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Analysis of a Low Boom Supersonic Flying Wing Preliminary Design

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Future Supersonic Flight

- Fast global travel, Mach=1.6 - 4.0
- High aero efficiency for low fuel consumption and pollution
- Quiet for environmental friendliness and stealth
- Extremely short takeoff/landing (ESTOL)
- Long endurance subsonic loitering at destination
- Intermediate vehicles between subsonic and hypersonic

Problems of Current Supersonic Airplanes

- Sonic boom, no flight above land
- High wave drag, high fuel consumption/cost
- Low Subsonic performance, long takeoff/landing distance, high airport noise

Sonic Boom: Lift is the major cause

- Front compression or shock generates pressure rise for pressure surface
- Expansion reduces pressure for suction surface
- Compression has higher Mach cone angle than expansion
- Expansion reduces pressure more than pressure rise of front compression
- A tail compression or shock needed to restore the low pressure to ambient value
- A N-wave may form if compression waves or shocks coalesce
- N-wave: Strong sonic boom loudness
- Long and smooth lift distribution beneficial to mitigate wave coalescing

Current strategies to Reduce Sonic Boom, Jones-Seebass-George-Darden Theory

- flat rooftop over pressure signature, Strong shock near aircraft, weakened to ground due to interaction with expansion waves
- Ramp overpressure signature, weak shocks or acoustic compression
- May generate strong shock in mid- and far field due to wave coalesce

Recent Efforts

- NASA N+2, N+3 Goal: Mach=1.6-2, passengers=25-100(N+3: 100-200), $R \geq 4000$, Boom=65-70 PLdB
- Lockheed Martin and Boeing are contracted to develop, Boom – 80 PLdB
- Gulfstream Quiet Spike^{T}M, Multi-steps spike to split a strong shock to multiple weaker shocks
- Long spike required
- Movable wing to improve subsonic performance, bring weight penalty
- Spike generates little lift, mitigation of the boom due to lift may be limited

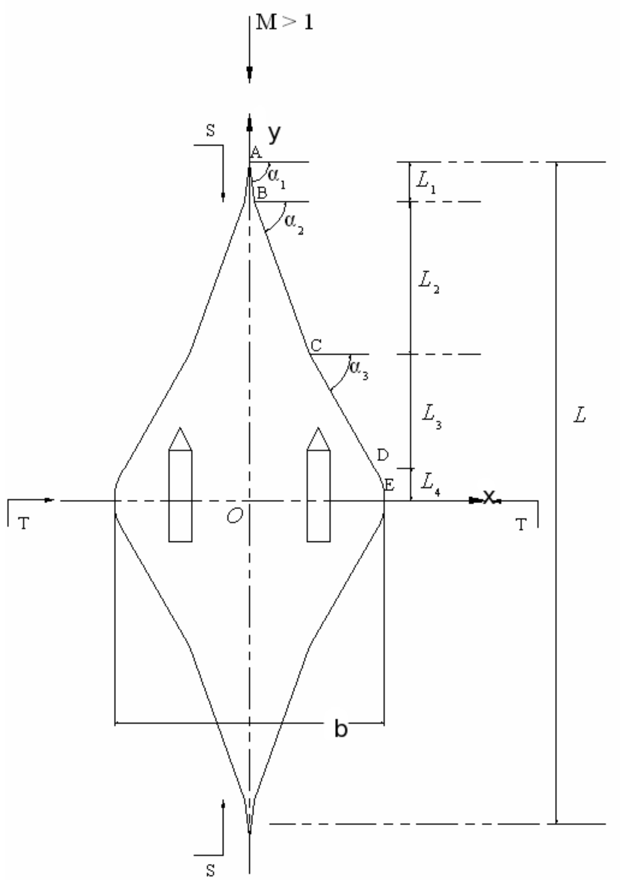
New Concept: Supersonic Bi-Directional Flying Wing (SBiDir-FW)

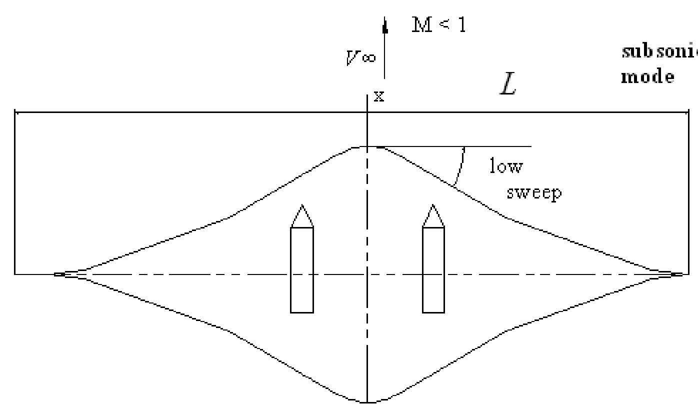
- Aimed at:

1) Low sonic boom
2) Low wave drag, high L/D
3) High subsonic C_L and L/D
4) Smooth ground over-pressure signature

Bi-Direction Planform Benefits Both Supersonic and Subsonic

Planform in supersonic mode(left) and subsonic mode(right)





Subsonic aspect ratio substantially increased

$$AR_{M<1} = ((\frac{L}{b})^2) * AR_{M>1} \tag{1}$$

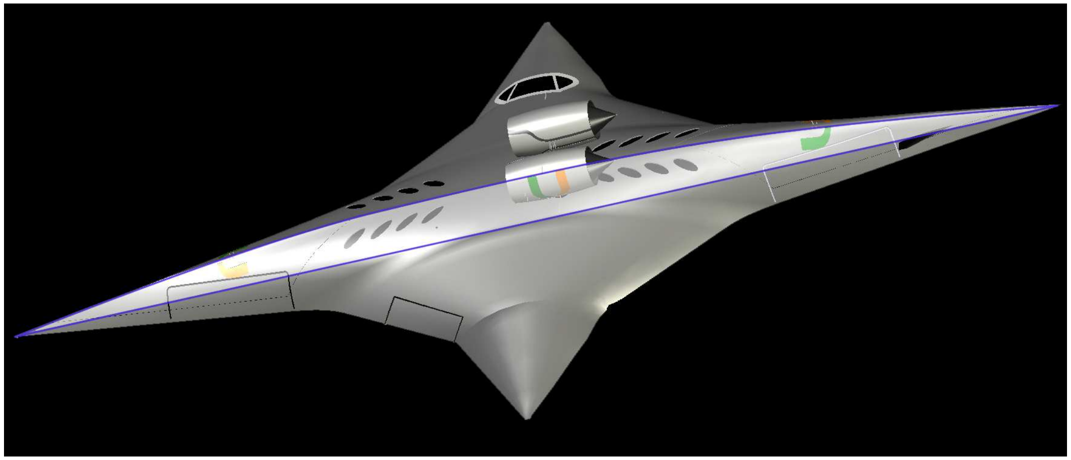
L=length, b=span.

Sweep angle at subsonic largely reduced:

$$\delta_{M<1} = 90^o - \delta_{M>1} \tag{2}$$

Flight Mode

Subsonic flying mode



Supersonic flying mode

Mode Transition Not Question Anymore: Rotating Dragon

Award Winner Drone, “Rotating Dragon”, Beijing Air Show, Sept. 2013

Potential Aerodynamic Advantages

• Maximum possible length(head to tail) and ultra high slenderness for lift distribution, which mitigate compression waves and shock waves coalescing to avoid N-wave on ground and reduce wave drag

• Compare diamond wing and delta wing with same planform area and sweep angle, the diamond wing length is $\sqrt{2}$ longer, span $\sqrt{2}/2$ shorter, and aspect ration is 50% smaller.

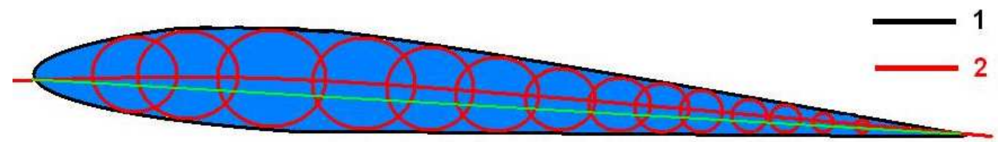
• High subsonic aspect ratio, low wing loading, high C_{Lmax} yields low takeoff/landing speed, low airport noise

• Large weight reduction due to small aspect ratio and zero sweep angle of $(t/c)_{max}$ line.

$$W_{wing} = C_1 C_2 C_3 W_{dg}^{C_4} n^{C_5} S_w^{C_6} A^{C_7} (t/c)^{C_8} (C_9 + \lambda)^{C_{10}} (cos\Lambda)^{C_{11}} S_f^{C_{12}} q^{C_{13}} W_{fw}^{C_{14}} \quad (3)$$

• Applicable to Hypersonic Vehicles

Geometry Model



Airfoil, meanline, and thickness distribution

• Arbitrary leading edge sweep and dihedral Angle to determine planform shape.

• Arbitrary meanline angle distribution to control loading distribution.

• Airfoil is created by adding a thickness distribution along the meanline.

• 1/4 Sine wave thickness distribution is used from LE to $(t/c)_{max}$ location.

- Geometry model flexible to generate any shape with the constraints that the geometry must be symmetric about the longitudinal and span axes.

- A GUI interface is created to allow users to vary the design parameters on screen by hand.

CFD Solver for near Field

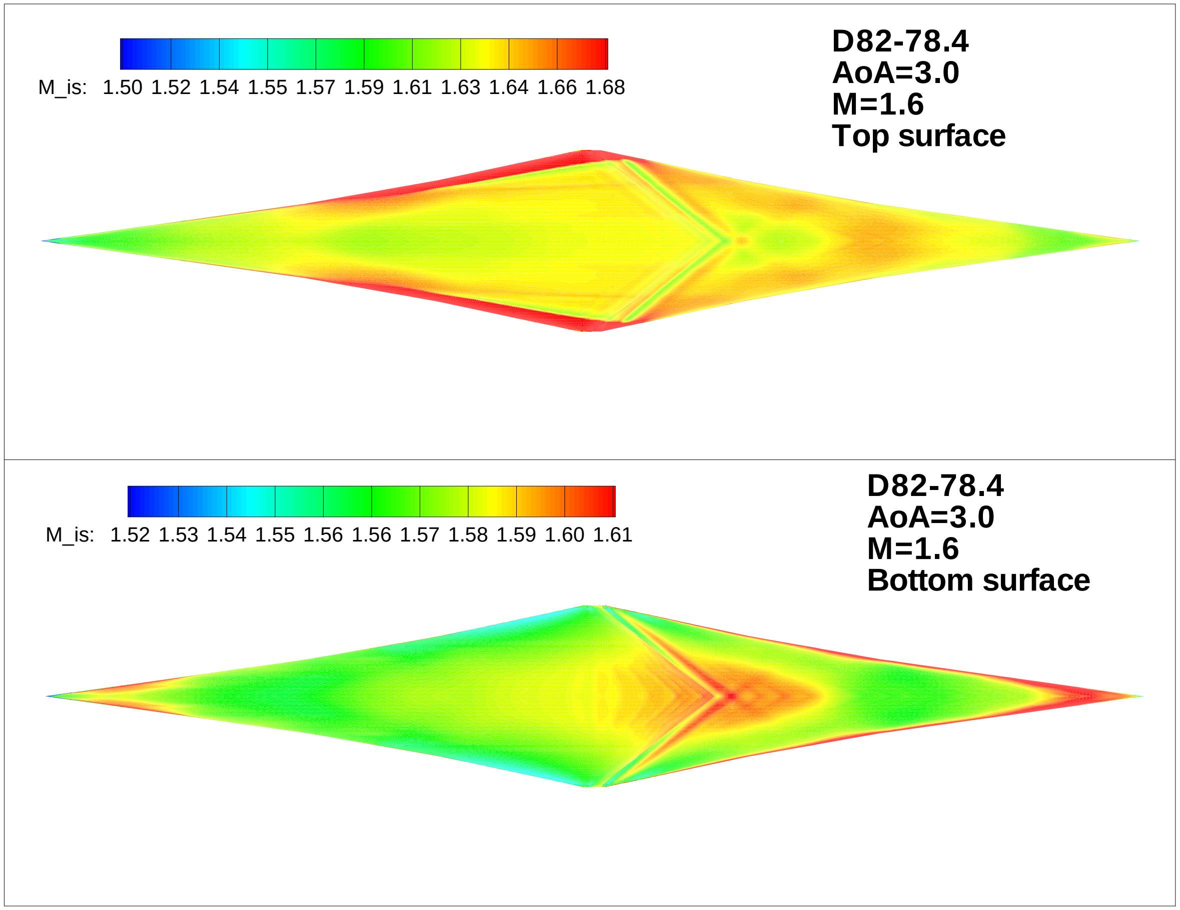
- 3rd (or 5th) order WENO scheme + Roe's or E-CUSP Approximate Riemann Solver
- Euler equations for inviscid flow to accurately calculate sonic boom
- Implicit time marching with Gauss-Seidel Line Relaxation
- Pressure drag and lift calculated by Euler solver
- Viscous drag calculated by analytic solution of supersonic flat plate, validated with CFD
- NASA sBoom code used to predict ground overpressure signature from near field

Validation

- NASA Cone
- Lockheed Martin Body of Revolution
- 69° Delta Wing with Fuselage

Low Boom Design, D82-78.4

Mission: 100 passenger, 4000nm range, Mach 1.6, Altitude $\approx 50kft$, AoA=3°



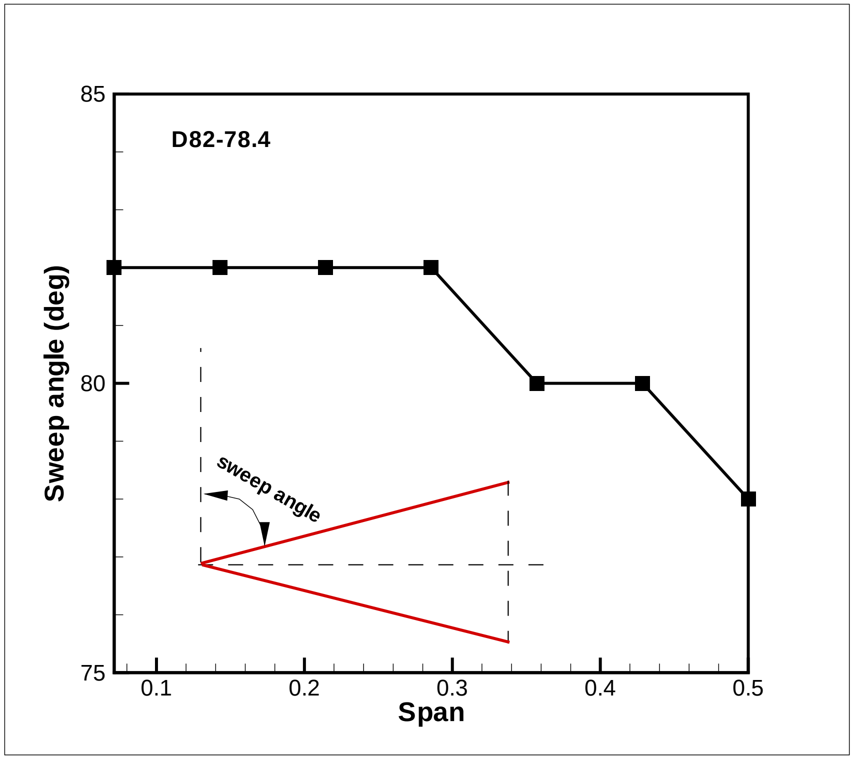
Suction and pressure surface isentropic Mach number contours

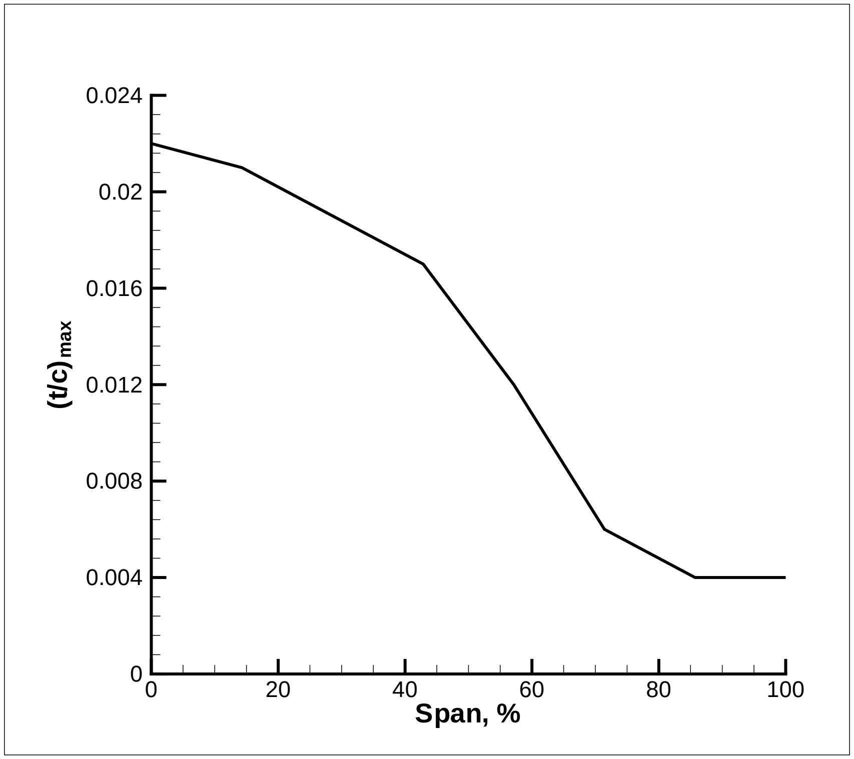
Results of D82-78.4

Range	Pass	Mach	Alt(ft)	W_{TO}(Lb)	EW(Lb)
4000nm	100	1.6	50000	196,543	95,833
Length(m)	Span(m)	Area(m^2)	Volume(m^3)	AR($M < 1$)	AR($M > 1$)
100	16.5	764	650	13.074	0.356
C_L	C_D	C_L/C_D	C_M		
0.05410	0.00663	8.15988	-0.00102		

Altitude(ft)	48000	50000	52000	56000	60000
Ground Boom PLdB	72.58	71.71	70.93	67.75	66.17

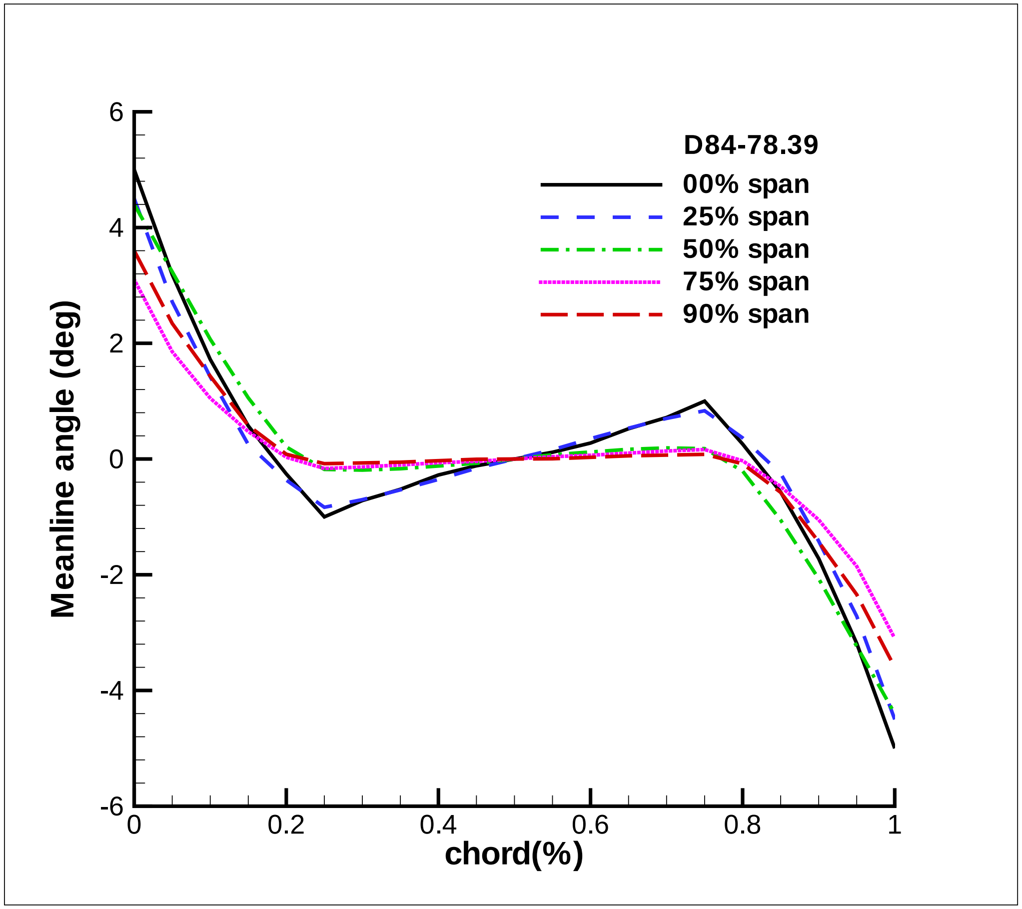
Left: Sweep angle 82° to 78°; Right $(t/c)_{max}$





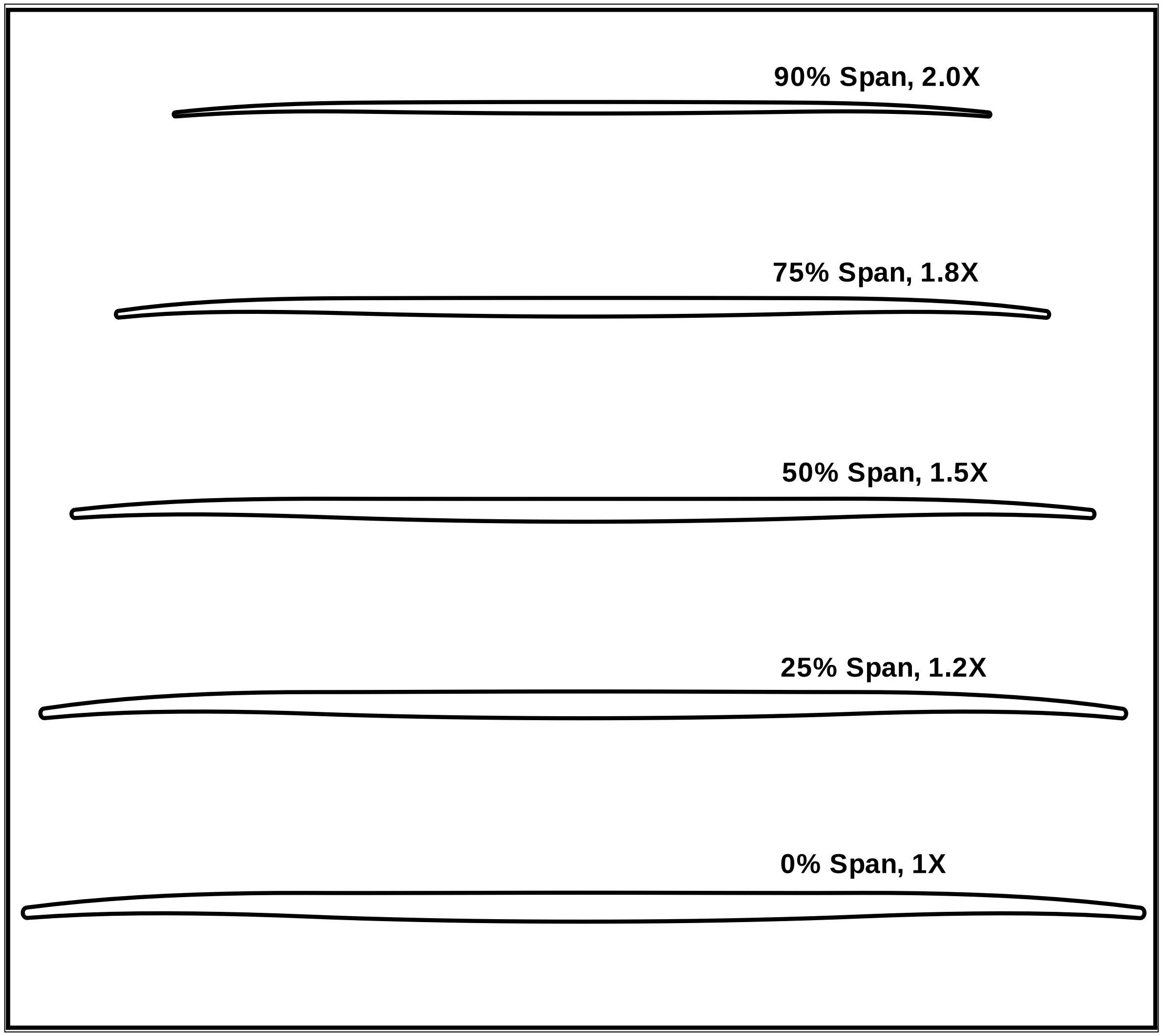
Non-monotonic Meanline angle

Critical to mitigate sonic boom due to reduced peak Mach number and smooth streamwise loading distribution



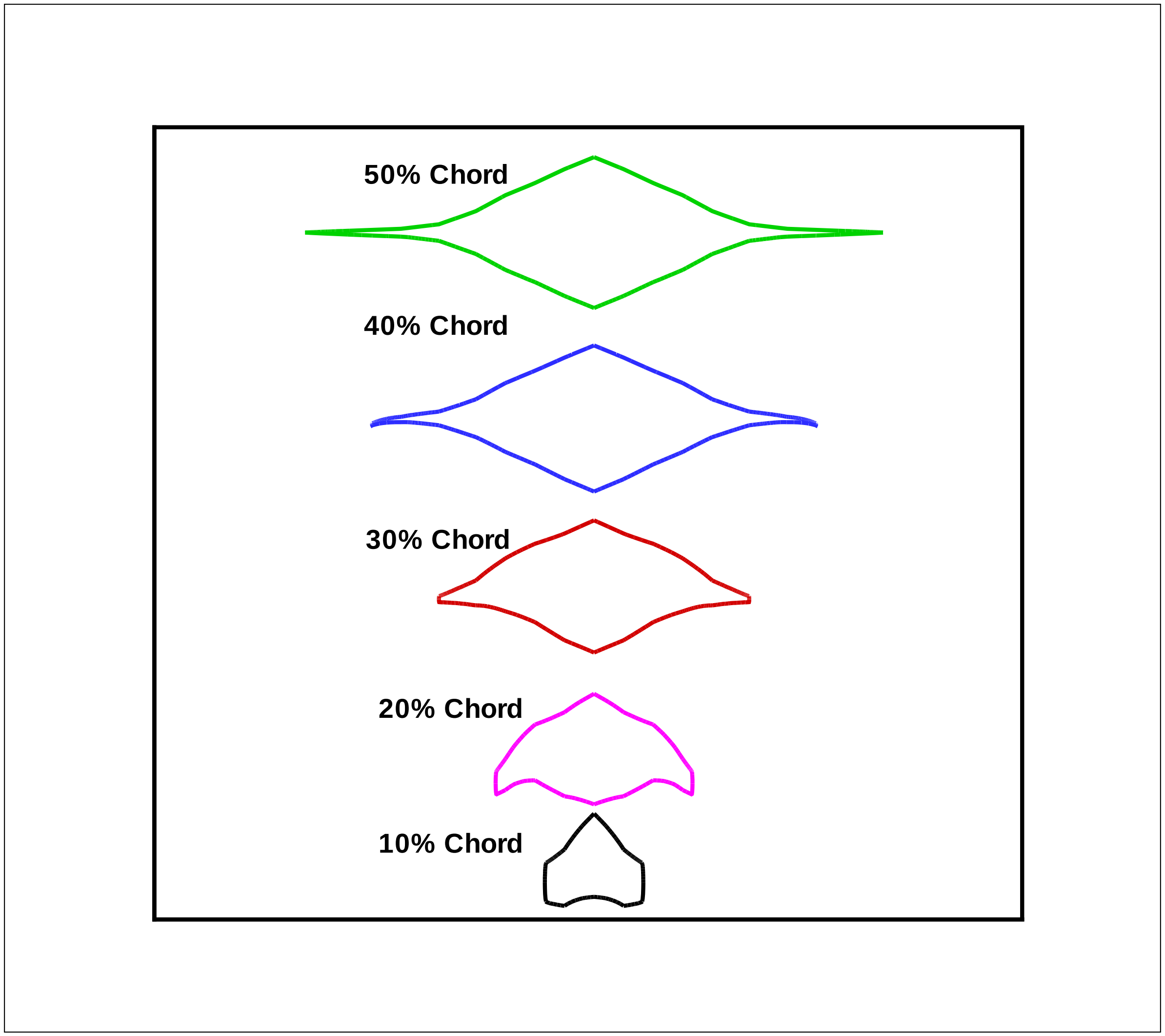
Supersonic Airfoil shape

Mid-chard reversed cambering due to non-monotonic meanline angle

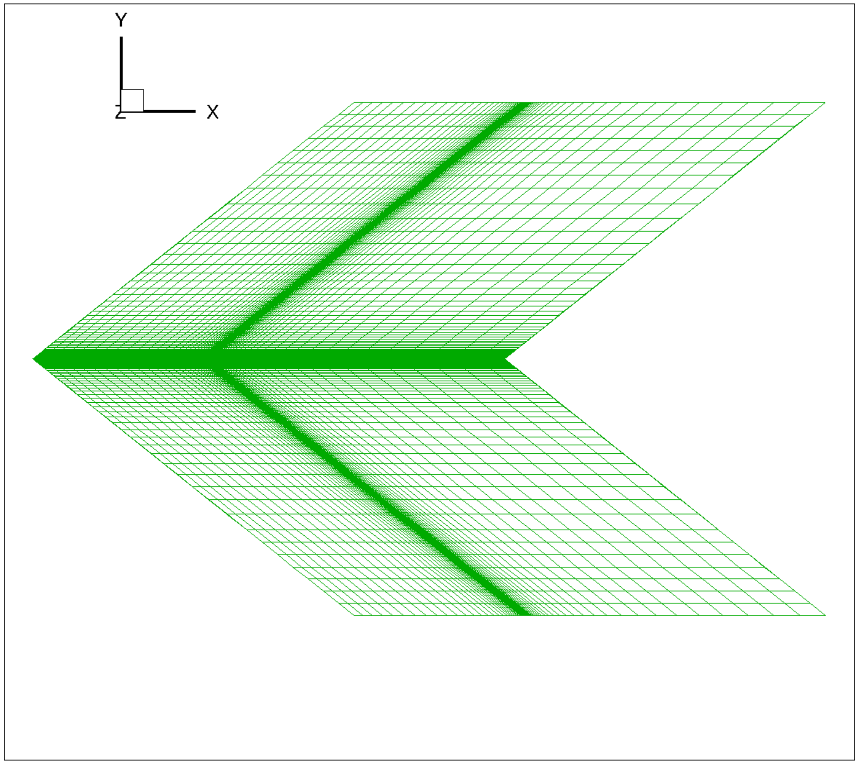


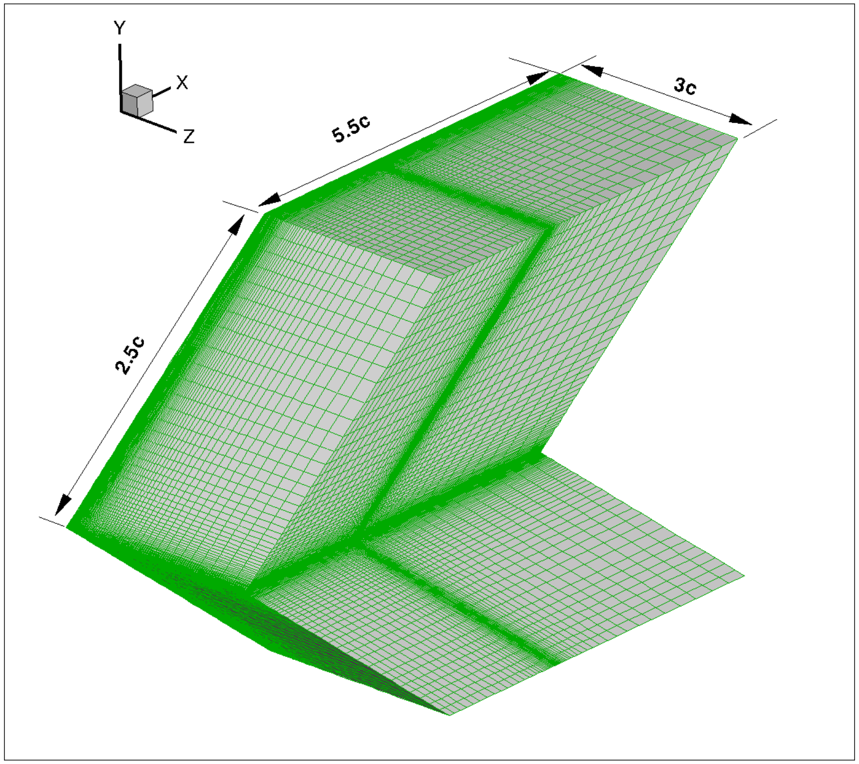
Subsonic Airfoil shape

No effort made to smooth subsonic airfoil yet



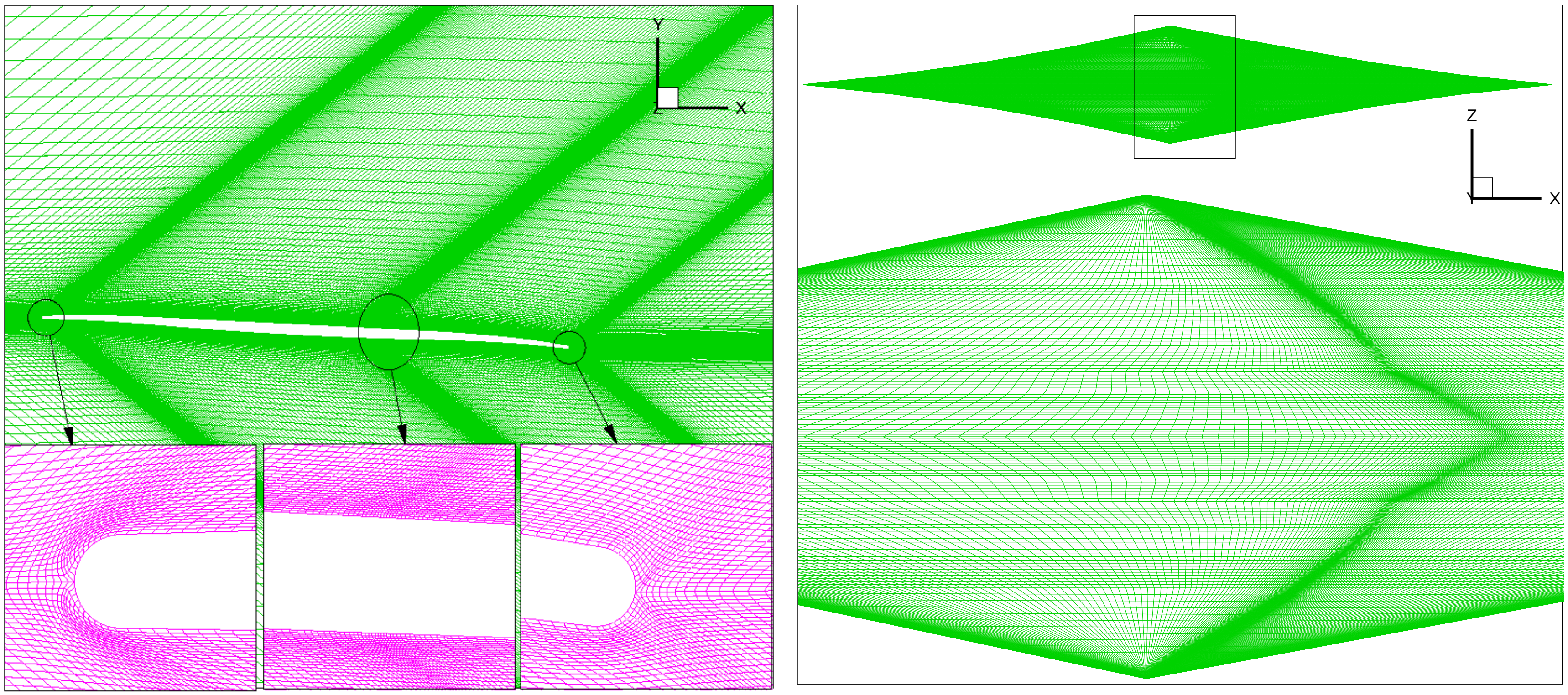
Mesh topology





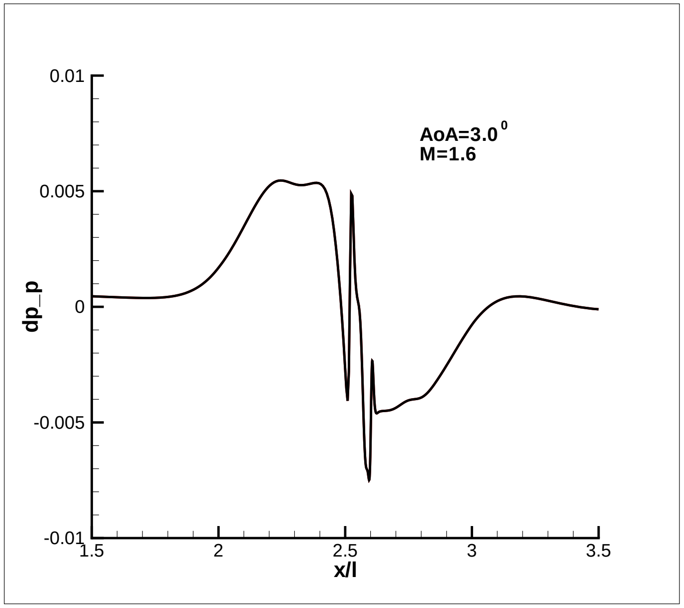
outside mesh (left), side view (right),
Size: $385 \times 129 \times 197 = 9.7M$

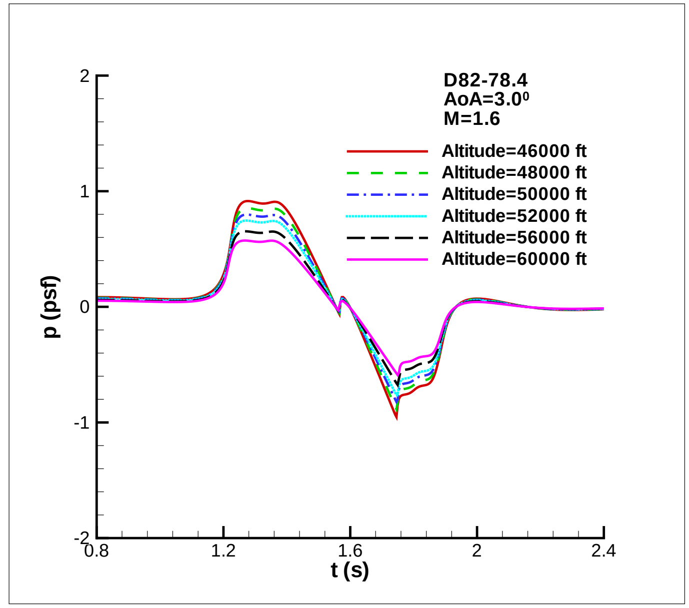
Zoomed mesh near the body



side view (left), surface mesh (right)

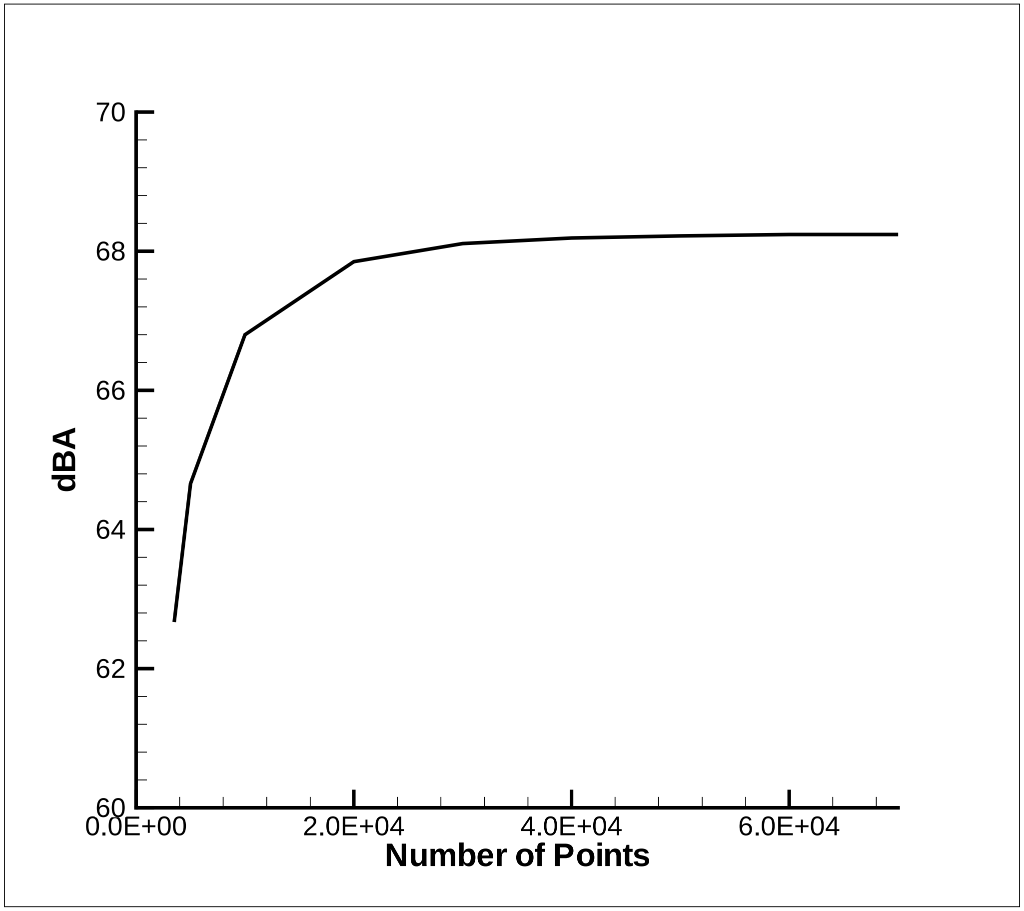
Overpressure Signatures



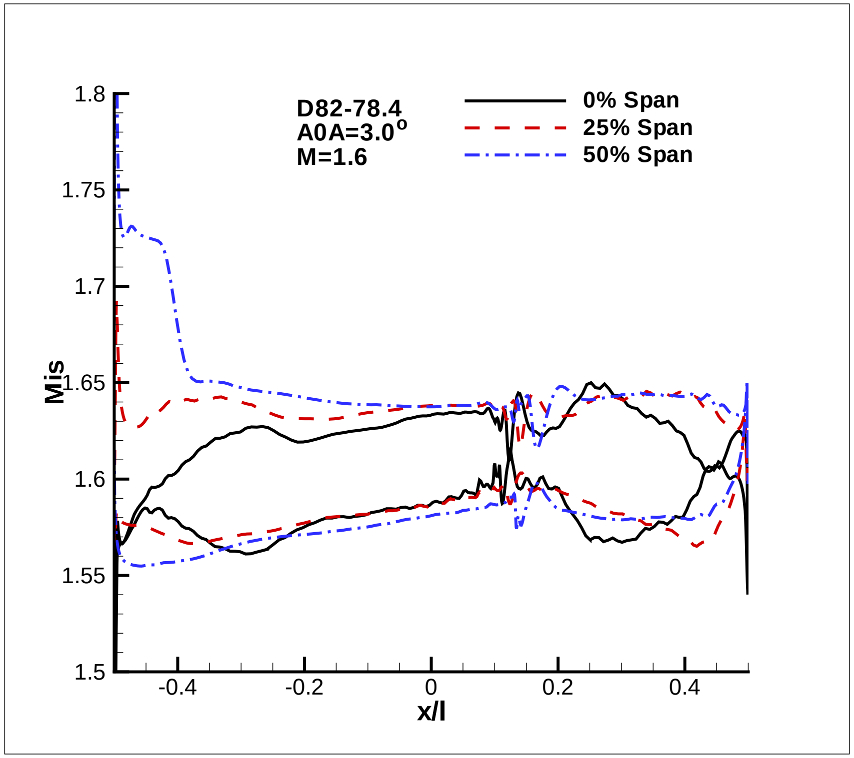


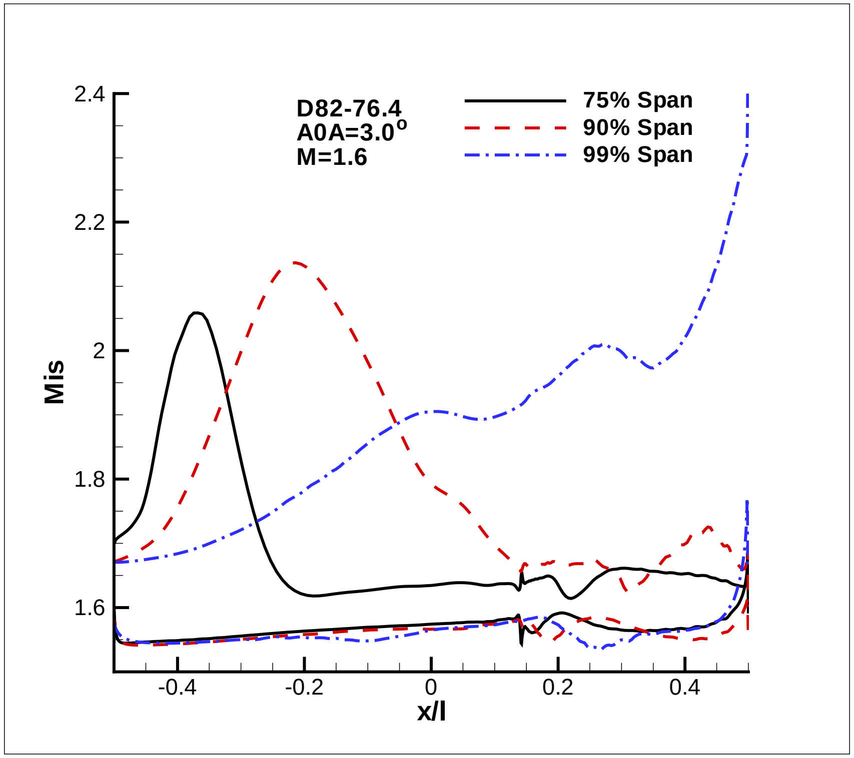
Left: 2 body below; Right: Ground (by NASA sBOOM code)

sBOOM code convergence study

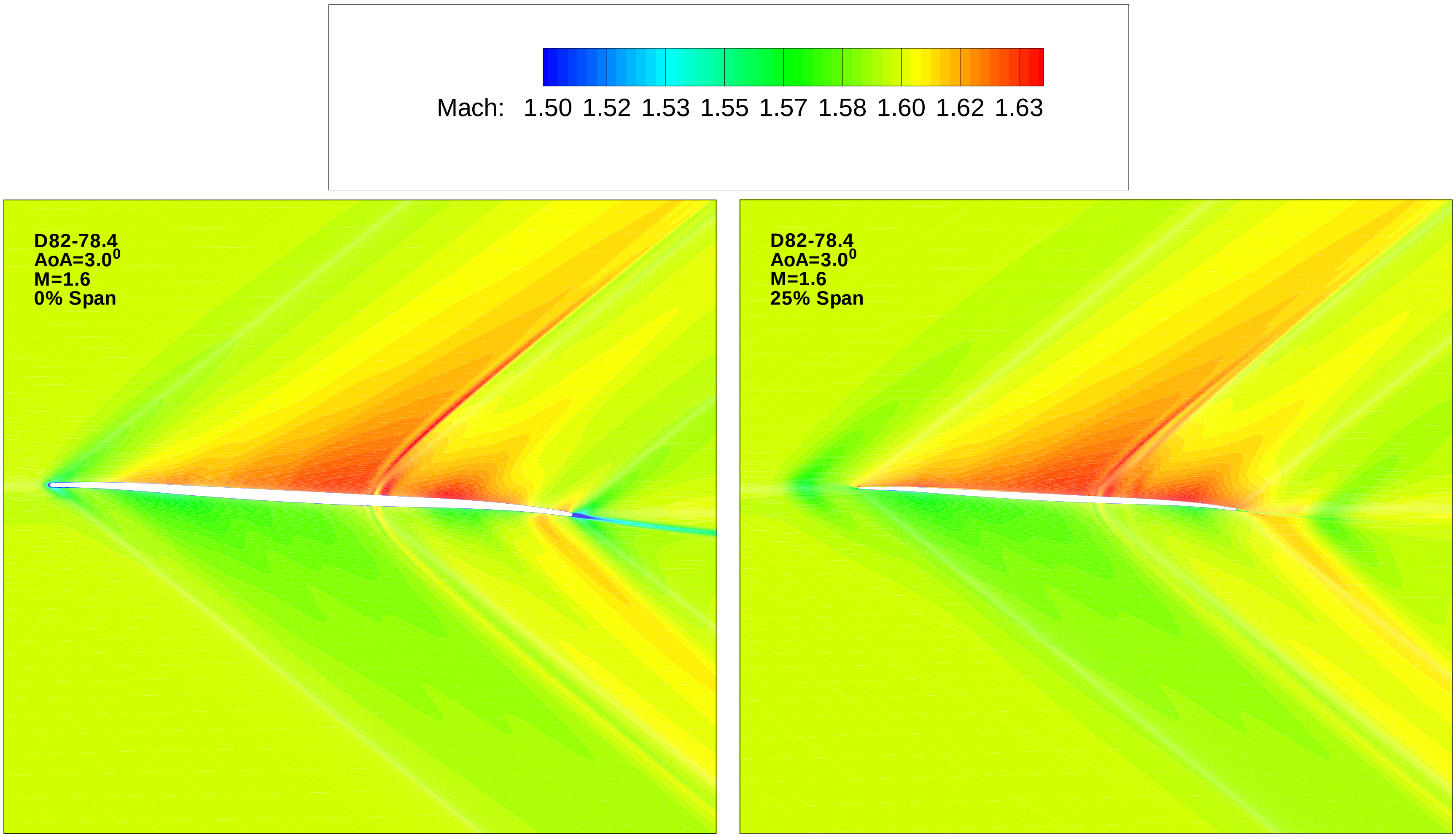


Surface Isentropic Mach number distribution

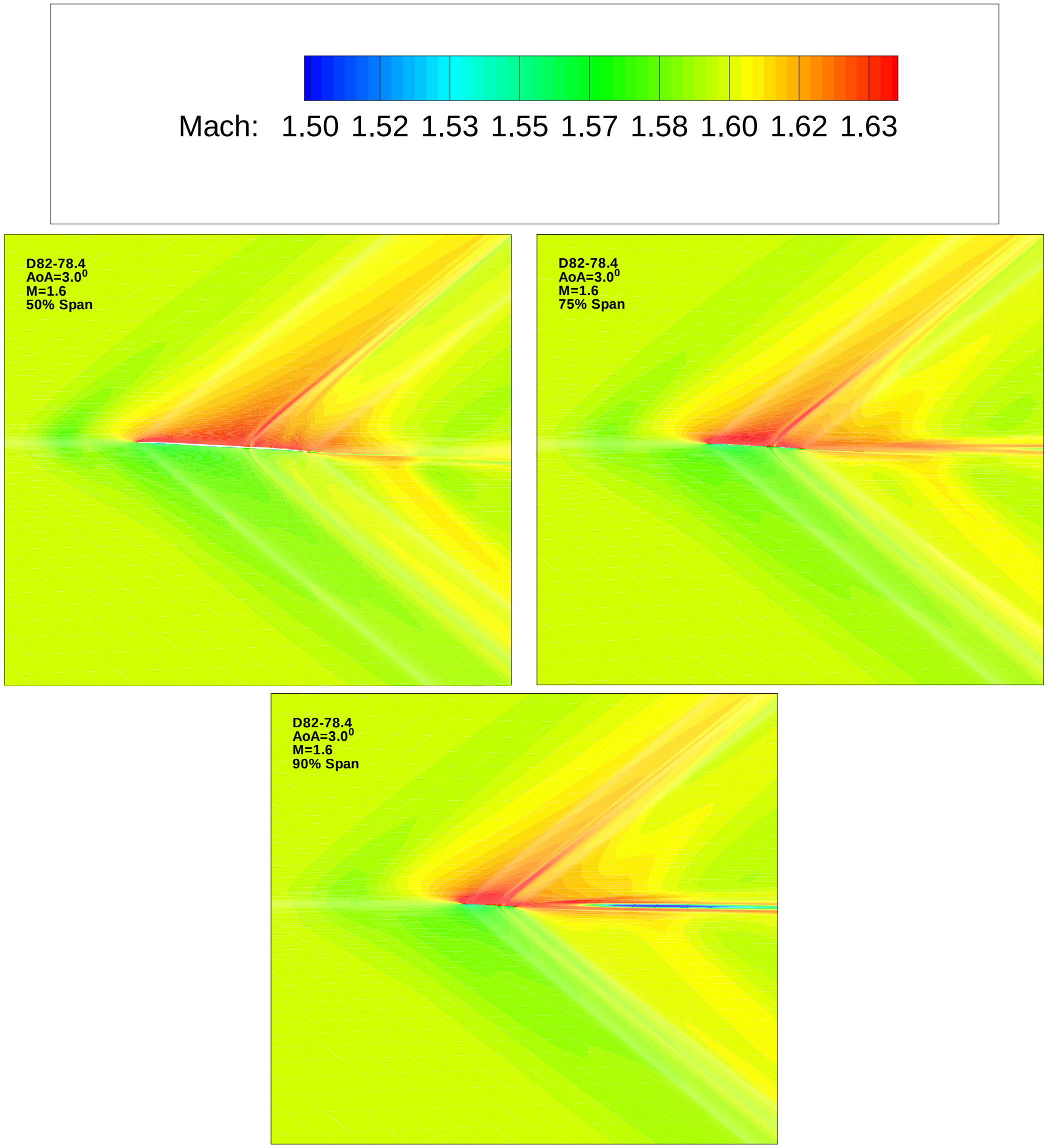




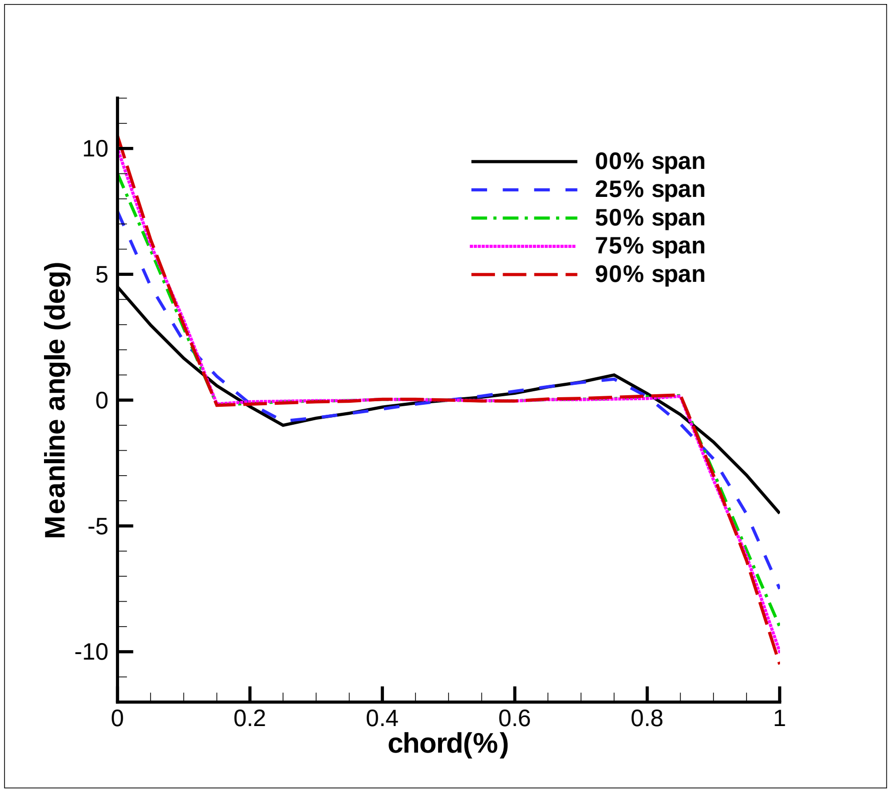
Mach number contours at different span



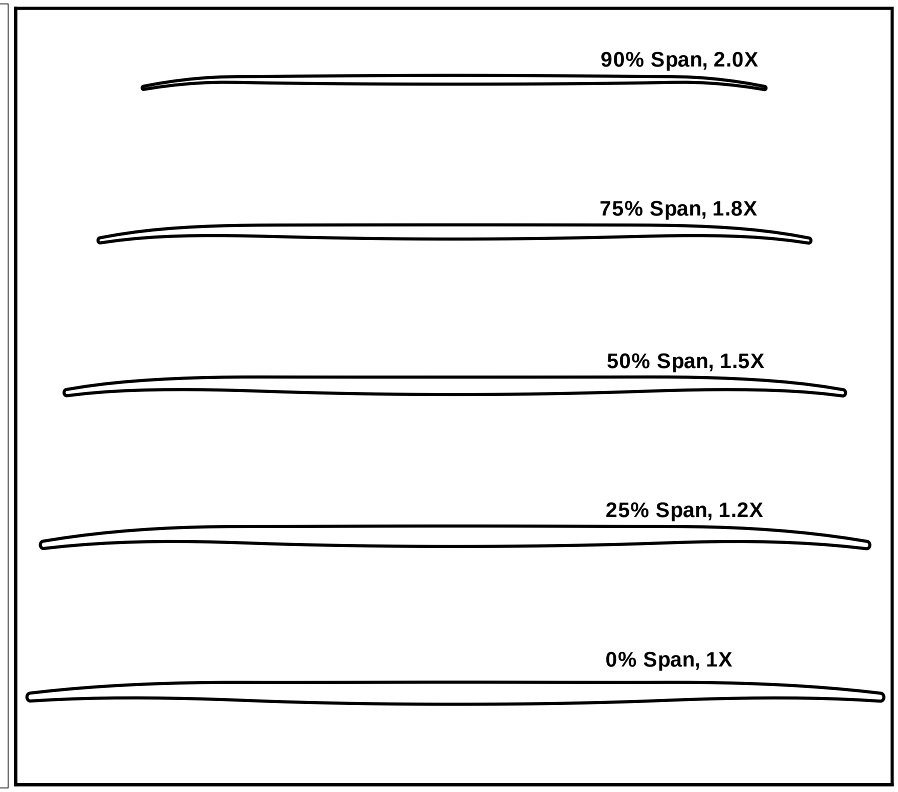
Mach number contours at different span



Increased L/D, D82-78.8



Meanline angle distribution of D82-78.8.

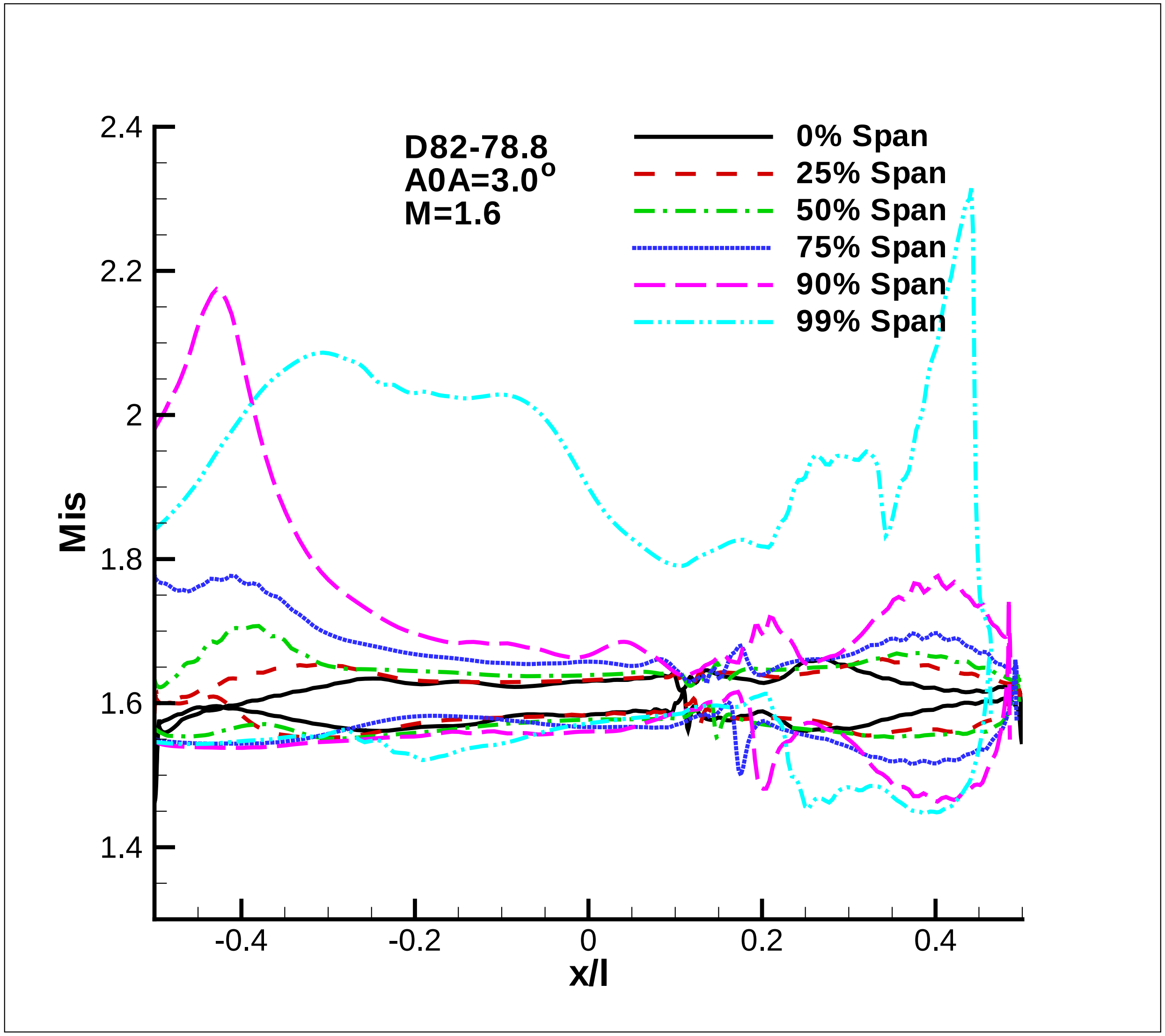


Supersonic airfoil shape at different span of D82-78.8.

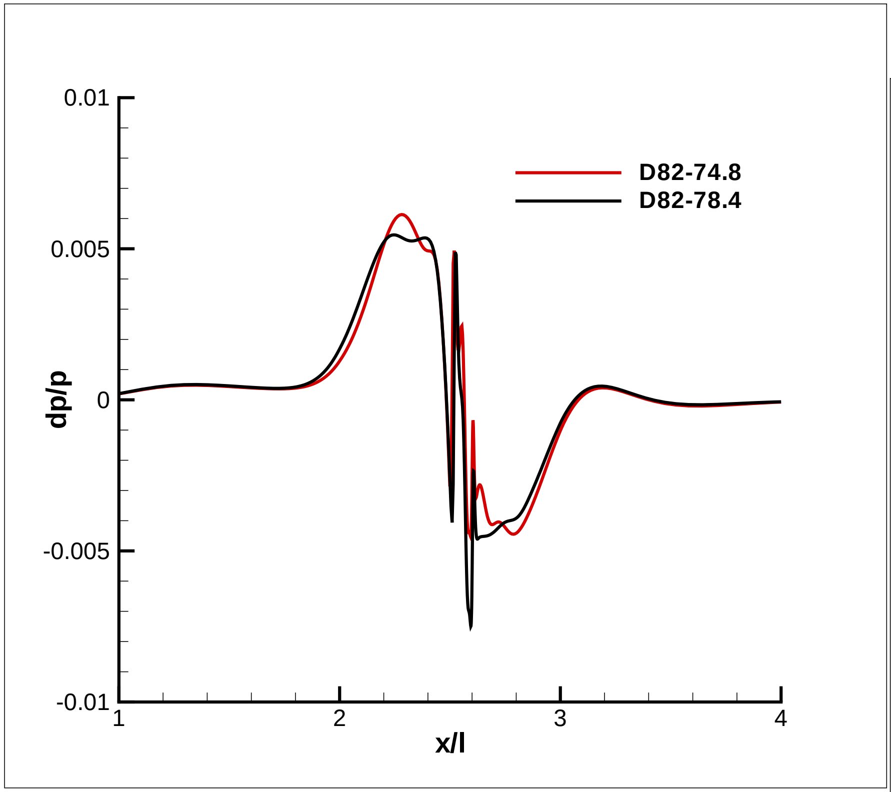
D82-78.8

Length(m)	Span(m)	Area(m^2)	Vol(m^3)	AR(sub)	AR(sup)
100	16.5	764	650	13.074	0.356
Cl	Cd	Cl/Cd	Cm		
0.06021	0.00705	8.54043	-0.00171		
Altitude(ft)	48000	50000	52000	56000	60000
Noise(PLdB)	76.24	74.57	71.91	71.60	70.78

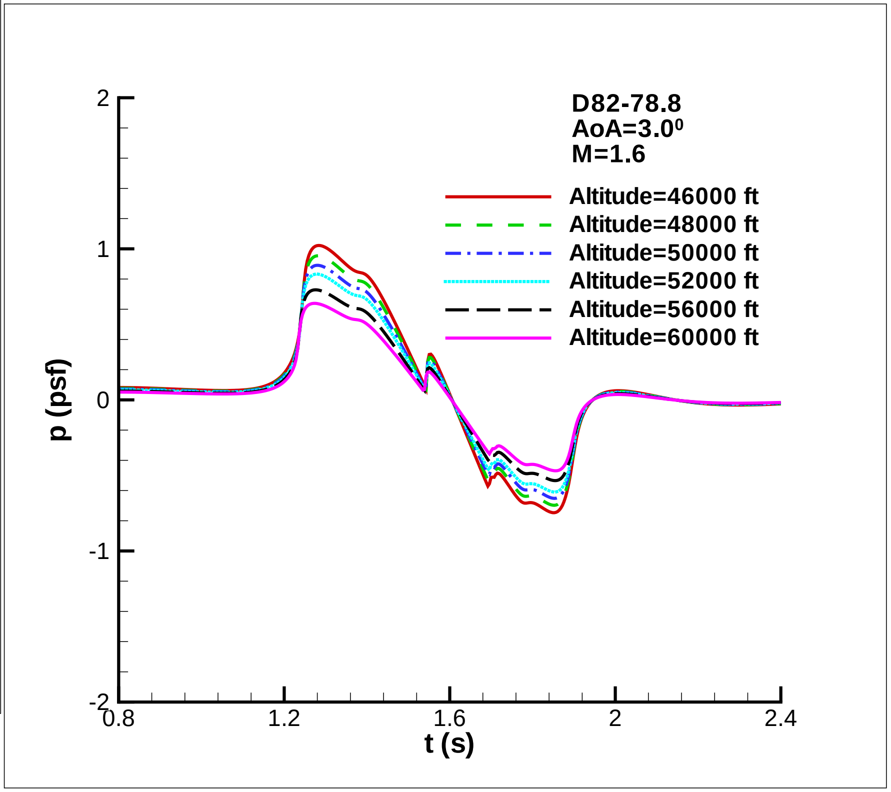
Mach chord distributions at different span



Overpressure 2-body below and ground

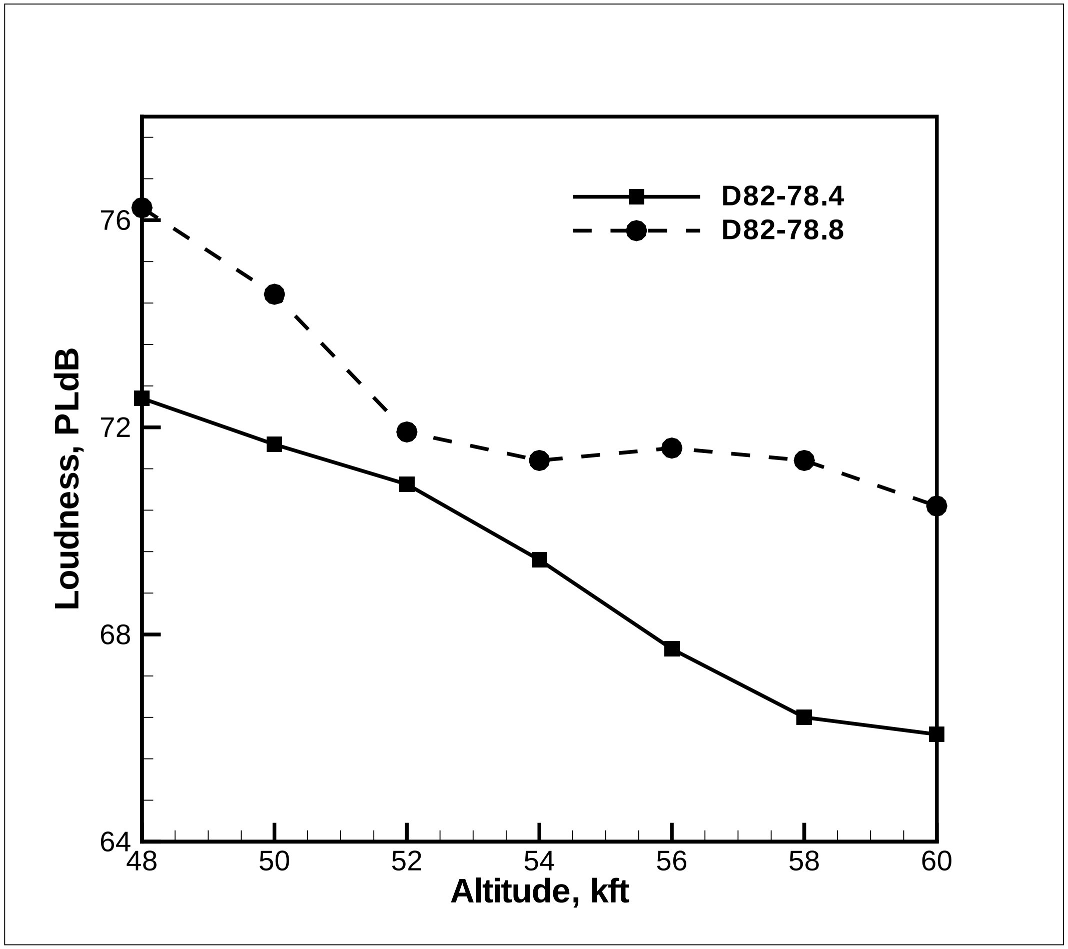


Chordwise isentropic Mach number distributions at different span of D82-78.8.

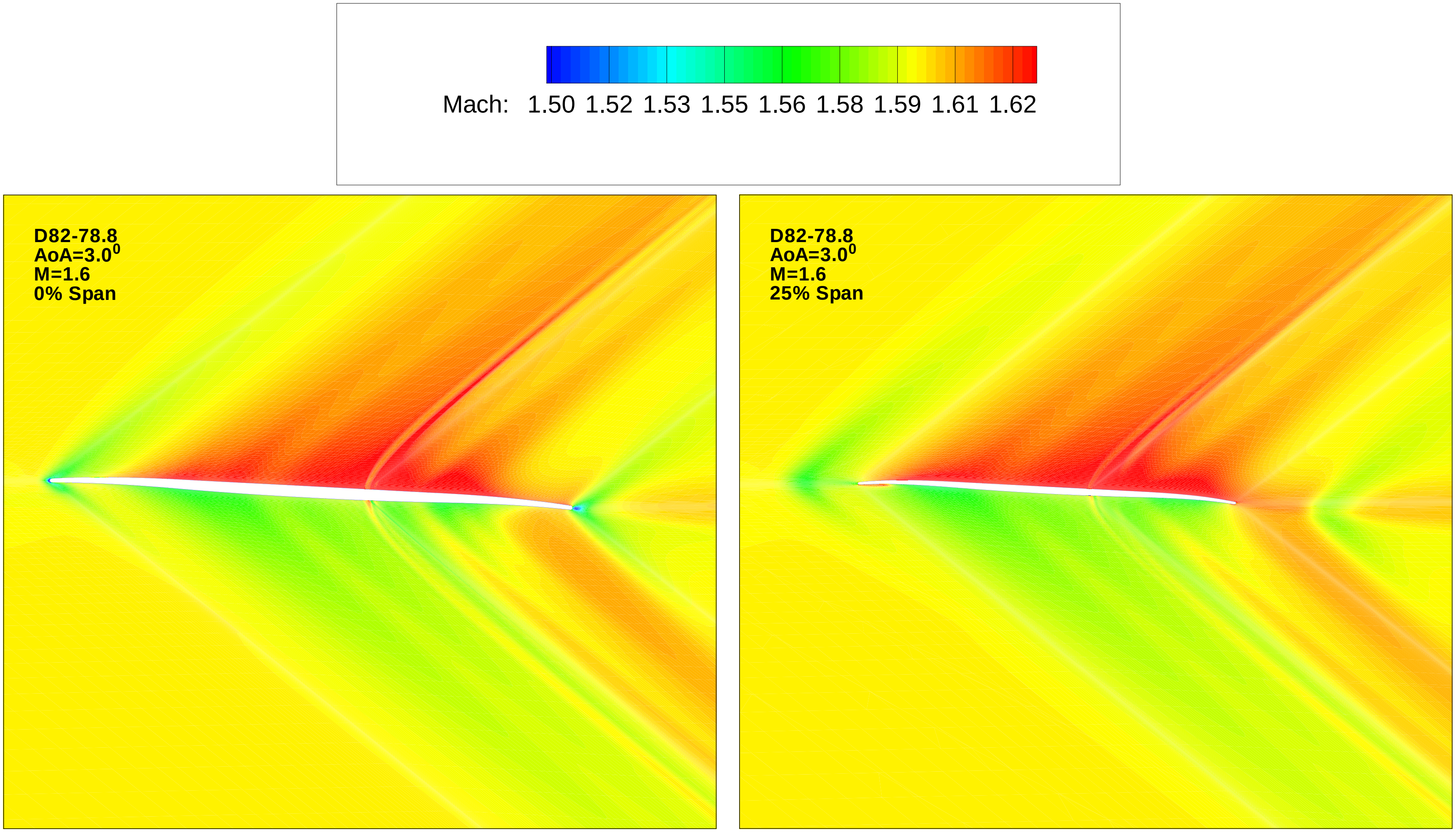


Ground overpressure sonic boom signature of D82-78.8.

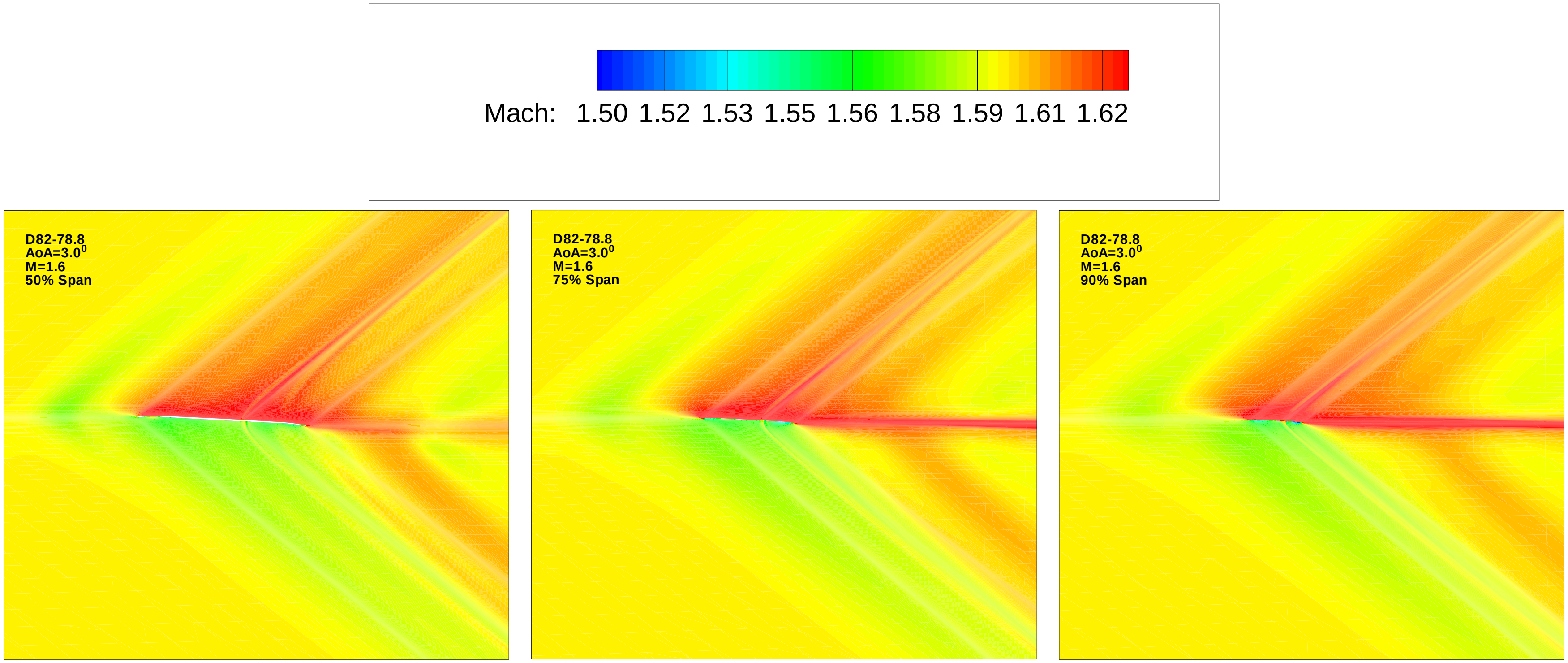
Ground boom level comparison



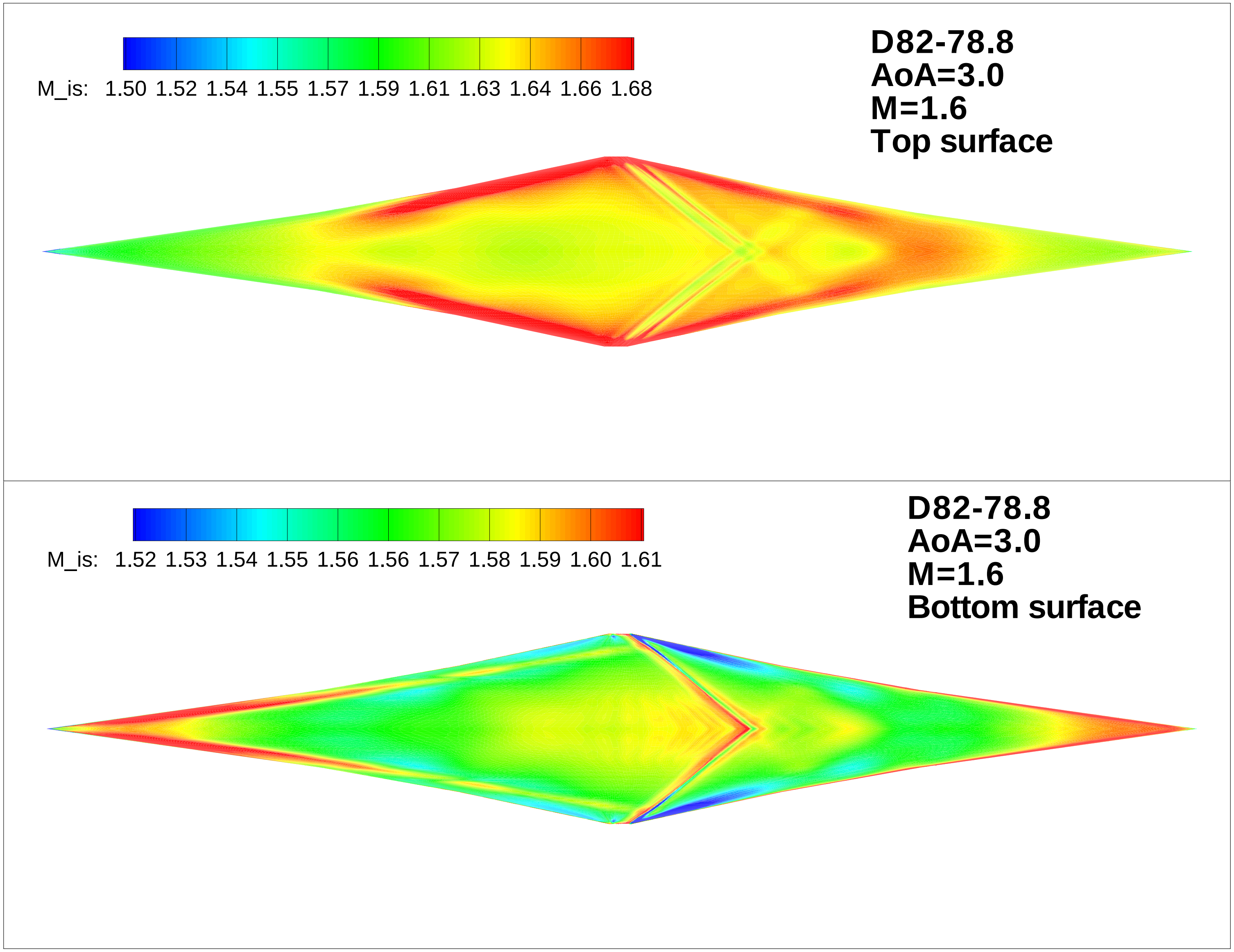
Mach number contours at 0 and 25% span, D82-78.8.



Mach number contours at 50%, 75% and 90% span, D82-78.8.

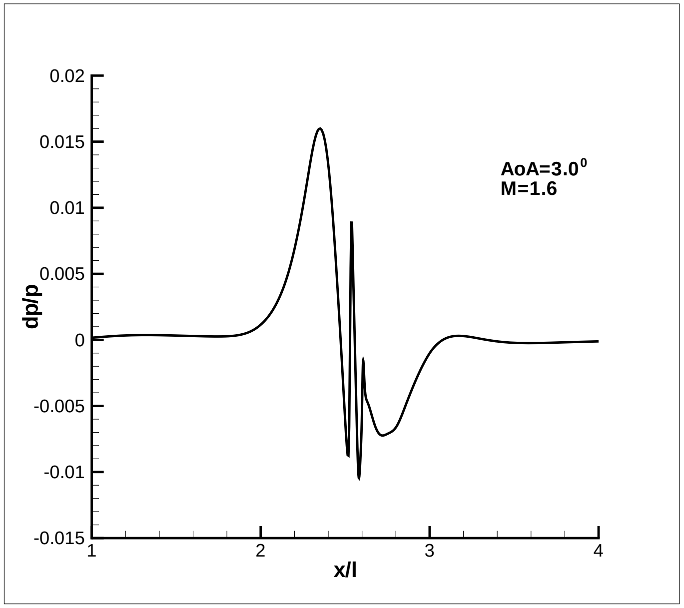


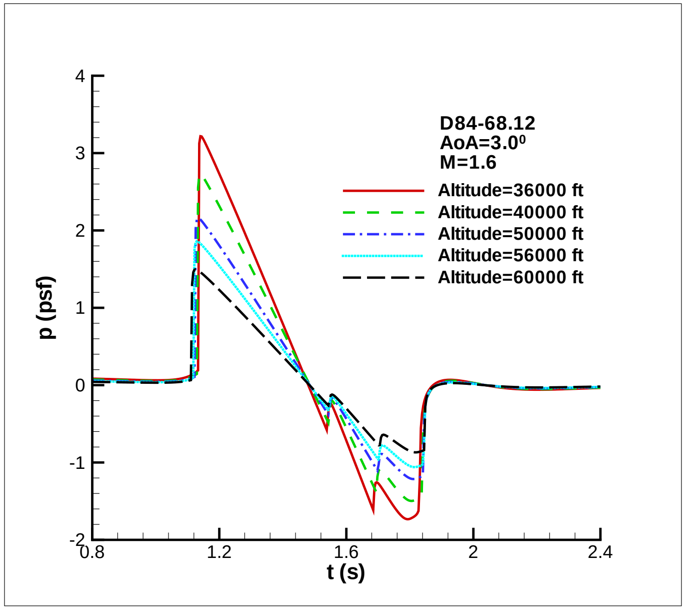
Suction and Pressure Surface Mach contours



High L/D design: D84-68.12, Refined mesh

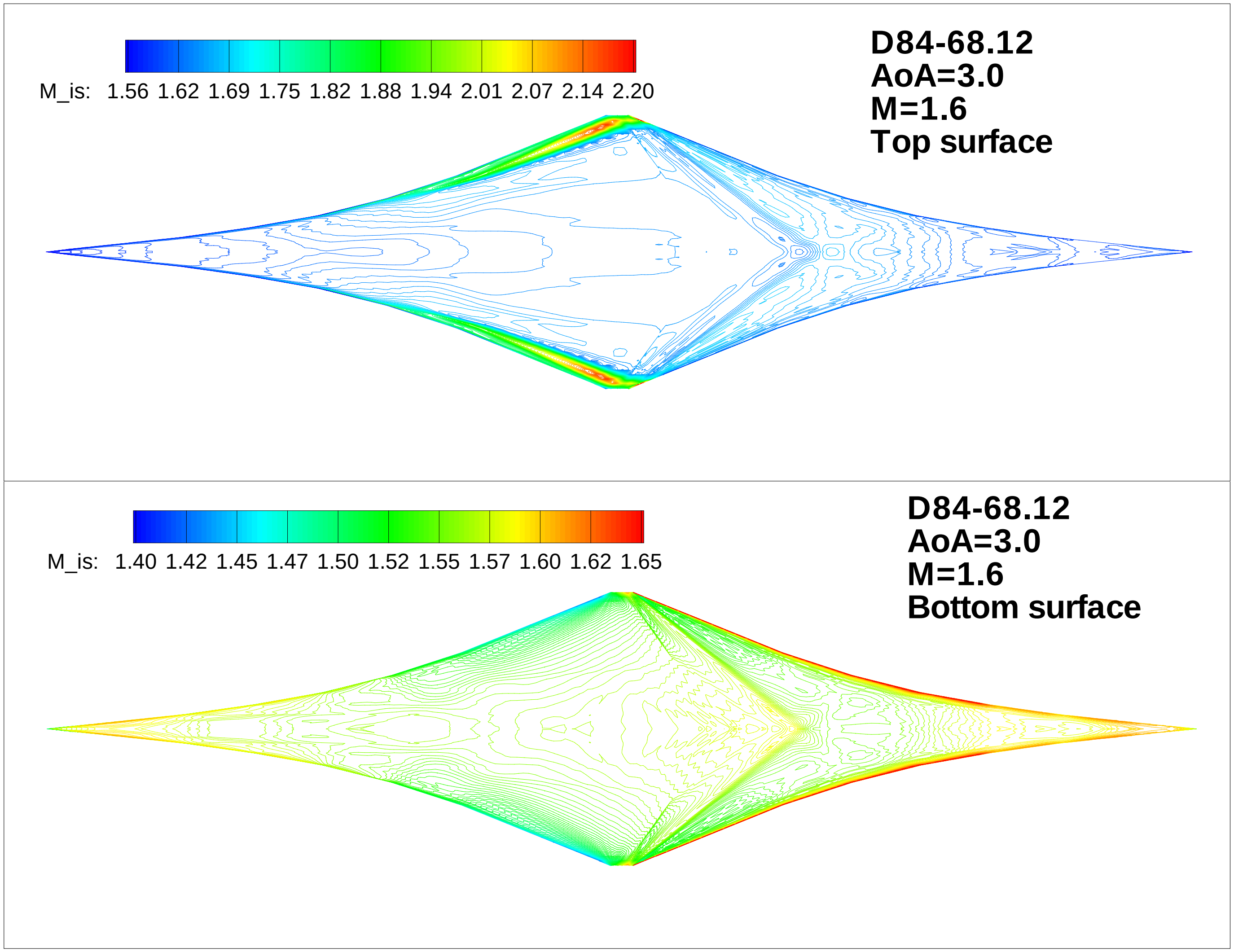
Length(m)	Span(m)	Area(m^2)	Volume(m^3)	AR(subsonic)	AR(supersor
100	23.7	891	585	11.23	0.632
Cl	Cd	Cl/Cd			
0.08437	0.00813	10.378			
Altitude(ft)	30000	40000	50000	56000	60000
Noise(PLdB)	102.00	100.02	96.46	93.32	92.07





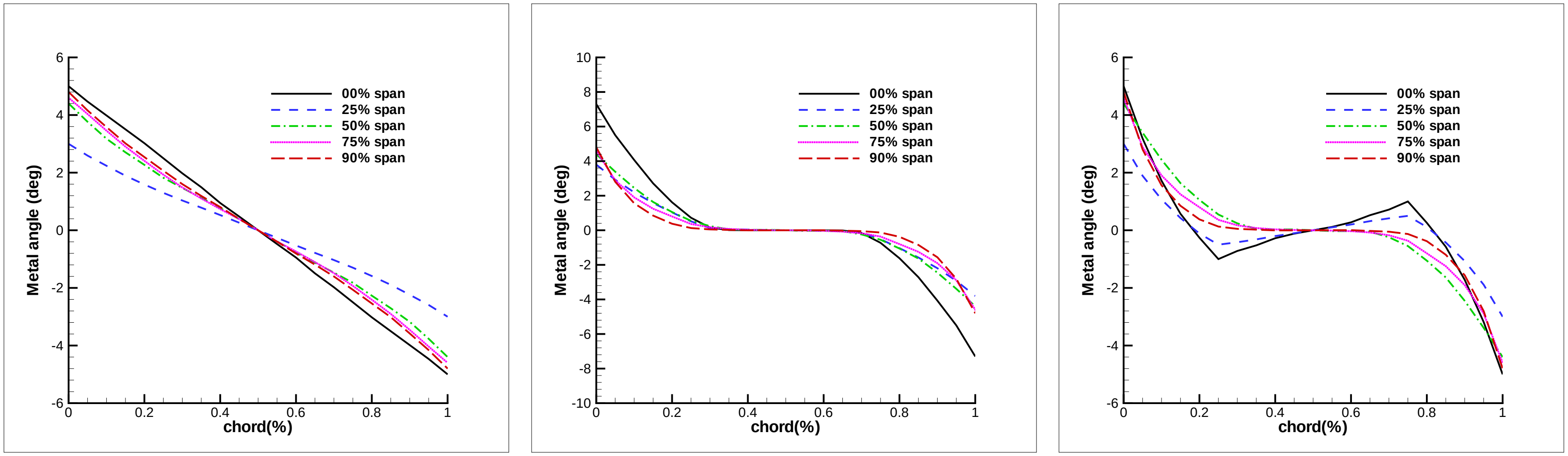
Left: over-pressure at 2 body below; Right: ground signatures

Results of D84-68.12

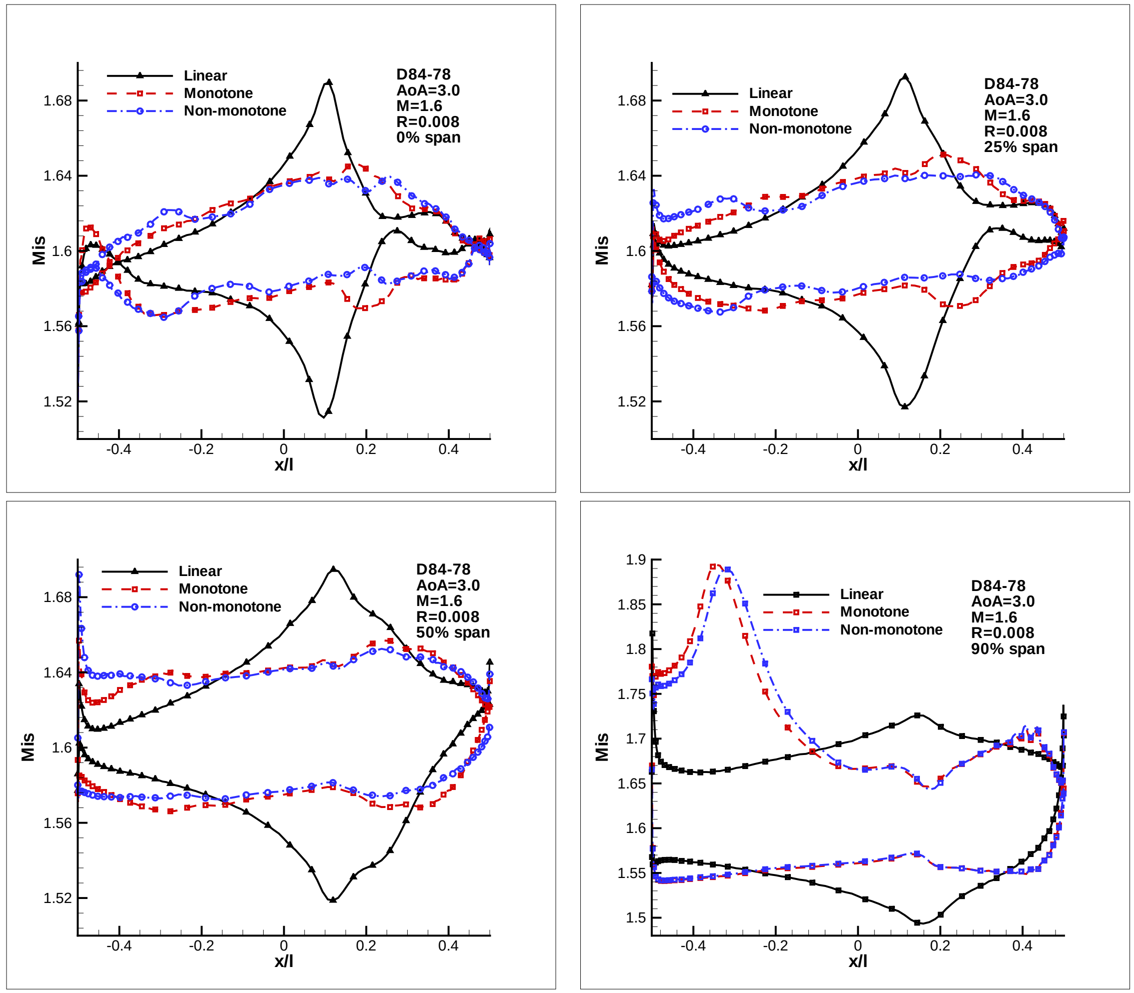


Wall surface isentropic mach number distribution

Meanline Angle Distribution Comparison, linear, monotonic, non-monotonic.



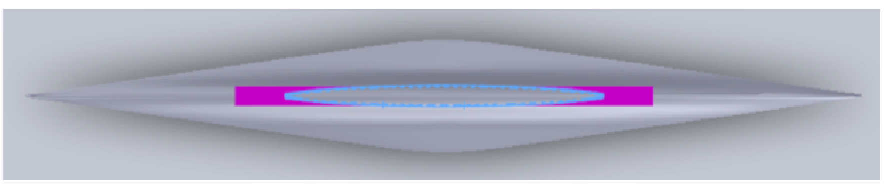
Surface chordwise Isentropic Mach number distributions, 20PLd
reduction from linear to non-monontonic

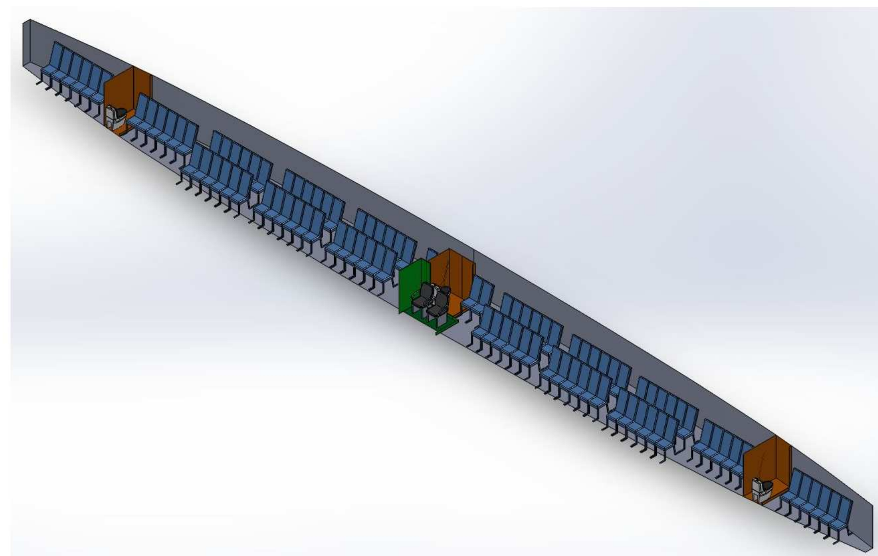


Cabin assembly

Left: the pink area is the seating area with minimum height of 1.8m.

Right: detailed 100 passenger seats arrangement including lavatories and crew cabin in the middle.





Conclusion

- A preliminary design of supersonic flying wing from trade study: Mach 1.6, 100 passengers, R=4000nm, L=100m, Alt=50kft, W_{TO}=196,543Lb.

- D82-78.4 Achieve L/D=8.2, ground sonic boom noise PLdB 72, 68, 66 at alt=50k, 56k, 60k.

- D82-78.8 Achieve L/D=8.54, ground sonic boom noise PLdB 72, at alt=52k

- Trade study at supersonic achieves high L/D fairly straightforwardly, but low boom is much more challenging.

- Design with variable sweep from 84° to 68° achieves a L/D of 10.4, PLdB=95(not shown in this presentation).

- Sonic boom on ground can be directly controlled by longitudinal loading distribution on SBiDir-FW surface.

- Non-monotonic meanline angle distribution very effective to mitigate compression wave coalescing and sonic boom.