Advanced Aircraft Design II: Summary

I. Introduction

Progress in fighters:

- Turbojet and swept wing (1940s)
- Autostabilisation (1950s)
- Guided weapons (1950s)
- Leaky turbojets 1960s)
- Microprocessors (1970s)
- Fly-by-wire and artificial stability (1970s)
- Composites (1970s)
- Stealth (1980s)
- Supermanoeuvrability (1990s)

Requirements:

- Lethality
- Manoeuvrability
- Handling qualities
- Radius of action
- Persistence
- Resilience
- Visibility
- Stealth

Classfication of jet fighters

- 1st generation (mid-1940s to mid 1950s)
- 2nd generation (mid-1950s to early 1960s)
- 3rd generation (early 1960s to circa 1970)
- 4th generation (1970 to mid 1990s)
- 4.5th generation (1990s to present)
- 5th generation (2005 to present)

Combat aircraft types:

- Reconnaissance
  - Strategic reconnaissance (U2, SR-71)
  - Tactical reconnaissance (derivative of fighter)
- Ground attack
- Interceptors
- Air superiority

II. Airfoil and wing planform

Trailing edge vortex drag:

- 75% of total drag during maneuvering
- 50% of total drag during cruise
- 5-10% of total drag in low altitude, high speed flight

Profile drag:

- friction drag (30% during cruise)
- form drag

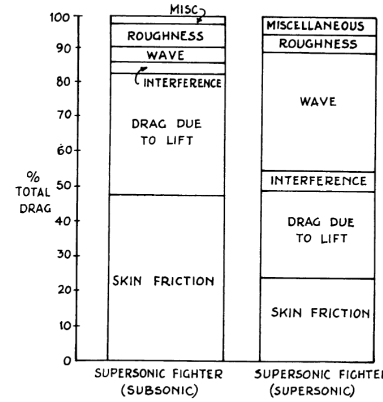
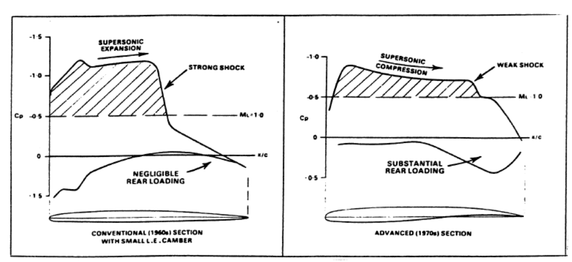


Fig. 1. Drag breakdown

External stores have a large effect on the flight envelope (flight envelope shrinks with stores), mainly due to increased drag and possibly aeroelasic/interference effects.

Airfoil design

General fact: thinner wings means heavier wings.
2nd generation fighters had thin wings for high speed flight, but this caused leading edge separation at subsonic maneuvers and buffet at low angels of attack. This resulted in a bat firing platform. There was a need for thicker airfoils with good transonic characteristics. The answer was the **supercritical airfoil**. The good characteristics were a result of a rapid flow expansion about the leading edge and isentropic recompression through beneficial wave interaction.



A comparison of ancient and modern high lift, transonic wing sections and pressure distributions,

Fig. 2. Supercritical airfoil

Supercritical airfoil:

- Increase the drag-rise Mach number for a given thickness ratio and sweep.
- Allow use of thicker wing for a given M_D and sweep in order to improve available wing volume and either reduce wing structure weight or increase the aspect ratio.
- Reduce wing sweep for a given M_D and thickness ratio, so improving lift and lift/drag ratio for take-off and

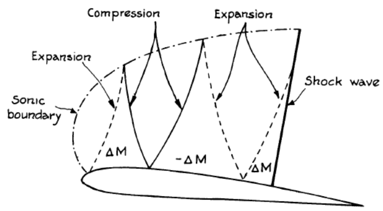


Fig. 3. Wave interaction

landing.

Conical drag:

- Improve off-design performance of supersonic fighters.
- Suppress leading-edge separation by increasing buffet C_L and postponing drag break.

Aspect ratio:

- Effect on
  - Trailing-edge vortex drag (aka induced drag)
  - Lift-curve slope
- High aspect ratio required for:
  - Long endurance ($\propto L/D$)
  - Long range ($\propto ML/D$)
  - Subsonic maneuvering (up to certain AoA)
  - Low AoA requirement at take-off and landing
- Drawbacks of high aspect ratio
  - Weight penalty
  - Supersonic drag increased
  - Sensitive to atmospheric upsets

Wing twist:

- To prevent tip stall
- To adjust spanwise loading and achieve minimum drag at a certain condition
- (sometimes also to adjust the pitching moment)
- (at high g-maneuvers aeroelastic bending causes aerodynamic twist, up to 10 deg)

Wing size:

- Gross wing size:
  - Large effect on drag
  - Crucial role for sizing the aircraft (weight and thus cost)
  - Snowball effect of wing size on airplane size
- What drives wing size?
  - Field performance – low wing loading desired for short fields
  - Subsonic cruise and loiter – medium wing loading desired
  - Sustained turn rate – low wing loading (high A for low $C_{D,i}$)
  - Instantaneous turn rate – low wing loading (high C_L)
  - High supersonic dash – high wing loading
  - Subsonic SEP – not directly affected by wing size
  - Low altitude & high speed – small wing, high wing loading
  - Gust response – small wing, high wing loading
- So what do we do?
  - Find the smallest wing that meets requirements
  - Opt for variable sweep

Wing tips:

- Kuchemann tip (Harrier)
  - Good transonic characteristics
- Raked tip (F-15)
  - Wing tip can be loaded higher than expected
  - Reduced bending moments
  - Reduced buffet
  - Increased dutch roll dampinning
- Straight tip (F-16)
  - Allows launcher rail
  - Could improve L/D

Taper ratio:

- Taper ratio in combination with moderate sweep:
  - Low supersonic drag
  - Increased spiral stability ($C_{l,\beta}$) through leading edge sweep
  - Effective trailing-edge flaps
- Cross-wind handling problems at high AoA
  - Increased rolling moment due to sideslip, $C_{l,\beta}$)
  - Less aileron control power due to swept trailing edge
- Reduces root bending moment and thus wing weight
- Higher loaded outboard sections
- Higher possibility of tip stall if combined with sweep: pitch-up and wing drop

Swept and delta wings

Benefits of wing sweep:

- Inventors: Adolf Busemann, Albert Betz, Hans Multhopp
- Velocity compnent perpendicular to the wing: $V \cot \cos \Lambda$
- Sweep delays drag rise and reduces peak drag
- At subsonic speeds sweep penalises L/D
- Reduction of tuck-under effect
  - Supersonic patch results in shift aft shift of aerodynamic center
  - Result = nose down pitching moment (tuck)
  - More gradual shift on a swept wing
- More gradual variation of lift coefficient across the transonic region
- Extension of buffet boundaries
  - Lower overspeeds at given Mach number and CL
  - Less strong shockwave terminating supersonic patch
  - Postponement of separation at the foot of the shock
- Reduction of gust reponse (good for high speed penetration)
  - Sweep reduces $C_{L,\alpha}$
- For thin, low aspect ratio wings: higher $C_{L,max}$

- Stable vortex separation induces vortex lift up to high AoA
- Stall might be more gradual
- With sweep back, wave drag becomes:
  - Independent of span loading
  - Linearly dependent on $(t/c)^2$
  - Minimized by spreading lift over large chord
- Wing can stay out of Mach cone (if sweep angle is large than Mach angle)

Penalties of sweepback:

- Limits of theory:
  - valid for infinitely long skewed wings
  - Flow perpendicular to isobars
  - Root and tip effects dominant on low aspect ratio wings
- Result:
  - Delay in M_{crit} overpredicted
  - In practice half of the expected amount in M_{crit} is possible
- Lift curve slope increases, until vortex breaks down at the trailing edge
- Loss of leading edge suction leads to increased lift-dependent drag
- With increasing leading edge radius the vortex will appear at higher angles of attack
- Structural problems
- Reduced effectiveness of high-lift devices
- Tip stalling (especially with combination of sweep and large aspect ratio)
- Increased rolling due to sideslip
- Increased drag due to lift
- (reduction of lift-curve slope $C_{l\alpha} \rightarrow$ nose-high attitudes at landing $\rightarrow$ raised cockpits required for visibility)
- Rolling moment due to side-slip is increased due to sweep.
- Reduction of wing controls and flaps
  - Flap leading-edge sweep dominant for its effectiveness
  - High flap sweep angles reduce ΔC_{Lmax}

As way to counter some of the downsides of sweep is the reduce the trailing-edge sweep and make the root chord larger (additional benefit here is that this strengthens the rear spar and central torsion box). So a good way to enhance supersonic maneuvering is to have a low aspect ratio, large wing.

Delta wing

- Alexander Lippisch (1931), Avro Vulcan (1947), Dassault Mirage I (1952)

Benefits of delta wings:

- Transsonic drag rise is more gradual and peak supersonic drag is reduced
  - Lift spread over broader chord (lower section cl)
  - Drag less sensitive to Mach number
  - Easier to obtain satisfactory cross-sectional area distribution (no HT)
- Gradual change of C_L and $C_{L\alpha}$ with M
- Leading-edge vortex gives better stall behavior
- Allows light wings with high bending and torsional stiffness
  - Thicker wings allow for more volume for fuel and gear
  - Flutter and aileron reversal can be eliminated
- Low wing loading allows for acceptable maneuvering and handling
- Smaller wings do not require folding
- Large wing area available for external stores

Disadvantages of delta wings

- Tailless deltas have high landing speeds and bad field performance
  - Low-lift curve slope requires high AoA
  - Tail clearance limits AoA
  - Unable to trim out the nose-down pitching moment from flaps
- High lift-induced drag in subsonic conditions
  - High thrust required
  - Trimmed lift loss at high AoA due to downloading trailing-edge controls
- Low wing loading
  - Although $C_{L\alpha}$ is low, L_α is high due to low W/S $\rightarrow$ gust response
  - High wing loading would compromize manoeuvrability
- Supersonic manoeuvrability restricted
  - Trailing-edge flight controls (elevons) are less effective
  - Large absolute shift in a.c. (needs to be trimmed and may demand c.g. shift)
- Excessive $C_{l\beta}$ at low speed
  - Large (leading-edge) sweep and high AoA disturbs desired relation between lateral and directional stability, Dutch roll becomes exaggerated, low wing and yaw dampers required.
- Pitch damping reduced (if there is no horizontal tail)
  - Risk of pitch induced oscillation
  - Pitch dampers might have to be installed
  - In case of horizontal tail use a low-mounted ht to avoid deep stall at high AoA

Unstable delta does have some other possible advantages, see Fig. 4.

Compound sweep delta (F-16 XL)

- Longer fuselage
- Twice the wing area
  - allows for more hard points
  - increases friction drag

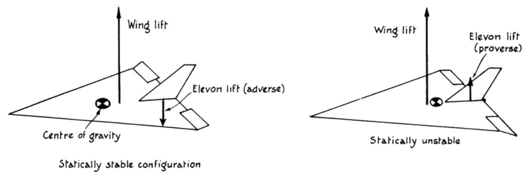


Fig. 4. Advantages of unstable delta

- Increased fineness ratio and wing fuselage blending
- Wing optimized for low-level supersonic speeds
- Trailing edge reflex included
- 70 deg leading edge within the shock cone of the nose
- 50 deg swept outboard wing with thin profile and sharp leading edge

F-16XL flying qualities:

- Lateral/directional stability is improved
- External loads no not adversely affect flying qualities

In modern air combat fighters delta wings are used because the high degree of leading-edge sweep promotes strong vortex formation at high AoA. It has low wave drag at supersonic speeds and the combination with a foreplane creates beneficial interference.

Variable swept wings, used for:

- Long-range subsonic cruise or long-endurance loiter on station
- High-supersonic interception and transonic low-altitude strike
- Operation from limited-length runways or aircraft carriers.

Using a variable sweep wing can also be used for low-altitude high-speed action (F-111), with the wings swept back the wing has a lower aspect ratio and lower $C_{L\alpha}$ so it is less sensitive to gust upsets. High sweep will also bring the a.c more aft and thus increase the corrective effect of C_m (pitch stiffness). When the low-altitude high-speed dash has been completed the aircraft can then benefit form the (low speed) advantages of an unswept, high aspect ratio wing (good take-off and landing performance, more efficient subsonic cruise and loiter, better subsonic sustained manoeuvring).

Disadvantages of variable sweep wings:

- Excessive static stability at high sweep (small c.g. excursion, large n.p. excursion) although reduced by aeroelastic effects...
- Large trim drag due to aft a.c. (induced drag of wing and horizontal tail)
- Large stabilizer deflections required at high AoA
- Hence: large down force of tail should be compensated by larger lift
- Even more aft a.c. at transonic conditions reduces maneuverability

Possible solutions are a translating wing or to move the pivot point outboard.

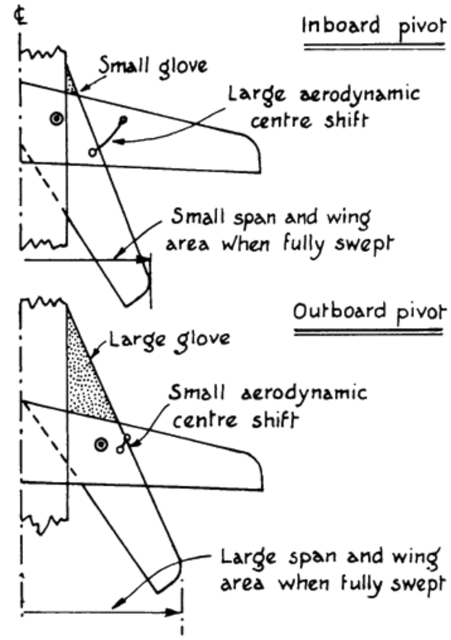


Fig. 5. Effect of glove size

Arguments for inboard pivot:

- Fully swept wing area and span are smaller
- gives the highest effective aspect ratio in the unswept condition
- more aeroelastic relieving effect on pitch stiffness.
- trim drag penalty is not particularly acute for combat aircraft using full sweep only for supersonic dash or low-altitude, high-speed penetration of limited duration
- Trim change can be hidden from pilot by pitch dampers
- The complications of fairing and sealing a fixed apex are avoided, allowing the use of full-span leading-edge high-lift devices.

Observations of sweep wing:

- Increasing sweep from 25 deg to 67.5 deg decreases the lift curve slope by 50 percent. This considerably lessens the susceptibility to gusts.
- Even at subsonic Mach numbers the stability increases greatly with increasing wing sweep notwithstanding the use of a fixed glove on the inboard wing. At supersonic speeds stability increases even more.
- Increasing wing sweep from 25 deg to 65 and 67.5 deg increases the drag rise Mach number from M = 0.75 to close to M = 0.90.

Forward swept wings:

Main problem is the combination of bending (aerodynamic twist) and torsion (geometric twist) that occurs when a forward swept wing is constructed using an isotropic material. By using an anisotropic material one can decouple the bending and torsion to obtain a wing that does not diverge. (it is also possible with isotropic material, but the structure would become quite heavy)

Advantages of forward sweep:

- Roll control and damping more effective at high AoA
- Reduced dihedral effect at high AoA
- Boundary layer drifts inboard (at high AoA)
  - Higher load inboard section
  - Inboard stall could create pitch-up (when behind c.g.). (Fences, inboard twist or limited area of aft sweep can prevent this)
  - Foreplane (canard) can produce downwash to keep the flow attached
- For same sock sweep less leading edge sweep required
- Higher aspect ratio → higher $C_{L\alpha}$ → higher C_L at take-off and landing when restricted by tail strike or pilot visibility
- Higher aspect ratio → lower $C_{D,i}$ → increased sustained turn rate and better cruise/loiter performance.

Disadvantages of forward sweep:

- If the root stalls, vertical tail could be in the wake
- Risk of divergence and new forms of flutter
- Higher aspect ratio → higher $C_{L\alpha}$ ⇒
  - Higher gust sensitivity
  - No aeroelastic relief
- Higher aspect ratio → lower $C_{D,i}$ → additional wave drag in supersonic conditions due to volume

High-lift devices

Three categories of leading-edge devices:

- Alter leading-edge pressure distribution
- Alter the boundary layer (blowing and suction)
- Combination of both

Leading-edge devices increase lift through increase of camber. They are most effective on sharp-nosed sections that are prone to separation. It is difficult to apply while maintaining a smooth knuckle. Typical deflection is about 25 degrees. Leading-edge devices cause a thicker wake over the trailing edge flap, this reduces the effectiveness of the trailing edge flap.

Kruger flap and slat without slot:

- Increase wing chord or increase nose radius or both
- Simple rotation about a hinge (Krueger flap)
- Extension mechanism

Slat with slot:

- Slat effect
  - Reduces suction peak on main component
  - Reduces adverse pressure gradient on main component
- Circulation effect
  - Slat in upwash of main wing
  - For Kutta condition at training edge of slat: circulation (=lift)
- Dumping effect
  - High-speed boundary layer discharges from slat training edge
  - Reduces adverse pressure gradient on slat
- Fresh boundary layer effect
  - A new boundary layer is formed on each new component
- Characteristics:
  - Possible increase in leading-edge camber
  - Possible increase in chord
  - Small change in C_m

Typical modern fighters have low C_{Lmax} and low $C_{L\alpha}$, they are driven by speed and weight requirements, usually resulting in thin wings with high sweep back. Blowing of high-lift devices would increase maximum lift but it also comes at the cost of unusable thrust. Note that high-lift devices can also be used to improve maneuverability.

III. Maneuverability

Requirements:

- Superior transonic maneuvering is an important specification
  - Requirements on instantaneous maneuvering (pitch, roll, yaw rates)
  - Requirements on sustained maneuvers (turn rate, climb rate)
- For sustained maneuvers high specific excess power is required
  - High lift, low drag, high speed, high thrust
  - Flight at high AoA leads to separation
  - Increase in drag, buffet and stability and control problems
- Result: degradation of combat capability:
  - Reduce pilot control and aiming accuracy
  - Full maneuvering capability is reduced
  - Chance of stalling and spinning the aircraft
  - Increase in drag reduces combat effectiveness

Specific excess power

Specific excess power is a measure of the ability to (re)gain energy by accelerating or climbing.

In level flight:

The normal load factor n can be computed by eq. 6.

$$T = D_0 + D_i \tag{1}$$

$$C_D = C_{D,0} + k(C_L)^2 \quad with \quad k = \frac{1}{\pi A e} \tag{2}$$

$$T - D_0 = kC_L^2 qS = k\left(\frac{nW}{qS}\right)^2 qS \quad with \quad q = \frac{1}{2}qV^2 \tag{3}$$

$$\Rightarrow \frac{T - D_0}{W} = kn^2 \frac{W}{qS} \tag{4}$$

$$n^2 = \frac{T - D_0}{W} q \frac{1}{kW/S} \tag{5}$$

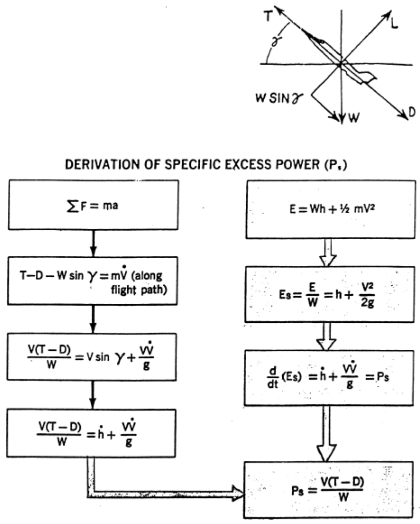


Fig. 6. Derivation of specific excess power

$$\Rightarrow n = \sqrt{\frac{T - D_0}{W} q \frac{1}{kW/S}} \quad (6)$$

The relation between turn rate(ω), normal load factor(n) and turn radius (R) is derived in eq. 12

$$V = \omega R \quad (7)$$

$$\frac{W}{g} V\omega = nW\sqrt{1 - \frac{1}{n^2}} \quad (8)$$

$$\frac{W}{g} V\omega = L \sin\phi \ ; \ \phi = \quad bankangle \quad (9)$$

$$W = nW\cos\phi \rightarrow \sin\phi = \sqrt{1 - \frac{1}{n^2}} \quad (10)$$

$$\omega = \frac{g}{V}\sqrt{\frac{T - D_0}{W} q \frac{1}{kW/S} - 1} \quad in\ rad/sec \quad (11)$$

$$R = \frac{V}{\omega} = \frac{V^2}{g}\frac{1}{\sqrt{n^2 - 1}} \quad (12)$$

In eq. 23 the relation between specific excess thrust and rate-of-climb (R/C) will be derived, starting with Newton's law along the flight path.

$$T - D - W\sin\gamma = \frac{W}{g}\frac{dV}{dt} \quad (13)$$

$$\frac{T - D}{W} V = V\sin\gamma + \frac{V}{g}\frac{dV}{dt} = \frac{dh}{dt} + \frac{V}{g}\frac{dV}{dt} \quad (14)$$

$$E = Wh + \frac{W}{g}\frac{1}{2}V^2 \ ; \ E = Total\ Energy \quad (15)$$

$$E_S = \frac{E}{W} = h + \frac{V^2}{2g} \quad (16)$$

$$\frac{dE_S}{dt} = \frac{1}{W}\frac{dE}{dt} - \frac{E}{W^2}\frac{dW}{dt} = P_S \quad (17)$$

$$\frac{dW}{dt} = 0; \ weight\ constant \quad (18)$$

$$\Rightarrow \frac{1}{W}\frac{dE}{dt} = \frac{T - D}{W} V = P_S \quad (19)$$

$$\Rightarrow P_S = \frac{dh}{dt}\left(1 + \frac{V}{g}\frac{dV}{dh}\right) \quad (20)$$

$$V_C = V\sqrt{\frac{\rho}{\rho_0}} = V\sqrt{\sigma} \ ; \ \frac{dV}{dh} = -\frac{V_C}{\sigma}\frac{d\sqrt{\sigma}}{dh} \quad (21)$$

$$P_S = \frac{dh}{dt}\left(1 - \frac{1}{g}\frac{V_C^2}{\sigma\sqrt{\sigma}}\frac{d\sqrt{\sigma}}{dh}\right) \quad (22)$$

$$\Rightarrow R/C = \frac{dh}{dt} = \frac{P_S}{1 - \frac{1}{g}\frac{V_C^2}{\sigma\sqrt{\sigma}}\frac{d\sqrt{\sigma}}{dh}} \quad (23)$$

Using specific excess power one can also determine the optimum energy climbs or make a plot of the airspeed vs. turn rate (so called ̈doghouse plot.̈

Flap scheduling

Program flaps to automatically suit flight mode.

Buffeting

1) Early formation of weak tip shock
2) Overtaken by aft-moving shock from distorted pressure field at wing root junction
3) At higher Mach forward shock appears parallel and close to leading edge
4) Forward shock moves inboard and intersects rear shock outboard of intersection is a strong shock with a large pressure rise. This invariably causes flow separation

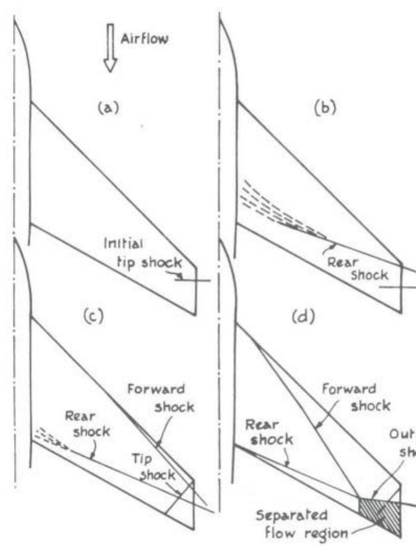


Fig. 7. Flow over swept wings

Vortex Lift

See figures 8, 9 and 10, that pretty much explains it.

Weapons vs. Maneuverability

- Weapon capability determines aircraft agility requirements (both for attack and defense)

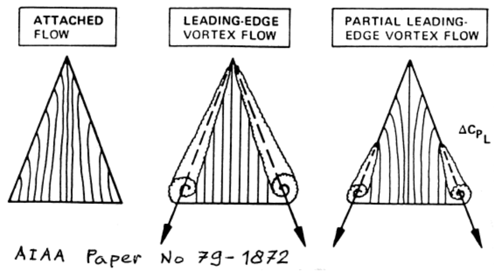


Fig. 8. Vortex lift

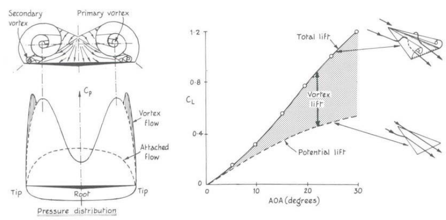


Fig. 9. Pressure distribution vortex lift

- Gun/cannon armament (ballistic unguided) is ”classical” solution
- Early warning radar and guided missile development has eliminated high altitude penetration (SAM)
- Air-to-air missiles have longer range and maneuvering capability, plus higher speed than opposing aircraft (but disengaging is difficult or impossible)
- Missiles have a minimum engagement distance, to lock on and stabilize flight plus a limited ”aiming cone”
- Cannon armament to supplement missiles
- Long range engagement (BVR) identification not certain
- Engagement may develop into close combat
- Missile capabilities improvements benefit from (short time) aircraft pointing capability
- This may be traded against energy conservation/management
- supermanoeuvrability

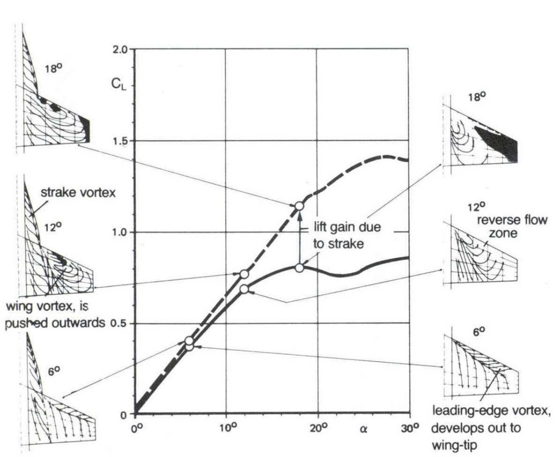


Fig. 10. Effect of strakes on vortex lift

IV. Air Intakes

Intake design criteria

- Spillage drag
- Internal performance (total pressure recovery)
- Inlet/engine airflow matching
- Flow distortion at compressor face
  - steady state
  - time-variant
- Bypass flow
- Inlet bleed requirements
- Interference with external flow
- Stealth (radar detectability)
- Boundary-layer diverter and bleed drag
- Intake buzz and bypass drag
- Flight and operational safety
- Foreign object damage

“The engine face average total recovery is of prime interest due to its direct effect on engine thrust.”

Steady state distortion:

- = pressure recovery pattern across the engine face
- = felt by compressor blades as variation in velocity
- Results in vibrations of the blades
- May cause stalling of blades on several stages
- Can result in engine surge

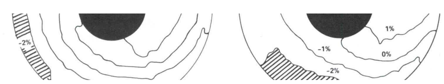


Fig. 11. Distortion

Dynamic distortion

- = how the distortion/turbulence pattern varies with time
- High distortion levels result in low pressure recovery
- Multi-shaft bypass engine more susceptible to distortion than pure jets

Spillage drag

- At high forward speed a low throttle setting: stream tube smaller than inlet
- Momentum loss of air that spills around the inlet = spillage drag.
- Intake may be matched to flow conditions by variable geometry, blow-in doors etc.
- Energy loss in bypass air, boundary layer bleed is proportional to mass flow velocity reduction

Boundary layer bleed

- Boundary layers impair pressure recovery
- Goal: to remove fuselage and intake boundary layer
- Means: use of boundary layer diverter
- Result for fuselage boundary layer diverter $\rightarrow$ diverter drag (momentum lost by diverted flow
- Result for intake boundary layer diverter: Boundary layer bleed drag (momentum lost from time they enter the intake until they leave the aircraft + exit door pressure drag)

- Goal: Make sure excess thrust due to higher pressure recovery is not lower than additional drag
- Boundary layer bleed is required for stable and undisturbed engine intake flow

Radar detectability

- Diverterless inlets
- Intake shaping very important for front radar cross-section

Intake design features

- Intake size
  - Usually sized for high-subsonic speeds
  - Excess airflow is diverted back to the freestream
  - Intake sizing should account for increased mass flow due to engine development
- Cowl lip shape
  - Fixed profile
  - Variable radius inlet
  - Suck-in doors (Alternative to high mass flow requirement, they suppress separation without adding thickness to the lips)
  - Blunt lip avoids separation at low speeds
  - Blunt lip will cause shock wave and boundary layer separation at high subsonic speeds due to spillage
  - Sharp lip causes flow separation at high angle-of-attack and low M $\rightarrow$ can lead to distortion
  - Alternative: variable radius inlet/auxiliary intakes
- Intake shape
- Sideplates
- Intake boundary-layer management
  - Fuselage boundary layer (separated by splitter plate)
  - Internal boundary layer (can be thinned by porous surfaces or diverted by throat slot bypass
- Engine bypass system
  - Air that is captured but not accepted by the engine can be bled off using the incorporated boundary layer bleeding system
  - Much larger quantity of air than just the boundary layer
  - If bypass/bleed are not used correctly a severe drag penalty can occur
- Intake duct length and shape
  - Air is decelerated by a (series of) shock wave(s)
  - Further diffusion required to decelerate to M =0.6
  - Compatibility with area ruling (outside) and diffuser shaping (internal)
  - Result often S-shaped duct
  - Duct length is trade-off between weight, distortion levels, diffuser losses (bl friction), (directional stability, example F-16)
- Intake location
  - Engine intake to be optimized with airframe: avoid disturbed flow, make use of precompression/flow straightening
  - No single configuration provided the best performance at all conditions
  - Side by side vs. separated engine/inlets: transonic vs. supersonic performance
  - Asymmetric engines have low spillage drag
  - 2-D inlets have good pressure recovery with acceptable inlet drag
  - Nose intake (mainly used in early jet fighters, suffered form high pressure losses due to wall friction, less flow distortion, no bl diverters necessary, no large radar dishes at the time)
  - Wing-root leading-edge intakes (small depth of intake face, rapid changes in cross section and low wetted area)
  - Side intakes (induced by shape of nose, underbody, canopy, nose droop and fuselage camber, subject to magnified AoA effects, need adequate handling of fuselage boundary layer)
  - Shielded intakes (reduce intake AoA during maneuvres, wing shielding improves pressure recovery, massive flow separation in sideplate at high angle of sideslip possible)
  - Ventral inlet (fuselage is an efficient flow straightener when wider than inlet, low distortion, large pressure recovery, magnified side-slip effect on intake inflow, nose wheel should be more aft, larger VT required)
  - Dorsal inlet (low RCS, bad high AoA performance)
  - Under wing inlet (under wing Mach number is lower (precompression), high AoA capability, forces caused by flow spillage might actually improve the lift of the airplane, increasing L/D and easy access)

Intake types

- First generation of supersonic intakes:
  - sharp-lipped pitot intake
  - long subsonic duct (high internal friction)
  - large total pressure loss due to normal shock wave
- Second generation: addition of conical spike (Mig 21)
  - Houses radar dish
  - Improves supersonic pressure recovery (oblique shock)
- Horizontal ramp inlet
  - Fuselage boundary layer diverter required
  - Long ramp lengths due to inlet aspect ratio (thicker boundary layer)
  - Variable geometry capability in the ramp angle changes for mass flow regulation
  - Large side areas require sideplates to prevent side spillage. Reduces stable mass flow range. BL growth on sideplate. Flow separation off leading edges of sideplate during sideslip conditions
  - Ramp and throat boundary layer removal to minimize terminal shock/boundary layer interaction – to improve subsonic diffuser performance and reduce distortion and turbulence. Aspect ratio chosen for best integration to aircraft configuration
  - Small cowl lip area available for cowl suction (reduction of spillage drag) but cowl drag is reduced.
  - Cowl lip shaping for subsonic high angles-of-attack

  - Possible inclusion of variable cowl devices to enhance inlet engine matching
  - Very good predictable angle-of-attack performance
    * Subsonic: Ramp reduces inflow angles. Cowl lip blunting can prevent internal flow separation.
    * Supersonic: Shock system moves forward relative to cowl lips: maintains low distortion level of intake air. Recovery may increase due to change in effective capture area.
- Half cone inlet
  - Variable geometry for mass flow regulation via translating cone
  - Throat boundary layer removal necessary to minimize terminal shock/BL interaction to improve subsonic diffuser performance and reduce distortion both steady state and time varying.
  - Lower cowl angles required due to nature of conical flow
  - Long length of cowl lip perimeter available for lip suction. Benefits to reduce spillage drag
  - Structurally more efficient
  - Splitter plate not required with proper diverter design (which would minimize leakage off cone edge)
  - AoA performance:
    * Subsonic: Lower cowl lip blunting required
    * Supersonic: Asymmetric compression, increased distortion. Shock pattern intersects plane of inlet. Large degradation in recovery
  - Stable mass flow ratio change at Mach 2.0 is approx 30 to 50% with an inlet design Mach number of 2.2
- Vertical ramp inlet
  - Variable geometry capability in ramp angle changes for mass flow regulation
  - Ramp and throat boundary layer bleed to minimize terminal shock boundary layer interaction and improve subsonic duct performance and reduce turbulence and distortion
  - Minimal side spillage areas due to aspect ratio (chosen for best integration of aircraft configuration)
  - Side plates eliminated to improve angle-of-attack performance. Increase stable spillage range
  - Large cowl/lip area – available for cowl suction – reduction of spillage drag
  - Good angle-of-attack performance:
    * Subsonic: Blunting of lower lip is required but internal flow separation is prevented
    * Supersonic: Shock pattern not greatly influenced by angle-of-attack. Small degradation in recovery.
  - Stable mass flow ratio at Mach 2.0: approx 10 to 30% with and inlet design Mach number of 2.2

Variable-geometry intakes

- Moving cowl
- Extra chin intakes
- Rotating intake cowl

V. Stealth

"The act of moving, proceeding, or acting in a covert way."

Advantages of stealth:

- Can penetrate highly hostile regions
- Provides initial breakthrough by shock and surprise
- Precision bombing
- High Survivability in hostile conditions
- One mission, multiple targets
- Cost effective in the long run
- High morale and confidence in the troops

Linear changes in aircraft survivability produce exponential changes in force effectiveness and aircraft attrition rates.

Susceptibility reduction:

- Threat warning
- Noise jammers and deceivers
- Signature reduction
- Expendables
- Threat suppression
- Tactics

Vulnerability reduction:

- Component Redundancy
- Component Location
- Passive Damage Suppression
- Active Damage Suppression
- Component Shielding
- Component Elimination/Replacement

Classification of aircraft signatures:

- Active:
  - Radar
    * Airframe
    * Engine Intake
    * Weapons
    * Navigational Radar
- Passive:
  - Infrared
    * Fuselage
    * Airframe
    * Exhaust plume
    * Tailpipe
    * Sun glint
  - Acoustic
    * Engine Parts
    * Engine Exhaust
    * Airframe
  - Visual
    * Airframe
    * Engine Exhaust Glow
    * Canopy Glint
    * Aircraft Lighting
  - Misc.

- ∗ Communication
- ∗ Countermeasures

Band Designation	Nominal Frequency
VHF	30-300 MHz
UHF	300-1000 MHz
S	2-4 GHz
C	4-8 GHz
X	8-12 GHz
K_U	12-18 GHz

TABLE I
FREQUENCY BANDS

NOTE: RCS varies with frequency. Long range with low frequency, long wavelength radars (resolution not so good), short range with high frequency, short wavelength (high resolution)

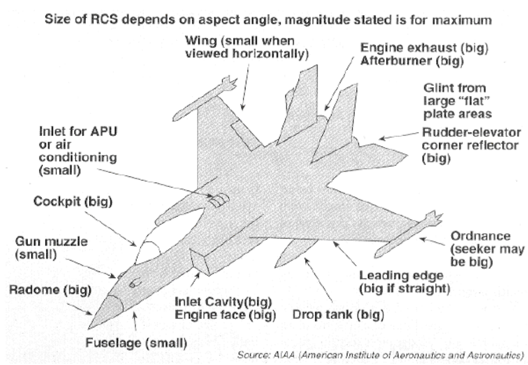


Fig. 12. Relative size contribution to RCS

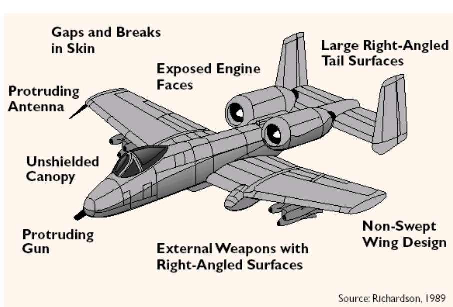


Fig. 13. Radar sources

Types of reflection:

- Diffuse reflection (rough surface)
- Specular reflection (smooth surface)
- Retro reflection (retroflecting foil of cat's eyes reflector)

Radar reflection type:

- Rayleigh Region ($\lambda > \alpha$)
- Resonant Region ($\lambda \approx \alpha$)
- Optical Region ($\lambda < \alpha$)

Radar detection range, see eq. 24.

Shape	Radiation Direction	RCS
Sphere of diam. A	any	πa^2
Flat plate (area A)	normal to surface	$\frac{4\pi A^2}{\lambda^2}$
Cone (semi cone angle δ)	Parallel to axis	$\frac{\lambda^2 \tan(\delta)}{16\pi}$
Ellipsoid (major axis 2a, minor axis 2b)	Parallel to 2a	$\frac{\pi b^2}{a^2}$
Paraboloid with apex radius of p	Parallel to axis	$4\pi p^2$
Circular ogive (nose semi angle δ)	Parallel to axis	$\frac{\lambda^2 \tan\delta}{4\pi}$
Circular cylinder (length L and radius a)	Perpendicular to axis	$\frac{2\pi a L^2}{\lambda}$
Trihedral (3 plane intersecting at 90°)	Any angle between two faces	$\frac{12\pi L^4}{\lambda^2}$

TABLE II
RADAR CROSS SECTIONS

$$R_{max} = \left[\frac{P_R \cdot G_R^2 \cdot \lambda^2 \cdot \sigma}{(4\pi)^4 \cdot N \cdot (S/N)_{min}}\right]^{1/4} \quad (24)$$

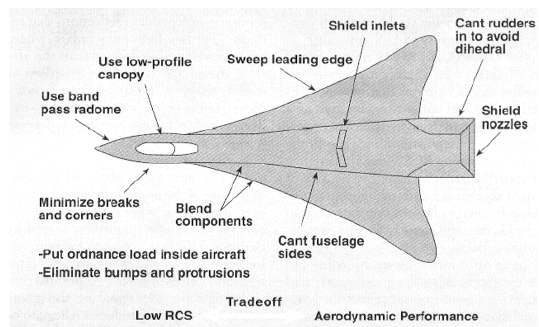


Fig. 14. Reducing the RCS.

Overall RCS reduction:

- Reflection:
  - Minimise overall size of the aircraft
  - Clean external geometry having no protuberances or gaps
  - Internal weapons carriage
  - Highly swept leading edges
  - Eliminate cockpit transparencies
  - Use of composites
  - Use of passive onboard detection system (FLIR, IRST)
  - Use of radar screen on engine air intakes
  - Appropriate shaping of the intake lips and inlet ducts
  - Stealth aircraft must be low probability of intercept (LPI)
- Absorption:
  - Attenuating RAM
  - Resonant RAM
- Active Interference

Planck's radiation law: eq. 25

$$E(\lambda, T) = \frac{2\pi \cdot h \cdot c^2}{n^2 \cdot \lambda^5}\left(\frac{1}{e^{\frac{h \cdot c}{n \cdot \lambda \cdot k \cdot T}} - 1}\right) \quad (25)$$

$$Q_{emitted} = \epsilon \sigma A T^4 \quad (26)$$

Plank constant	$h = 6.626 \cot 10^{-34} Js$
Boltzmann constant	$k = 1.3806 \cdot 10^{-23} J/K$
Speed of light	$c = 229\ 792\ 458 m/s$
Refractive index	$n = 1$ (for vacuum)

TABLE III
CONSTANTS

Sources of IR signature:

- Emitting surfaces (engine casing, nozzle, exhaust plume, other associated hot parts and airframe)
- Reflecting surface (sun glint off the airframe opaque surfaces and transparencies like cockpit canopy

VI. Fuselage Design

Functions of the fuselage is to accommodate:

- crew
- communications and navigation equipment
- the flight control system
- search and fire-control systems
- large proportion of its fuel load
- Engine(s)
- Components of the landing gear
- Gun + ammunition
- Missiles, bombs, flares

Nose and forward fuselage

Forebody shape is driven by

- Cockpit visibility requirements which usually govern forebody camber.
- High-AoA handling which influences the length, cross-sectional shape and application of nose strakes
- Requirement for radar and laser-ranging installations influece the nose size and shape
- Crew accommodation, including cockpit canopy design, governs the cross-sectional area

Forward camber: positive camber generates a negative pitching moment, so reducing the forebody camber will reduce the horizontal tail download required.

Forebody vortex flow:

- has dominant effect on stability in post stall (high AoA conditions)
- vortices are shed from the nose of the airplane
- fin subjected to wing wake and vortices shed by the forebody
- it is influenced by nose fineness ratio (large yawing moments if large fineness ratio), bluntness, cross-sectional shape and the use of nose strakes (aka spin strakes/strips)

Forebody effect on stability

- A well-designed forebody can also contribute to positive directional stability at high angle of attack
- Requirement = stable separation
- Vertical ellipse = unstable in yaw
- Horizontal ellipse = stable in yaw
- Flattened fuselage is longitudinally less stable (nose-up pitch)
- Nose strakes allow for symmetric vortex formation
- Apex of vortices is fixed
- Strakes improve lateral/directional stability
- Strakes prevent spinning
- Strakes deteriorate RCS
- the effect of strakes is also dependent on other components and can also be destabilizing in yaw.

Nose shape affected by radar

- Primary geometric factors affecting radar performance:
  - Location of a pitot-static boom, nose strakes (and sometimes AOA and angle-of-sideslip vanes) adjacent to the radome.
  - High fineness ratio, resulting from aerodynamic shaping of the nose for low drag.
  - Aerodynamic shaping of the nose cross-section for good high-AOA directional stability
- Trade-off between
  - Low drag
  - Excellent high-AoA characteristics
  - Acceptable radar performance

Forebody affected by crew

- Lage fineness ratios desired for supersonic flight, this requires low cross-sectional area → no more side-by-side cockpits, but rather tandem.
- High visibility for the pilot improves survivability.

Center Fuselage

Center fuselage accommodates:

- Main ducts for engines
- Fuel tanks
- The main undercarriage (optional)
- Armament bay (optional)
- Ejection units for stores (optional)
- Pipes, cables and wiring

Some requirements in the design of the center fuselage are space, accessability (especially for engines) and vulnerability of systems.

- Internal engines: when engine grows, more space is required.
- Podded engines:
  - Engine growth easily realized
  - No need for fuselage boundary layer diverter
  - More wetted area
  - Heavier structure (of pods)
  - Less wing weight (inertia relief)
  - Less intake weight (no S-duct)
  - OEI condition is more critical

  - Better longitudinal stability (pancake area aft)
  - Better directional stability (mode side area)

Area rule: *Any two bodies which have the same area distribution, will experience the same amount of wave drag independent of their actual shape.*

- "Sears" bodies describe the optimum shapes for minimum wave drag.
- "Sears-Haack" body = minimal drag for given length and volume.
- "Von Karman ogive = minimal drag for given length and cross sectional area.

Differential area ruling

- Favorable lift interference is created by differential area ruling
- Requires lower AoA to attain certain C_L
- Reduces drag due to lift (remember this is proportional to $C_L \tan\alpha$)
- 5% increase in sustained turn rate at M=1.2
- Favorable pitching moments with reduced trim drag

Area ruling conclusion:

- Lowest body drag:
  - Large fineness ratio
  - Proper area ruling
- Issues:
  - Large pitching moment of inertia
  - Large yawing moment of inertia
  - Small rolling moment of inertia
  - Hazard of **inertia cross coupling**

Rear Fuselage

Requirements:

- Have to be compatible with large tail plane angles
- Minimize leakage between HT and fuselage through gaps
- House HT actuators (pivot axis of HT should be close to its AC for actuator sizing)
- House engine (usually in the back to reduce structural heating and acoustic effects)

VII. Fins and Rudders

Functions:

- Balance in asymmetric flight
- Ensure maneuverablilty
- Provide directional stability (weathercock function)
- Spin prevention/recovery

$\frac{\partial C_n}{\partial \beta}$ **must be positive.**

Fin area requirements:

- Directional moments generated by
  - Destabilizing forebody
  - Stabilizing fin
- Fin size dominated by
  - destabilizing fuselage
  - requirement to suppress sideslip rapidly
  - lateral stability requirements
- Result
  - Difficult to predict required fin size for directional stability

External store asymmetry:

- Imbalances occur when stores are released asymmetrically
- Mass asymmetry causes rolling moment
  - Can be balanced by aileron deflection
  - Aileron deflection produces variable rolling moment during high-g maneuvers
  - Required lateral moment can be relieved id airplane is allowed to sideslip but this requires sufficient directional stability
- Missile firing generates asymmetric flow field, this can generate a yawing moment

Compressibility effects:

- Fin usually becomes less effective at higher Mach numbers

At high angles of attack the low energy wake (wake of the wing/forebody) can immerse the fin, this can result in yaw-off due to directional instability.
At subsonic speeds it is mainly the fin height that influences stability (not so much the area). However, because of fuselage vortex interaction with the vertical fin, at high angels of attack and at yaw angle, a higher fin can cause reduced stability.

Twin fins

- Can reduce required tail height ($\rightarrow$ less aeroelastic penalties)
- Mutual interference at subsonic conditions reduces effectiveness and could render a single fin more effective
- Most beneficial in supersonic conditions; beyond a certain Mach number there is no mutual interference, the Mach lines do not interfere with the other tailplane

Reasons for applying twin fins on the F-14:

- "End plating" effect if the twin verticals results in far more effective horizontal tail control.
- Twin verticals provide a more constant value of $C_{n\beta}$ and high $C_{n\beta}$ for improved Dutch roll characteristics.
- Rudder control redundancy for combat survivability.
- Better infrared stealth due to exhaust shielding.
- No spine boom required to mount fin between engines
- Reduced height makes them less sensitive to flutter
- Larger distance form centerline required less heavy structure $\rightarrow$ lower temperatures, less noise.
- Lower height means less hanger space required

Reasons for not choosing twin fins on YF-16:

- Flow separations from both forebody and wing at high AoA interacted adversely with twin verticals.

- Under certain combinations of α and β visible buffeting of the tails occurred.
- Single fin reduced friction drag due to lower required wetted area.

The fin is usually placed as far aft as possible (taking into account area ruling and interference between horizontal and vertical tail at high AoA).

Canting the fins:

- Reduce rolling moment.
- Reduce radar cross-section.
- Reduce adverse interference with forebody vortices, wing vortices and nacelle vortices.
- Toe angle may be required to reduce vortex interference.

Fin shape:

- High aspect ratio is beneficial for effectiveness
- Low aspect ratio is beneficial for stall behaviour
- Alternative: dorsal fin
- Raked fins on Russian fighters: increase in flutter speed

Ventral fins:

- Oppose roll due to sideslip
- Is destabilizing in roll:
  - offsets the dihedral effect
  - good for Dutch roll characteristics
- Low aspect ratio
- High structural stiffness
- At low AoA might interfere with fuselage stores

Rudders

Design factors

- Crosswind landing (often most critical)
- High AoA flight (spin recovery)
- Asymmetric stores
- Asymmetric thrust (engine failure, engine unstart)
- Transonic effectiveness

High AoA flight

- The rudder effectiveness is determined by the wing planform and its stall pattern (position of the stalled wake w.r.t. the rudder). Also (part of) the rudder can be blanked by the wake from the horizontal tail. If the rudder is not used for spin recovery however that is no problem,
- Right yaw + right aileron:
  - combined with low $C_{n\beta}$ at high AoA: sideslip to the left is induced
  - combined with low $C_{l\beta}$: a roll to the left in incurred (**roll reversal**)
- If aileron reversal occurs switch to rudder-only roll control beyond a certain AoA, this is automatically done via Aileron-Rudder Interconnect (ARI)

Transonic effectiveness

- Compressibility effects reduce effectiveness of hinged control surface in transonic and supersonic speeds
- Aeroelastic distortion reduces effectiveness of rudder at high dynamic pressure
- $\Rightarrow$ high aspect ratio rudders not used; wide, swept rudders are used as well as all-moving fins

VIII. Nozzles and aft bodies

Nozzles are needed to control the expansion of exhaust gasses, by preventing uncontrolled expansion one can achieve increased gross and net thrust.

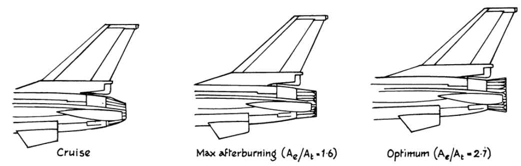


Fig. 15. Area ratio changes by a factor of 1.7 to 1.8, theoretically something like 3 would be best but that would result in very large areas and lots of drag.

Off-design operation, low supersonic speeds:

- Nozzle expands flow below back pressure.
- Corrective shock wave occurs.
- Shock-induced separation follows.
- Effective loss not as high as in ideal case (normal shock), but the total loss is still substantial

Off-design operation, low subsonic speeds:

- Divergent part acts as subsonic diffuser
- Velocity decreases downstream
- pressure increases downstream
- Adverse pressure gradient can cause unstable separation
- Causes the jet stream to attach to one side and then the other
- Causes violent vibrations

Thrust vectoring is the manipulation of jet exhaust such that the resultant reaction forces augment or replace those forces normally generated by the aerodynamic control surfaces of the aircraft.
Thrust vectoring can give you increased range (no need for trim-deflection of control surfaces), improved agility and better survivablilty.

Axis-symmetric nozzles

- High strength/weight
- Easier to cool
- Less leakage between upper/lower ramps and sidewalls

2D thrust vector control

- Reduced complexity
- Easy integration with aft fuselage
- More effective TVC
- Lower IR signature

Thrust vectoring conclusion

- Only increases maneuverability at low speeds
- Can replace (some part of) control surfaces and could reduce weight; no RCS benefit, small benefit in endurance
- Can allow for lower landing speeds if TVC can roll the airplane (limited by impaired pilot visibility)

Afterbody contours: How to reduce subsonic boattail drag?

- Expansion of the nozzle until its area coincides with that of the nacelle. This can eliminate base drag but it causes jet over-expansion and internal losses.
- Careful design of the boat-tail. A minimum boat tail angle at $15°$ has been suggested, the maximum angle is dominated by boundary layer fatigue. If the angle is smaller than $10°$ this will result in extra length, with extra skin friction and excess rear fuselage weight. (possible solution is the addition of a nacelle-to-nozzle fairing (F-16))
- Operation of the nozzle at limited area ratio

Boundary layer separation on the boat tail might cause:

- Excessive boat tail drag
- Violent buffeting

Reduction in boat tail angle:

- Causes flat base area
- Clean boundary layer detachment at the rim of the fuselage
- Does not result in too high drag when close to an exhaust

Interference drag

- Change in boat-tail pressure w.r.t. tail without nozzle and jet + nozzle drag + change in gross thrust due to the external flow field
- interference drag reduces with increased nozzle spacing (optimum spacing to minimize total drag $s/d = 2.5$)