Supersonic Leading Edges

- On top of the Mach cone angle (keeping the entire aircraft within the shock cone generated by the aircraft’s nose), another important consideration of high-speed flight is keeping the wing leading edge subsonic at the maximum speed.
- The disturbances caused by the root of a swept wing in supersonic flow propagate behind the Mach cone but not upstream of it. If a wing leading edge is swept less than the Mach cone, then it is continuously encountering undisturbed supersonic air; such a leading edge is said to be a supersonic leading edge.
- On the other hand, a leading edge that is swept more than the Mach cone continuously encounters air that has been disturbed by the wing root and the rest of the wing inboard of it; such a wing can have a subsonic airfoil shape with a rounded leading edge because the air can deflect around it without creating a strong normal shock. For this situation, the leading edge is said to be a subsonic leading edge.

Pitchup

- A high-performance aircraft with swept surfaces and relatively low aspect ratio often experiences a phenomenon called pitchup. It is characterized by an undesirable nose-up pitching moment at high angles of attack, which tends to make it difficult to avoid a stall.
- This tendency is often aggravated by "V-tail" (butterfly tail) designs. Pitchup would make an aircraft with a conventional mechanical control system dangerous to fly.
- A wing’s susceptibility to pitchup is related to its aspect ratio and sweep.
Stealth Technologies

- 5th generation fighter aircraft and bombers (also cruise missiles) have been designed to minimize their signatures to radars and other sensors. The details of stealth technologies are not available to the general public, but some basic concepts can be studies here.

- Aspect (or aspect angle): is a term commonly used in discussions of air combat in general and low-signature shaping in particular to describe the angle from which a threat is viewing or attacking the subject aircraft (similar to azimuth but often includes elevation).

Low Radar and Sensor Signature

- **Leading Edge Sweep:** the most fundamental shaping concept when designing for low radar signature is to sweep back all leading edges on an aircraft. Swept leading edges can prevent radar waves that strikes aircraft from the front from reflecting-back toward the direction from which they were sent.

- **Planform Alignment:** ensures all the leading edges on the aircraft have the same sweep angle, so that radar waves striking an aircraft all reflect in the same direction.

- **Trailing Edge Sweep:** radar waves that strike a conducting aircraft surface induce traveling waves in the skin material, and they sparkle back into space at the edge of the surface. Traveling edge must be carefully designed to minimize this effect. Planform alignment of all edges (both leading edges and trailing edges) are often aligned parallel, in order to limit the angle of radar "spikes" that would get strong returns of radar signature.
Low Radar and Sensor Signature (Continued)

- **Fuselage Shielding:** if radar waves do not strike a wing surface, they never induce traveling waves in the skin. Radar waves striking and reflecting from an aircraft fuselage reflect and never reach the portion of the aircraft's wing that is in the **radar shadow of the fuselage**.

- **Aligned Vertical Trails:** vertical tail surfaces are tilted and swept in such a way that both their leading and trailing edges are planform aligned with the leading edges of the wing and stabilator, in order to limit angle of "spikes."

- **Chines:** a sharp corner, or chine, between the sloped upper and lower sides of the low Radar-Cross-Section (RCS) fuselage will reduce radar signature.

- **Sharp Leading Edges:** a sharp leading edge will help reducing radar signature; however, this is also a required aerodynamic design for supersonic leading edge (lower wing sweep angle than the Mach angle of designed supersonic flight: usually must have leading edge flaps for low-speed aerodynamic lift augmentation).

- **Radar-Absorbing Materials (RAMs):** a special charcoal tended aircraft coating materials can achieve very low RCA by reducing the intensity of the reflected radar energy; although maintenance could be costly and labor intensive.

- **Scarfed Inlets:** Planform alignment is difficult for the engine inlet rip, because that edge must form a complete box. Some part of the must be perpendicular to the aircraft flight path. This perpendicular portion must be minimized by sloped sides and inlet lips that are "scarfed," or swept back, in both the vertical and horizontal planes.

(SIDE NOTE)

- One of the (actually) most important passive sensor is "**human eye**" (often augmented by a good optics or electro-optical scanners). Reducing aircraft's visual signature is often called "camouflaging." This is commonly accomplished with a paint that matches the aircraft's color to its surroundings. **Medium to dark gray** with no sharp changes in color usually produce the lowest visual signatures for most background and in most lighting conditions.
Low Radar and Sensor Signature (Continued)

- **Engine Inlet Screens**: metal screens over its engine air intakes prevents radar waves from entering the inlets (associated with considerable loss of total pressure in the air flow: not possible for supersonic flight).

- **Serpentine Inlet Ducts**: to eliminate radar reflections from engine compressors without resorting to screens, inlet ducts can be bent, in order to achieve *line-of-sight blockage*. Radar waves reflect many times off the duct walls as the waves go down the duct to the compressor face and then bounce back.

- **Long Leading Edges**: stealth aircrafts have very long, straight leading edges that are much longer than the radar wavelengths that will produce narrower radar "spike." A strong narrow spike can be steered away from threats (much preferred than weaker broad spike).

- **Coated Canopies**: a cockpit (avionics boxes, displays, and pilot’s helmet, etc.) can be a strong radar reflector, an effective radar-shielding coating (iridium-tin oxide) can prevent radar waves entering/leaving through cockpit canopy.

- **Avoiding Right Angles**: any "right-angled" surface of an aircraft will act like a direct mirror-light reflection (a strong reflection directly going back to the source) over a wide range of incidence angles. Tilted vertical tails and sloped fuselage sides can minimize this.

- **Weapon Bays & Minimize Access Panels**: obviously, smoother the surface, the better stealth. If weapons are carried under the wing, it will significantly increase radar signature. At the same time, storing all weapons into the weapon bays will reduce the total amount of weapons to be carried: it is a trade-off.
RCS Fuzzballs & InfraRed (IR) Control

- **Radar Cross Section (RCA) fuzzball** indicates the massive difference between stealth v.s. conventional non-stealth aircraft.
- **InfraRed (IR) Sensor** is a passive device, and mainly detect hot parts of aircraft. The jet engine exhaust temperature needs to be carefully controlled to minimize the IR sensor signature.

Shaping (Design) for Engine-Airframe Integration

- Recall: **area rule** . . . in order to minimize the "wave drag," at the supersonic flight, based on the Sears-Haack body area distribution, some supersonic aircraft employs "wasp waist" shape of aircraft fuselage, called the area rule.
- Many supersonic fighter aircrafts, actually, deviate (to some extent) from the ideal pattern of Sears-Haack body area rule, due to the need to integrate engine inlets for the aircraft's engines into the shape of the aircraft.
- The jet engines to work most effectively, the engine inlet needs to be located in an area of relatively **high total pressure**. The Sears-Haack body, although minimizes wave drag, produces a stronger oblique shock wave at the very front (total pressure is significantly reduced behind the shock wave). This is not desired.
- Instead, a more "slender" nose shape will, instead, produce a several weaker oblique shock waves ahead of the engine inlet, resulting in higher total pressure at the engine inlet. This means that wave drag might be higher, but better for engine thrust.
[Lift] The Whole Aircraft Lift Analysis

- NACA 64A 204 airfoil with maximum thickness at 50% chord
- Sweep angle of the line of the maximum thickness points of the airfoils: $\Lambda_{t/c, \text{max}} = 20$ deg
- The flapped area for the trailing-edge flaps: approximately 150 ft$^2$
- Flap hinge line sweep angle: $\Lambda_{HL} = 10$ deg

- Aspect ratios of the wing and horizontal tail are:
  Eq(4.2) $AR = b^2 / S = 30^2 / 300 = 3$ and $AR_r = b_r^2 / S_r = 18^2 / 108 = 3$
- Span efficiency factor (same for both wing and horizontal tail) is:
  Eq(4.24) $e = 2\left[2 - AR + \sqrt{4 + AR^2 \left(1 + \tan^2 \Lambda_{t/c, \text{max}}\right)}\right] = 2\left[2 - 3 + \sqrt{4 + 9 \left(1 + \tan^2 20^\circ\right)}\right] = 0.723 = e_r$
- 2-D airfoil lift-curve slope for the NACA 64A 204 is approximately 0.1/deg; and for 3-D wing:
  Eq(4.14) $C_{L_{\alpha}} = \frac{c_{L_{\alpha}}}{1 + \frac{57.3 c_{L_{\alpha}}}{\pi eAR}} = 0.0543/\text{deg} = C_{L_{\alpha}}$

- The effect of strakes on the wing needs to be included:
  Eq(4.32) $C_{L_{\alpha}}(\text{with strake}) = C_{L_{\alpha}}(\text{without strake}) \frac{S + S_{\text{strake}}}{S} = \left(0.0543/\text{deg}\right) \frac{300 + 20}{300} = 0.0579/\text{deg}

- Distance between quarter-chords from main wing to tail: $l_h = 14.7$ ft
- Wing taper ratio: $\lambda = 3.5/16.5 = 0.21$, and offset distance of tail: $z_h = 1$ ft

Eq(4.33) $\frac{\partial \kappa}{\partial \alpha} = \frac{21}{AR^{0.5}} \left(\frac{c_{\text{avg}}}{l_h}\right)^{0.25} \left(\frac{10 - 3\lambda}{7}\right) \left(1 - \frac{z_h}{b}\right) = \frac{21}{3^{0.5}} \left(\frac{0.0572/\text{deg}}{14.7}\right)^{0.25} \left(\frac{10 - 3(0.21)}{7}\right) \left(1 - \frac{1}{30}\right) = 0.82$
Lift (Continued)

- Whole aircraft lift-curve slope can be estimated as:

\[
C_{Lw}(\text{whole aircraft}) = C_{Lw}(\text{wing+body+strake}) + \Delta C_{Lw}(\text{horizontal surfaces}) = C_{Lw}(\text{with strake}) + C_{Lw}\left(1 - \frac{\partial \varepsilon}{\partial \alpha}\right)\frac{S}{S} = 0.0579/\text{deg} + 0.0543/\text{deg}(1 - 0.82)(108/300) = 0.0616/\text{deg}
\]

- Once the lift-curve slope is known, and using the fact that the F-16's landing gear limits its maximum usable angle of attack for takeoff and landing to 14 deg, we can calculate its \(C_{L\text{max}}\):

\[
\Delta\alpha_a = \Delta\alpha_{a_{\text{L\&L}}} = S_L \cos \Lambda_{\text{h.l.}} = 5.44 \text{ deg}
\]

\[
\text{Eq}(4.27) \quad \Delta\alpha_a \frac{S}{S} = C_{L\text{max}} = 0.0616/\text{deg}(14 \text{ deg} + 5.44 \text{ deg}) = 1.20 \text{ (for takeoff & landing)}
\]

- Hence, maximum lift coefficient is:

\[
C_{L\text{max}} = C_{Lw} \cdot \alpha_{\text{a max}} = C_{Lw}(\text{whole aircraft}) \left(\alpha_{\text{max}} - \alpha_{L=0}\right)
\]

\[
C_{L\text{max}} = 0.0616/\text{deg}(14 \text{ deg} + 5.44 \text{ deg}) = 1.20 \text{ (for takeoff & landing)}
\]

- Lift coefficient, for a given angle of attack, is simply:

\[
C_L = C_{Lw} \cdot \alpha_a = C_{Lw}(\text{whole aircraft}) \left(\alpha - \alpha_{L=0}\right)
\]
Drag (1): Parasite Drag

- The first step in determining the parasite drag is to estimate its wetted area: this can be done in a variety of ways... if the aircraft is drawn on a CAD system, a function is available to determine $S_{wet} = 1,495 \text{ ft}^2$. Alternatively, the approximated $S_{wet}$ can be estimated by a set of simple shapes: $S_{wet} = 1,418 \text{ ft}^2$, then: $C_{D_{min}} = C_f \left( S_{wet} / S \right) = 0.0037 \left( 1,418 / 300 \right) = 0.0175$

Drag (2): Induced Drag

- The value of the Oswald's efficiency factor ($e_0$) can be estimated:
  
  Eq(4.48) \quad e_0 = 4.6 \left( 1 - 0.033AR^{0.53} \right) \left( \cos \Lambda_{LE} \right)^{0.1} - 3.3 = 0.914

Eq(4.38) \quad k_i = 1 / \left( \pi e_0 AR \right) = 0.16

- F-16's average chord is: $\bar{c} = b / AR = 30 / 3 = 10 \text{ ft}$, with standard sea-level condition and $M = 2$, $Re = \rho \bar{c} / \mu = \left[ \left( 0.002377 \text{ slug/ft}^3 \right) \left( 0.2 \times 1.1164 \text{ ft/s} \right) \left( 10 \text{ ft} \right) \right] / \left( 0.3737 \times 10^{-6} \text{ slug/ft} \cdot \text{s} \right) = 14,200,000$

- Using eq(4.10): $C_D = c_d + C_{D_i} = \left( c_{d,\rho} + c_{d,f} \right) + \frac{C_L^2}{\pi eAR}$ and airfoil data for NACA 64A 204 with the Reynolds number of $9 \times 10^4$, we generate table 4.4 (F-16 Wing-Alone Drag-Coefficient Variation). From this table, it is apparent that $C_{L_{min,D}} \cong 0.04$. Assuming that a well-designed aircraft will have its minimum drag at approximately the same $C_L$ where the wing alone has its minimum drag:
**F-16 Whole Aircraft Analysis (4)**

Eq. (4.53) \[ C_{D_b} = C_{D_{max}} + k_1 C_{L_{max}}^2 = 0.0175 + 0.116(0.04)^2 = 0.0177 \]

Eq. (4.49) \[ k_2 = -2k_1 C_{L_{min}} D = -2(0.116)(0.04) = -0.0093 \]

Eq. (4.38) \[ C_D = C_{D_b} + k_1 C_L^2 + k_2 C_L = 0.0177 + 0.116C_L^2 - 0.0093C_L \]

**Drag (3): Supersonic Drag**

- For Mach numbers less than \( M_{crit} \),
  
  \[ M_{crit} = 1.0 - 0.065 \left( \frac{100 T_{max}}{c} \right)^{0.6} = 1.0 - 0.065(4)^{0.6} = 0.85 \]

  \[ M_{crit} = 1.0 - \cos^{0.6} \Lambda_{LE} \left[ 1.0 - M_{crit\text{(unswept)}} \right] = 1.0 - \cos^{0.6} 30^\circ (1 - 0.85) = 0.865 \]

  \[ M_{c_{D_{max}}} = 1/\cos^{0.2} \Lambda_{LE} = \frac{1}{\cos^{0.2} 40^\circ} = 1.05 \]

- The wave drag is: Eq. (4.42) \[ C_{D_{wave}} = \frac{4.5\pi}{S} \left( \frac{A_{max}}{l} \right)^2 E_{WD} \left( 0.74 + 0.37 \cos \Lambda_{LE} \right) \left[ 1 - 0.3 \sqrt{M - M_{c_{D_{max}}}} \right] \]

  With \( A_{max} = 25.5 \text{ ft}^2 \) and \( l = 48.5 \text{ ft} \):

  At Mach 1.05: \( C_{D_{wave}} = 0.0263 \)

  At Mach 1.5: \( C_{D_{wave}} = 0.0235 \)

  At Mach 2: \( C_{D_{wave}} = 0.0208 \)

- Finally, the supersonic \( k_1 \) values are: Eq. (4.54) \[ k_1 = \frac{AR(M^2 - 1)}{4AR\sqrt{M^2 - 1} - 2} \cos \Lambda_{LE} \]

  \[ = 0.128 \text{ (at Mach 1.05)} \]

  \[ = 0.252 \text{ (at Mach 1.5)} \]

  \[ = 0.367 \text{ (at Mach 2)} \]
Drag polar results are summarized in table 4.5, we can, then, compare against actual values in table 4.6.

- The predicted values agree reasonably well with the actual values.
- The predicted values of $k_i$ are particularly good match.
- The 8% lower subsonic $C_{D_0}$ values were to be expected in part because of the 5% lower estimate of wetted area.
- F-16 wing is swept 40 degrees, and it uses an airfoil with a rounded (rather than sharp) leading edge. This was an appropriate choice of airfoil for an aircraft optimized for air-to-air combat at Mach 0.9. However, when exceeding Mach 1.3, its wing leading edge becomes a supersonic leading edge. Normal shocks form ahead of the rounded leading edge, and wave drag increases.
- The fixed geometry of F-16’s air inlet produces a great deal of additional wave drag and flow separation at high supersonic Mach numbers.
- F-16 is optimized for subsonic maneuvering, not supersonic cruise, and so it should not expect to achieve the lowest possible supersonic drag.
- (On contrary, for example, F-106 Delta Dart, is optimized for supersonic flight with minimized wave drag at supersonic flight)