Longitudinal:

The basic aerodynamic characteristics are illustrated in Figure 9-1. This is the pitching moment curve. For modern airplanes the stability may not be a major issue (within reason), but the envelope defining the maximum nose-up and nose down moments that can be generated is critical. The minimum value of nose-down pitching moment is a critical condition.

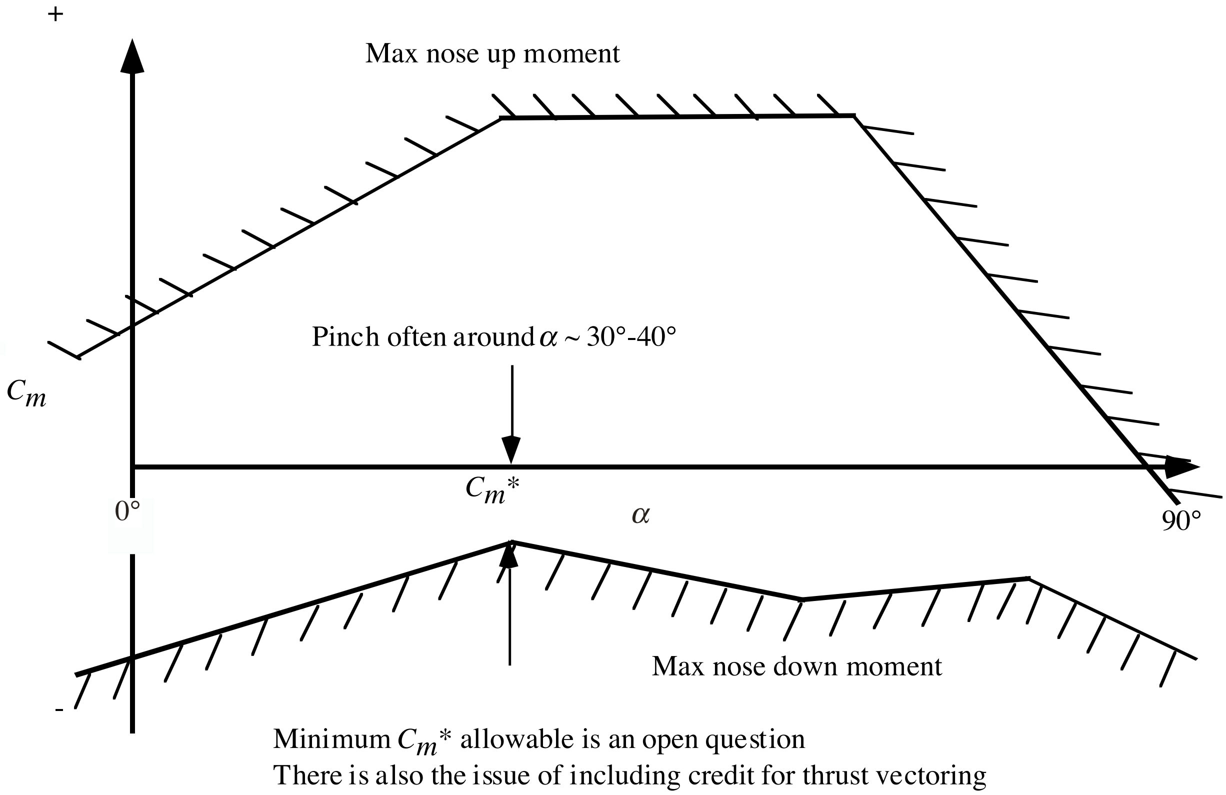


Figure 9-1. Typical example of pitching moment assessment chart.

Wind tunnel data for the F-16 contained in Figure 9-2[5] shows that for this *cg* location the F-16 is limited in angle of attack at which it can be trimmed to obtain $C_m = 0$. Thus the control system is designed to limit the angle of attack that the F-16 can reach to prevent the airplane from encountering a problem.

The following values of suggested design criteria for nose down pitching moment were developed by Marilyn Ogburn and John Foster at NASA Langley, supported by the Navy.[6] These are design goals for modern maneuvering aircraft.

	Pitch accel in 1st second (rad/sec^2)	Minimum pitch rate at 2 sec & after command input (deg/sec)
Desirable	-0.25	-24.0
Safety	-0.07	-5.0

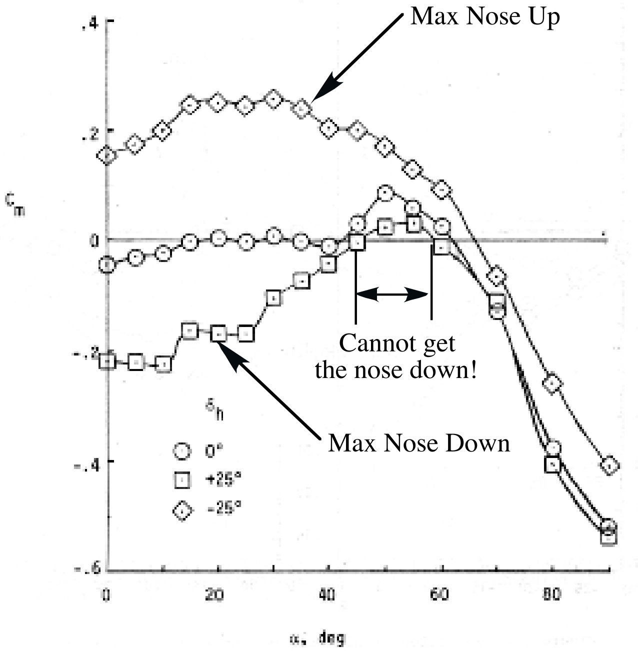


Figure 9-2. Pitching moment wind tunnel data for the F-16[5]

9.2.2 Lateral/Directional

The typical directional characteristics are assessed in terms of the directional stability, $C_{n\beta}$. Figure 9-3 provides the generic expectation, while Fig. 9-4 contains wind tunnel results for an F-5.[7] Initially the vertical tail provides the stability. However, at angles of attack where the wake from the wing prevents the tail from operating in clean flow the vertical becomes ineffective. At higher angles of attack the long forebody on modern fighters can be designed to provide direction stability.

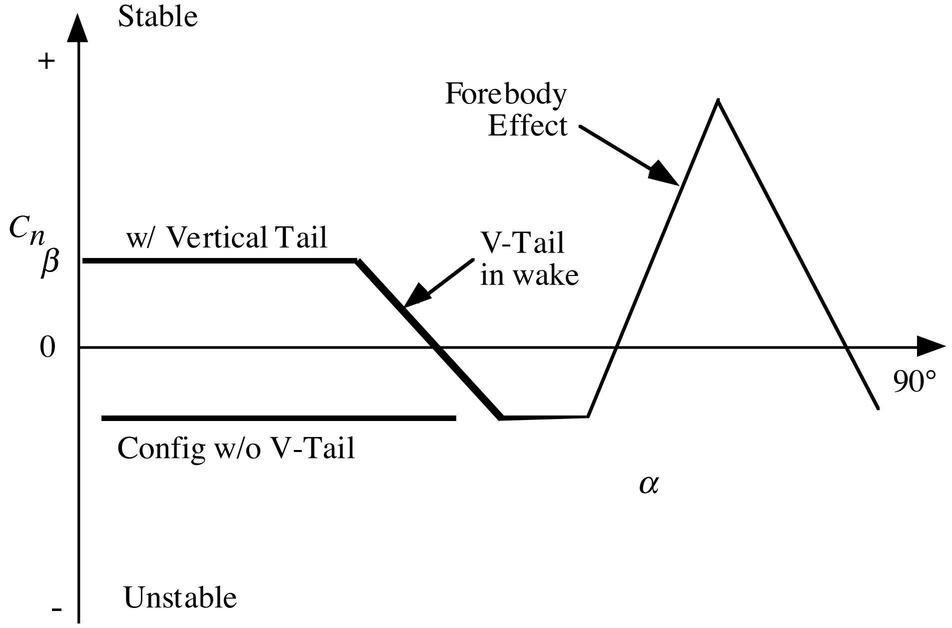


Figure 9-3. Generic directional aerodynamics characteristics

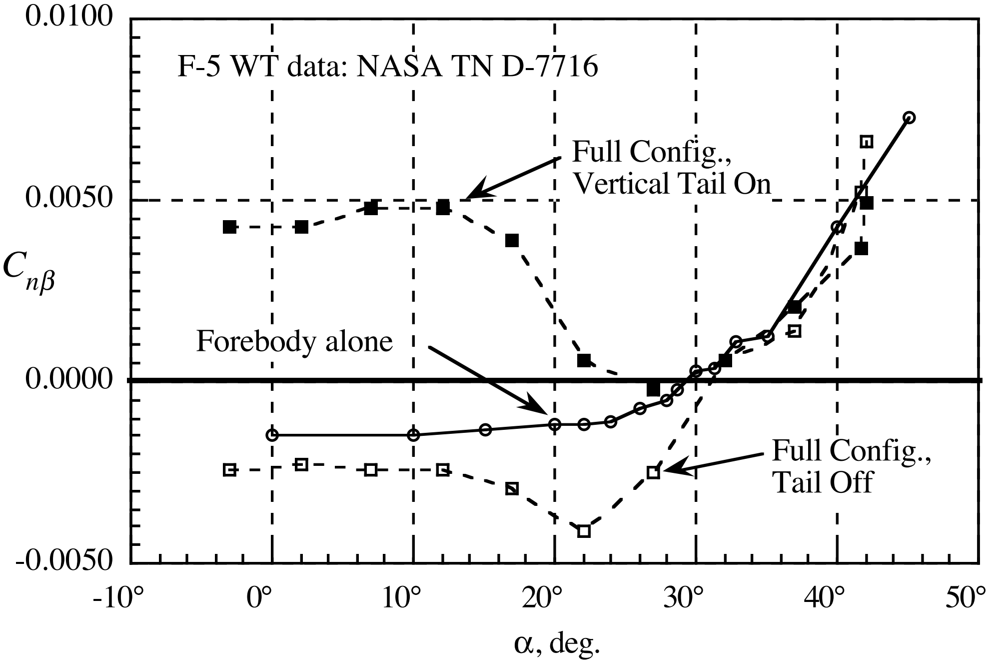


Figure 9-4. Directional characteristics of the F-5[7]

Figure 9-5. Shows the generic characteristics for lateral characteristics, which is examined in terms of $C_{l\beta.}$ Initially, wing dihedral or sweep will cause the stability derivative to decrease with angle of attack. However, for swept wing, asymmetric flow separation characteristics cause the curve to "break" and abruptly become positive. Figure 6 contains actual characteristics of an F-4, with the effects of the maneuvering slats, which are seen to be extremely beneficial.[8]

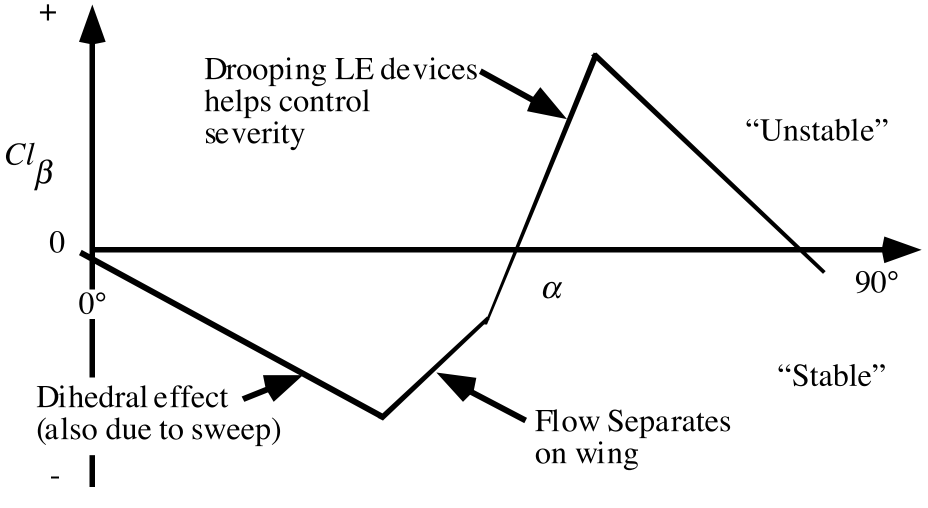


Figure 9-5.Generic lateral aerodynamic characteristics

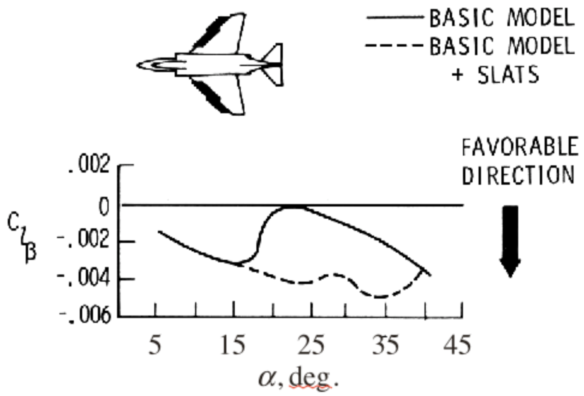


Figure 9-6. Lateral characteristics of the F-4, including the effects of the maneuver slats [8]

These characteristics are used to establish the basic lateral/directional static stability. One of the complications associated with canard aircraft is the wide variation in these characteristics with canard setting. The trailing vortex system from the canard interacts with the leading edge vortices of the main wing, forebody vortices and also the vertical tail. Thus the lateral/directional characteristics of canard configurations play a large role in deciding if a canard configuration is practical.
Recall that for classical static stability:

- directional stability (must be in the stability axis): $C_{n_\beta} > 0.0$
- dihedral effect (also promoted by wing sweep): $C_{l_\beta} < 0.0$

9.3 Flight Mechanics of Hi-α

Controllability of flight at high angle of attack can encounter several different types of problems.[9] arise. Here are some brief descriptions of terms you are likely to encounter.

Departure:	This occurs when the airplane departs controlled flight. It may develop into a spin.
Wing drop:	This is caused by asymmetric wing stall (or unstall) [**a roll-type problem**]
Wing rock:	The aerodynamic rate-damping moments become negative and the wing starts to oscillate in roll. This is associated with an interaction of the separated flow above the wing, typically the leading edge vortices that are above the wing.
Nose slice:	When the aerodynamic yaw moments exceed the control authority of the rudder, the airplane will tend to exceed the acceptable sideslip angle and depart through a yawing motion [**a yaw-type problem**].

The basic aerodynamic characteristics described above are often used to try to assess, at least approximately, how susceptible the aircraft is to departure. In reality, you also need dynamic aerodynamic characteristics, but these are usually not available early in the design process.

Some static derivative based dynamic criteria are available to provide guidance. Greer[10] provided a summary of directional data for numerous aircraft, as well as a very easy to read description of the departure problem as it changed from piston fighters to high-speed swept wing jet fighters.

> Quoting from Greer: "In the late 1940s low-aspect-ratio swept-wing fighter configurations began to emerge, and it soon became apparent that they would behave very differently at the stall than their predecessor straight-wing configurations. Whereas straight-wing configurations generally experienced a roll-off type of divergence at the stall because of one wing dropping before the other and unstable damping in roll immediately after stall, the swept-wing configurations began to show a directional divergence at high angles of attack." Thus, it appeared that both $C_{n\beta}$ and $C_{l\beta}$ were important. Again from Greer: "A theoretical analysis group headed by Leonard Sternfield, then of Langley, studied the problem and concluded that the divergences occurred when the C-term of the stability quartic became negative and they developed a simplified form of the C-term and called it $C_{n\beta_{dyn}}$, or the directional stability parameter. The derivation of this parameter is given in the appendix." Greer's report shows the correlation of various aircraft data with this parameter. The reasonable correlation showed that this parameter could be used to estimate when aircraft departure would become likely. Note that Lutze, *et al*[11] show how this parameter can be derived in very general terms. The discussion of $C_{n\beta_{dyn}}$ by Calico[12] is also useful.

9.3.1 C_n beta dynamic (actually, this may not be a real good predictor, only approximate[13]):

$$C_{n\beta_{dyn}} > 0$$

where:

$$C_{n\beta_{dyn}} = C_{n\beta}\cos\alpha - \left(\frac{I_z}{I_x}\right) C_{l\beta}\sin\alpha$$

> This is an open loop parameter

> Greer's suggested means to improve resistance to directional divergence included increasing the vertical tail size ($C_{n\beta}$) and using leading edge slats ($C_{l\beta}$). The vertical tail size was increased in the case of the F-100 aircraft. Just looking at pictures of the original design give the impression that the tail was too small. However, since the vertical tail loses effectiveness at high angle of attack, this by itself is not sufficient.

9.3.2 LCDP: the lateral control departure parameter, (this *is* a good predictor[13])

$$LCDP = C_{n\beta} - C_{l\beta}\left(\frac{C_{n\delta a}}{C_{l\delta a}}\right) > 0$$

- Negative values imply roll reversal. The pilot commands roll in one direction, and the plane rolls the other way!
- This is a closed loop parameter. To improve this value, the control sytem can be used to include the use of the rudder at high angle of attack. This can dramatically improve the value of LCDP at high angle of attack, and is known as an ARI, or aileron-rudder interconnect

Figures 9-7 and 9-8 show the lateral/directional characteristics of the F-16, together with $C_{n\beta_{dyn}}$ and LCDP. Figure 9-8 shows the significant effect the ARI has on LCDP.

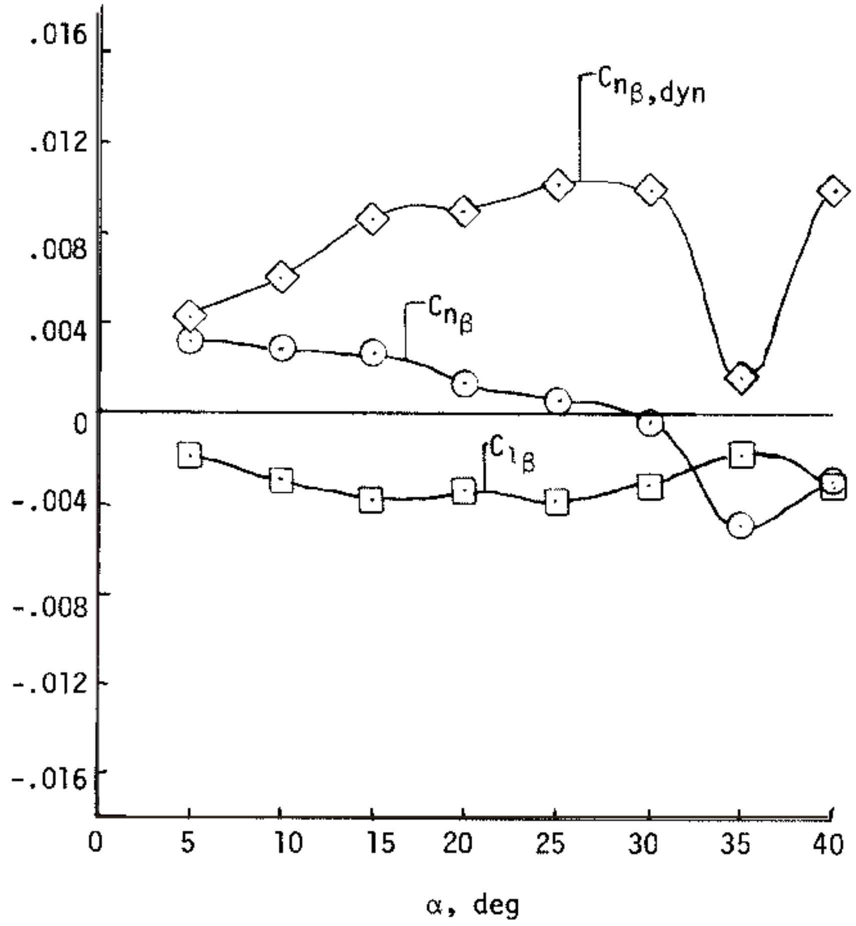


Figure 9-7. Static parameters and $C_{n\beta_{dyn}}$ (from Ref. 5)

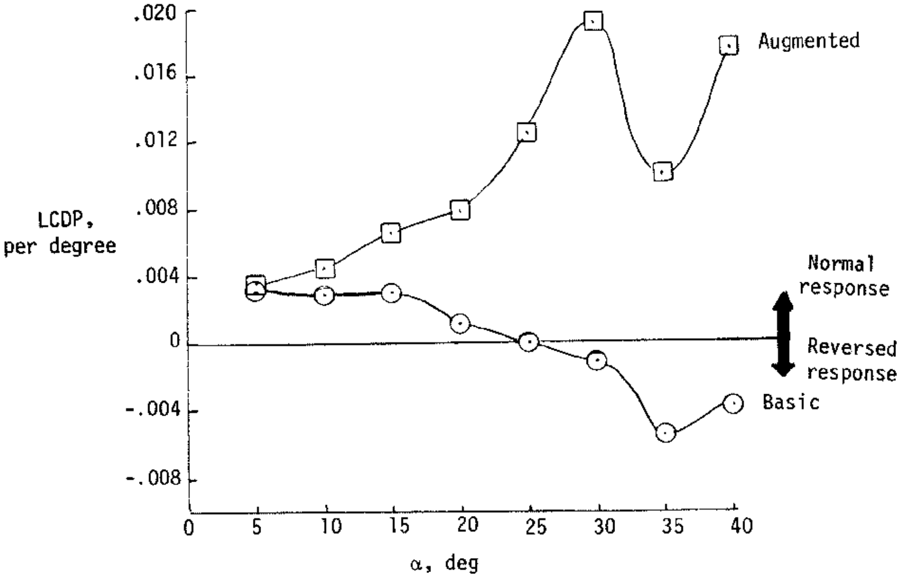


Figure 9-8. LCDP for the F-16 WT test data (from Ref. 5).

Some effort has been made to correlate the values of these parameters to define regions in which something can be said about departure characteristics. These parameters have been combined to suggest the best region to operate in the design space. The original chart is due to Weissman,[14] but Bill Bihrle added some more details,[15] and is given in Figure 9-9.

Other requirements:

- Dynamic derivatives: (generally from forced oscillation testing)

$C_{n_r} < 0.0$ (yaw damping) not too pro spin

$C_{l_p} < 0.0$ (roll damping) < 0 to prevent wing rock

9.3.3 The spin

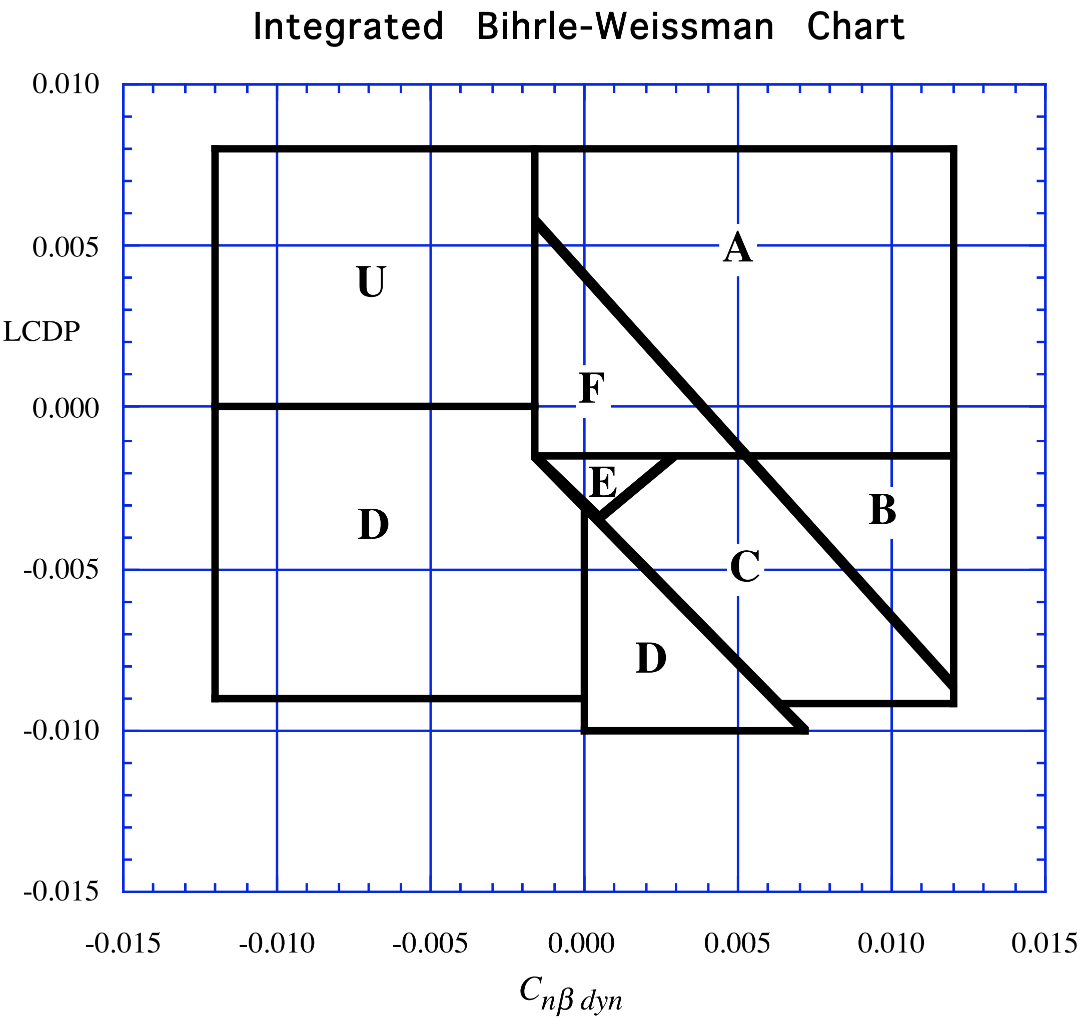
We haven't said much about spins. If the departure developes into a spin, there a few things that are known. First, the mechanics depend on the sign of the term $(Ix - Iy)$.

- If $(Ix - Iy) > 0$, the plane is said to be wing heavy (typically GA airplanes),
- If $(Ix - Iy) < 0$, the plane is said to be fuselage heavy (typically modern supersonic fighters),

Also, we have some rough guidelines to recover from a spin:

- If $(Ix - Iy) > 0$, ailerons are applied *against* the spin, elevator down
- If $(Ix - Iy) < 0$, ailerons are applied *with* the spin

A key survey on spins is again by Chambers,[16] and should be studied for further insight.



With following key:

A - Highly departure and spin resistant
B - Spin resistant, objectionable roll reversals can induce departure and post stall gyrations
C - Weak spin tendency, strong roll reversal results in control induced departure
D - Strong departure, roll reversals and spin tendencies
E - Weak spin tendency, moderate departure and roll reversals, affected by secondary factors
F - Weak departure and spin resistance, no roll reversals, heavily influenced by secondary factors
U - High directional instability, little data

Figure 9-9. The Bihrle-Weissman chart (Ref. 15)

9.4 Control Effectiveness with angle of attack

Control effectiveness tends to diminish as the angle of attack increases. This is especially true for the ability to generate yawing moment. Figure 9-10 shows the reduction in control forces with angle of attack for the same F-16 wind tunnel test illustrated previously.[5] Figure 9-11 shows a somewhat novel way of generating yawing moment for a canard configuration. Here, differential canard is used to make up for the loss of rudder effectiveness. Differential tail is also used to make up for the rudder.

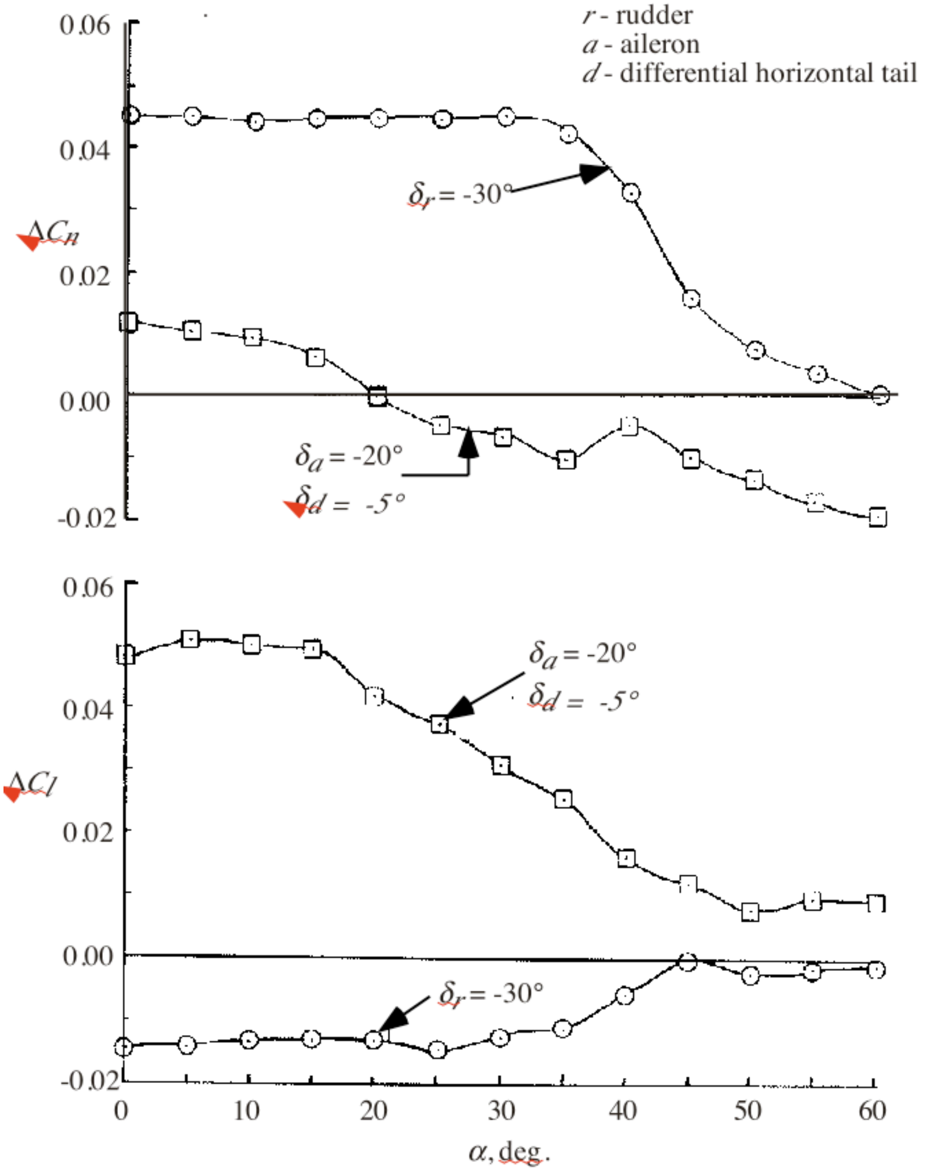


Figure 9-10. Control effectiveness loss as angle of attack increases for the F-16 (from Ref. 5)

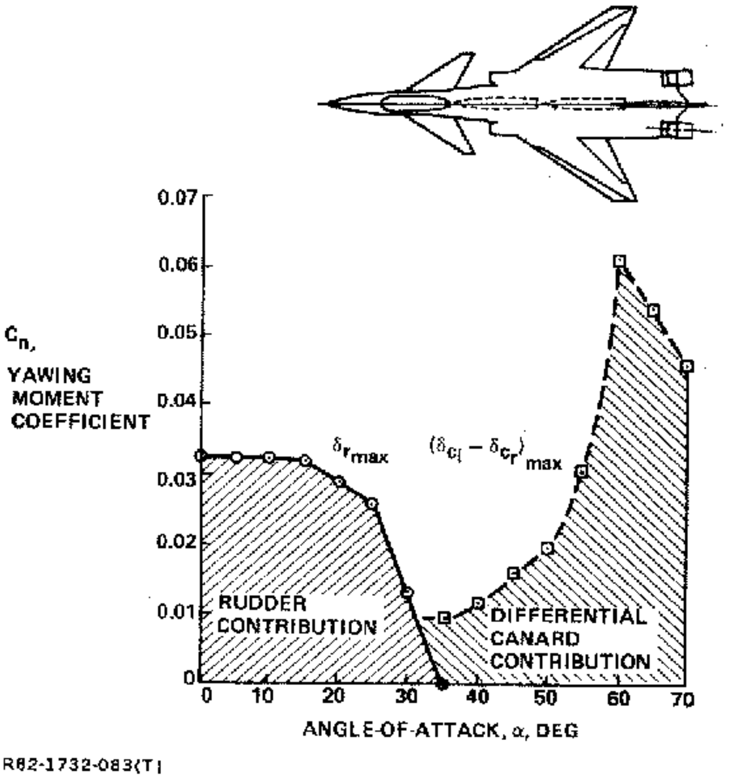


Figure 9-11. Yawing moment from rudder and differential canard on the STAC (from Ref. 22)

Note that thrust vectoring can also play an important role in providing control power at high angles of attack. This also means that the thrust must be provided so as to create a moment arm. Sometimes this is a problem, and also prevents the use of deflected thrust to be used for trimmed lift.

9.5 An Example: Putting it all together, the F-22

The F-22 is the most recent airplane to require high angle of attack capability. Charles Wilson from Lockheed Martin gave a talk at Virginia Tech in November of 1996. He left a copy of the charts he used in his discussion of the high angle of attack development effort. He showed the effect of the LE flap schedule on the lateral/directional characteristics and the nose down pitching moment across the angle of attack range including the effect of thrust vectoring. Finally, he included the maximum roll rate as a function of angle of attack, also showing the benefit of thrust vectoring, and in comparison with the F-15. Copies of selected viewgraphs from his presentation are shown here in Figures 9-12 through 9-15. A related paper on the F-22 is by Clark and Bernens.[17]

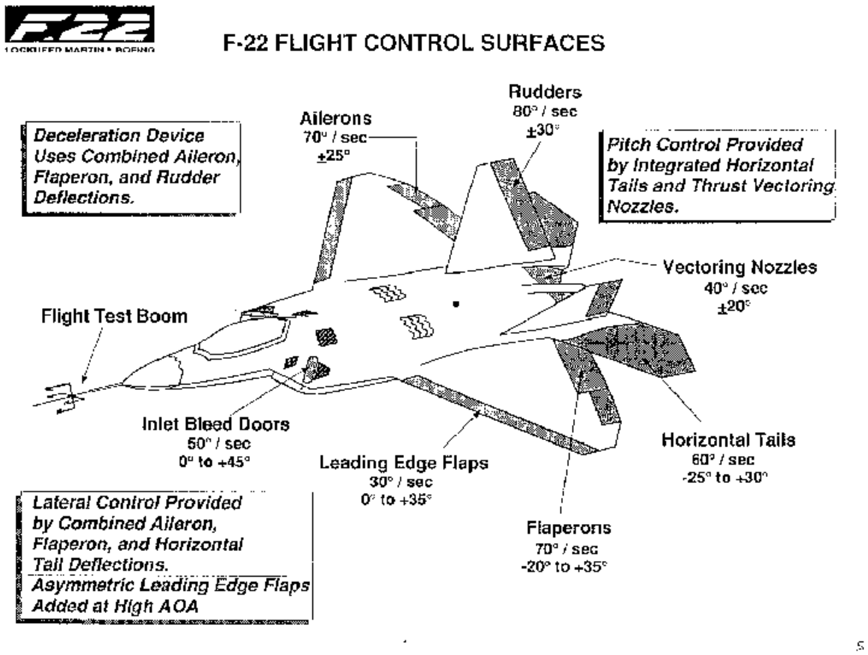


Figure 9-12. F-22 (Courtesy of LMAS)

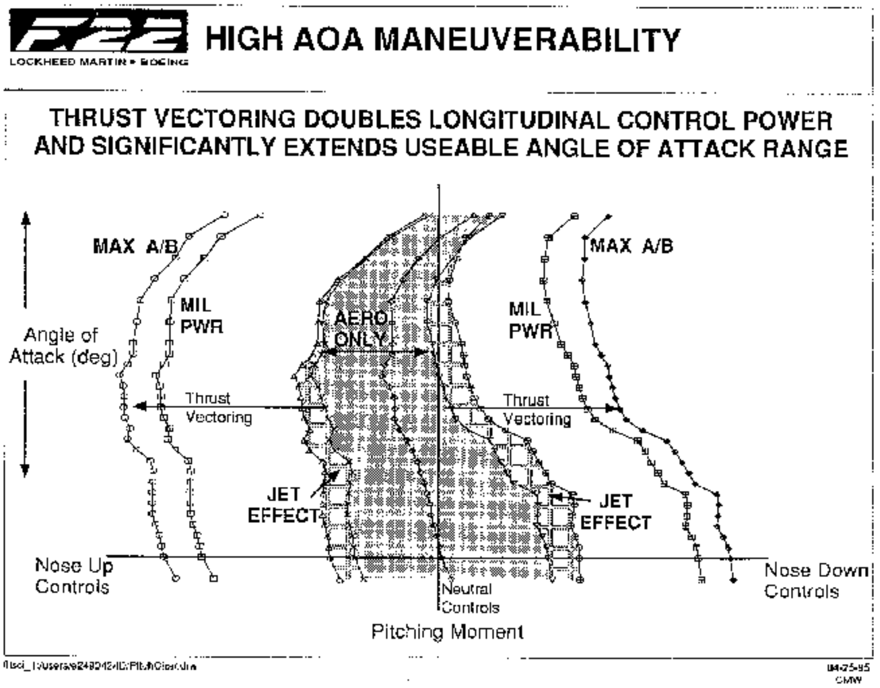


Figure 9-9-13. Pitching moment chart for the F-22, including thrust vectoring (again without scales) (Courtesy of LMAS)

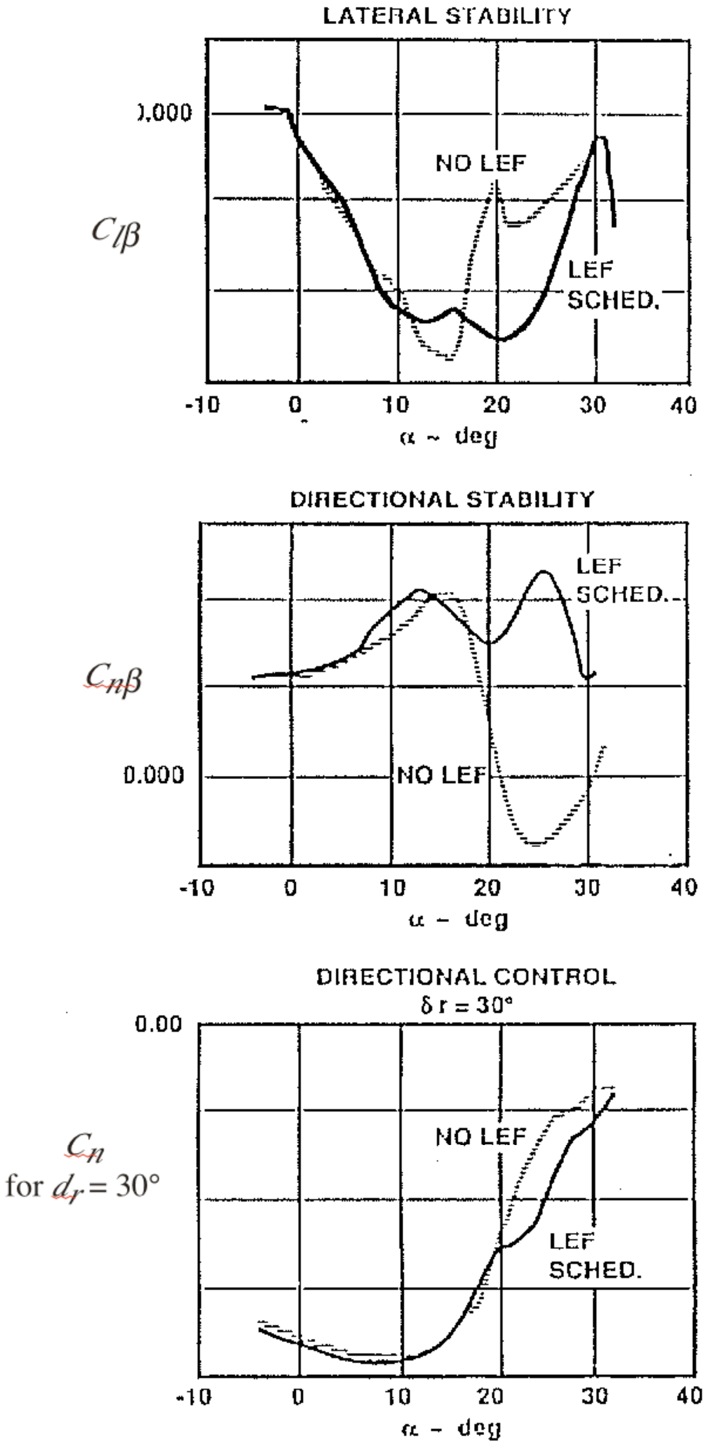


Figure 9-14. Lateral/directional characteristics on the F-22 (Note the absence of scales) (Courtesy of LMAS)

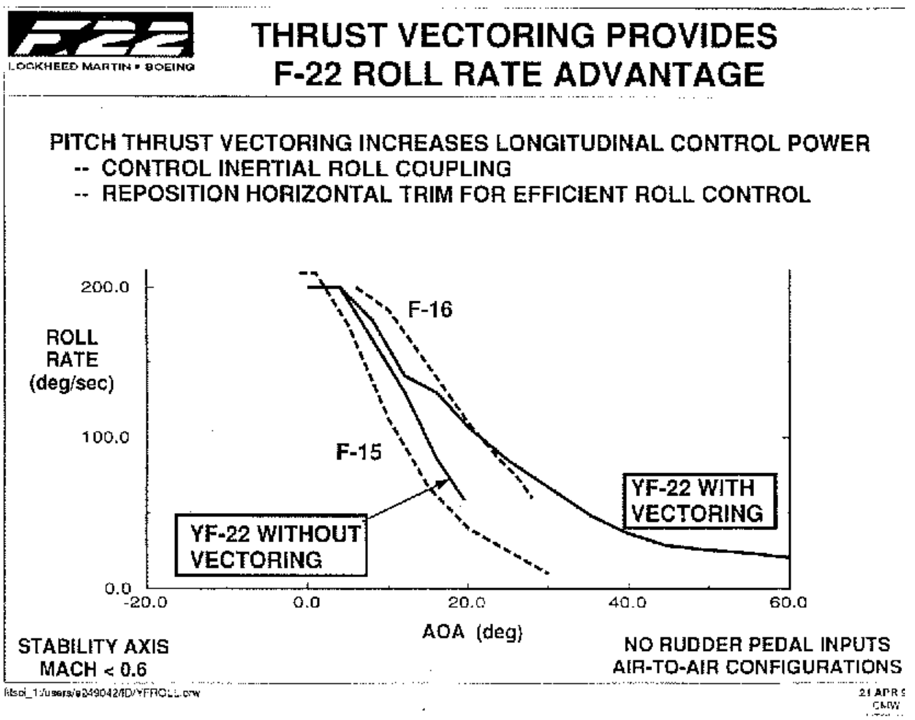


Figure 9-15. Role rate performance, showing the effect of thrust vectoring. (Courtesy of LMAS)

9.6 Some configuration issues: Amazing Stories

Story No. 1: Flow Asymmetries

In many cases, as the angle of attack increases, the flow develops asymmetrically even though the body is as nearly perfectly symmetric as possible, and the body is not yawed! The effect is to produce a side force over the nose of the body and hence a yawing moment for the vehicle. This is particularly important for fighter aircraft with long forebodies.

In fluid mechanics terms, an axisymmetric body can produce an asymmetric flow at certain angles of attack. This is not too surprising, the flow is simply unstable, recall the Kármán vortex street. Perhaps the key study relevant to fluid mechanics of aircraft at high α was a fundamental study done by Lamont[18] in the NASA Ames low-turbulence 12-ft. pressure wind tunnel. An ogive cylinder was studied over a range of angles of attack (20° to 90°) and Reynolds numbers (0.2×10^6 to 4.0×10^6). More importantly, the model was tested at numerous different roll angles, which should not have resulted in any changes in the results. However, the results showed large variations in the side force with roll angle at angles of attack starting at about 30° or 35°. Reynolds number effects were also identified. For our purposes it turns out that the low and high Reynolds results were similar, but there was a large Reynolds number range, which unfortunately includes most of the wind tunnels, where there was a significant variation in the Reynolds number effect. This could explain something I used to hear from engineers at the Full Scale Tunnel at NASA Langley. Their claim: “we get the right answer, the one found in flight.” Turns out they were operating at a very low Reynolds number, and hence, fortuitously got the right answer. The problem of Reynolds number scaling effects applied to high angle of attack flow has received continuing attention.[19]

A fix for flow asymmetry: small nose chines were added to fix the separation location at the nose. An example is the X-29 aircraft.

Story No. 2: The role of the forebody on stability at high α, the F-5 nose story

At low angle of attack, the vertical tail provides directional stability. However, as the angle of attack increases, its effectiveness decreases. Typically this occurs because it’s operating in the wake of the wing flowfield. However, some aircraft start to exhibit increasing stability at higher angles of attack. In particular, the F-5 was tested at NASA Langley, and a novel investigation was made.[7] Directional stability was found for the entire configuration. Then, the vertical tail was removed. Finally, the forebody alone was tested. As expected, at low alpha the tail provided directional stability. The contribution of the tail started to disappear at about 17° or 18° α. The vertical tail on and off data were essentially the same starting at 30° α. However, at this angle of attack, directional stability was becoming positive and increasing rapidly. When the forebody was tested alone, the results agreed with the other configurations beginning at about 30° α. Thus, the conclusion was that the forebody was responsible for creating a stable configuration even though it had significant side area ahead of the center of gravity.

The reason for this phenomena? The vortices shed from the nose developed asymmetrically with sideslip. The vortex on the lee side left the surface, while the vortex on the windward side remained close to the surface (in effect “blown” onto the surface). The low pressure under the windward vortex thus in effect “sucked” the forebody back toward the zero sideslip condition, the condition for stability. The forebody result was simulated computationally by Mason and Ravi.[20]

As a result of the favorable forebodycharacteristics found in the wind tunnel data, many investigations have been made to find good forebodies.[21] Chines have been of interest due to their good stealth characteristics also. One problem: forebodies with too much directional stability tend to lack yaw damping, and want to “swing past” the unyawed position. Hence, a combination of directional stability and yaw damping must be found. The F-22 nose reflects this trade. The nose was set to have minimum basic flow asymmetry, while having reasonable yaw damping and directional stability.

Story No. 3 The complexity of component interaction at high angle of attack.

The Research Fighter Configuration (RFC) was a joint project between Grumman and NASA Langley to understand high angle of attack aerodynamic design within the context of a supersonic cruise/maneuver and transonic maneuver airplane. Anticipating success based on a previous program with a smaller canard,[22] the configuration was designed and several wind tunnel models were built. The design was tested at NASA Langley and at Grumman. Essentially, the results for the different models and different facilities agreed.

It was found that the directional stability of the model was extremely sensitive to the canard setting, and that the twin vertical tail version of the airplane had a significantly lower maximum lift because of an adverse interaction with the vortices from the wing. This configuration showed complicated interactions between the forebody vortices, the canard trailing vortex system, the wing leading edge vortices and the vertical tail. No open literature report was ever published on this work.

9.7 Exercises

9.8 References

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> Nominal characteristics of the following: XP-92, YF-102, XF4D-1, F-8, F-86D, Mig 15, Bell D-188A, X-15, A-7, F-4E, F-111, F-5, XB-58, Winged missile, Lockheed SST, Initial Boeing SST B2707, NASA Generic SST.

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