SciTech2015, Jan. 5-9, 2015, Orlando, FL

Conceptual Design of High Wing Loading Compact Electric Airplane Utilizing Co-Flow Jet Flow Control

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Background

- Global climate change calls for clean vehicles to reduce carbon emission.

- Electric road vehicles became more and more popular.

- Low battery energy density is a challenge for all vehicles.

- Electric airplanes(EA) start to attract attention, but struggling for payload and range.

- General Aviation(GA) EA is an active area due to relatively low total energy requirement.

- The current EA is too large in size, too small for payload, and too short for range

Cessna 172, conventional GA using reciprocating engine.

4 passengers, range=700nm, wing span=11m, CL=0.32, L/D=9, W/S=68.6kg/m^2

e-Genius, EA, broke 7 world records, July 2014.

2 passengers, range=216nm,wing span=14.56m, CL=0.57, L/D=26, W/S=61.8kg/m^2

Taurus G4 EA, winner of the Green Flight Challenge, 2011.

4 passengers, range=250nm, wing span=21.36m,
CL=0.50, L/D=28, W/S=69.6kg/m^2

Embraer Regional Jet ERJ145XR.

50 passengers, range=2000nm, wing span=20.04m, shorter than that of Taurus G4.

Motivation

- Can we keep a GA EA at a small size, but still have a useful payload and range?

- Small size GA is easier for storage and more efficient use of numerous small airports.

$$W = L = 0.5 * \rho_\infty V_\infty^2 S C_L \tag{1}$$

$$W/S = 0.5 * \rho_\infty V_\infty^2 C_L \tag{2}$$

- Must have radically higher wing loading and cruise lift coefficient.

- Conventional GA, cruise C_L=0.3-0.5, higher than that will have poor aero efficiency and stall margin.

- If we can achieve L/D comparable to conventional design, small S saves energy because

$$T = D = 0.5 * \rho_\infty V_\infty^2 S C_D = 0.5 * \rho_\infty V_\infty^2 S \frac{W}{L/D} \qquad (3)$$

Objective

- Design a 4 passenger EA with similar size to a conventional GA using reciprocating engine.

- Double the range of a same size conventional EA by carrying more battery.

- Pursuing a revolutionary airfoil performance.

Strategy

- Co-Flow Jet (CFJ) flow control wing to achieve ultra high cruise lift coefficient, C_L(e.g. 1.3) and excellent cruise L/D(e.g. 24) at low C_μ.

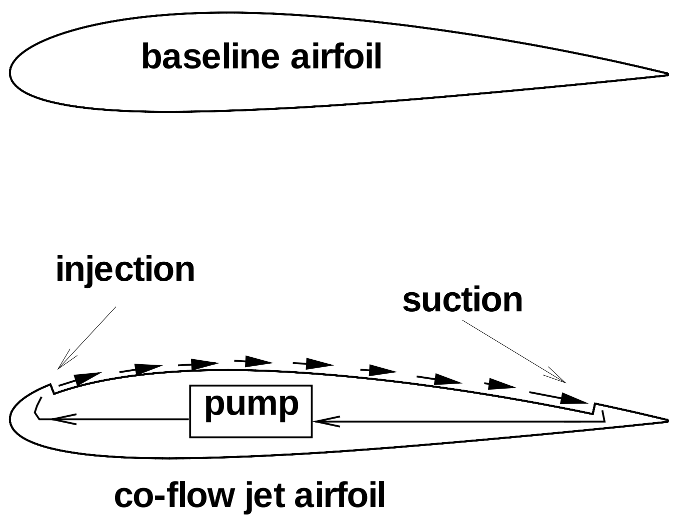
- CFJ wing to achieve high maximum C_L (e.g. $\geq$ 4.8) to shorten takeoff/landing distance.

- High cruise C_L yields high wing loading.

- A same size EA using CFJ can carry more battery to have substantially longer range;

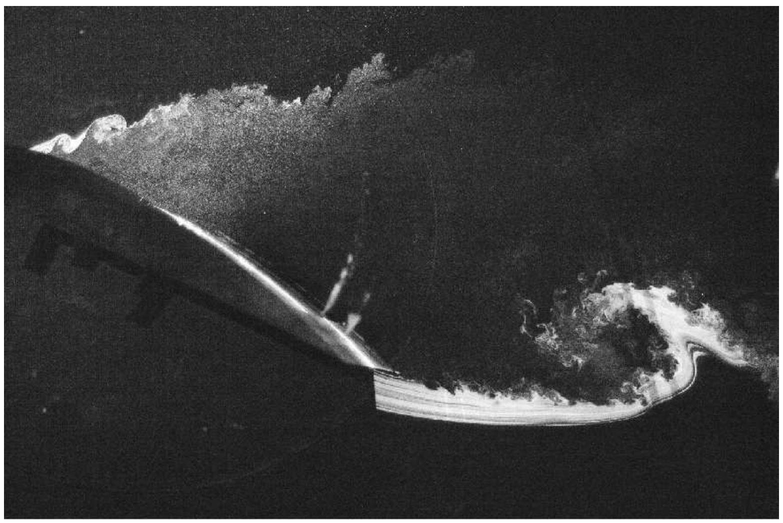
- For the same range, the EA using CFJ will have much smaller size.

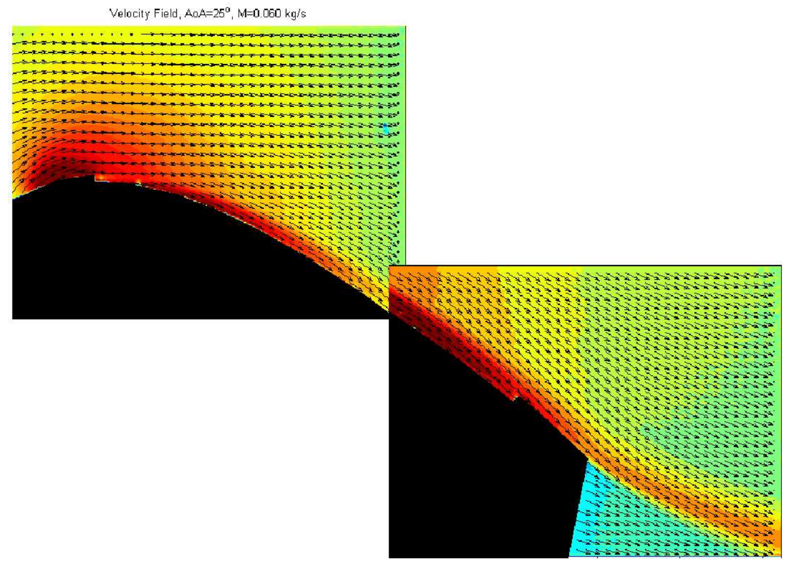
Co-Flow Jet Airfoil



- Ultra high lift
- Reduce drag (or generate thrust)
- High stall AoA
- Low energy expenditure

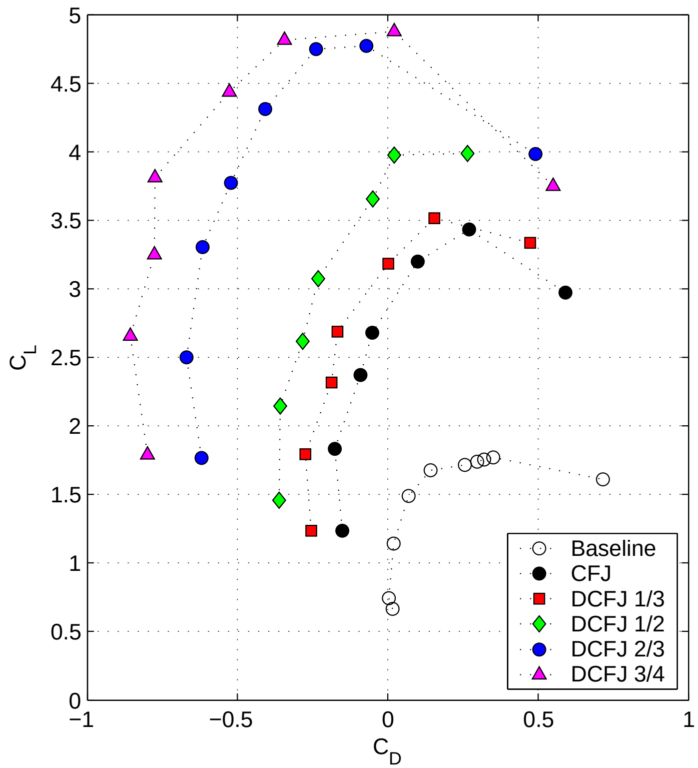
Wind Tunnel Testing of Co-Flow Jet Airfoil

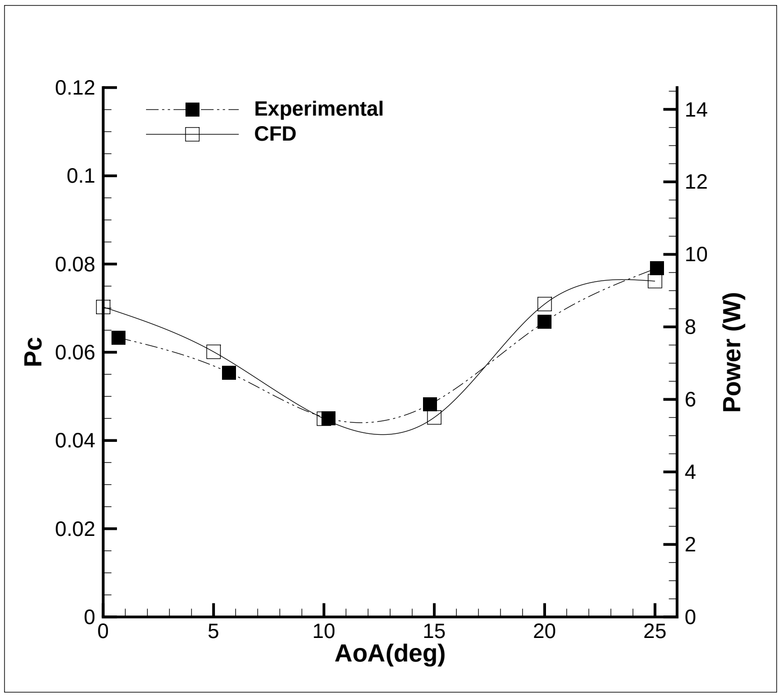




Baseline(left) and CFJ (right) NACA 6415 airfoil at AoA=25°

Wind Tunnel Testing of Co-Flow Jet Airfoil





CFJ airfoil drag polar($C_\mu = 0.25$) and energy expenditure($C_\mu = 0.08$)

CFD Numerical Solver

- 3D Reynolds averaged Navier-Stokes equations in generalized coordinates
- 5th order Weighted Essentially Non-Oscillatory (WENO) shock capturing schemes
- Low Diffusion E-CUSP Scheme as Riemann Solver for Shock Waves
- 4th conservative central differencing scheme for viscous fluxes with WENO stencil width
- Slalart-Allmaras one-equation turbulence model
- Implicit Unfactored Gauss-Seidel Time Marching for CPU Efficiency and Solid Convergence
- Code intensively validated for CFJ airfoils and DLR-F6 wing/body lift, drag and moment prediction

CFJ Forces calculation

Lift and drag

$$D = R'_x - F_{x_{cfj}} \tag{4}$$

$$L = R'_y - F_{y_{cfj}} \tag{5}$$

Jet Reactionary Forces

$$F_{x_{cfj}} = (\dot{m}_j V_{j1} + p_{j1} A_{j1}) * cos(\theta_1 - \alpha) - (\dot{m}_j V_{j2} + p_{j2} A_{j2}) * cos(\theta_2 + \alpha)$$

$$F_{y_{cfj}} = (\dot{m}_{j1} V_{j1} + p_{j1} A_{j1}) * sin(\theta_1 - \alpha) + (\dot{m}_{j2} V_{j2} + p_{j2} A_{j2}) * sin(\theta_2 + \alpha)$$

CFJ Parameters

Injection jet momentum coefficient:

$$C_\mu = \frac{\dot{m} V_j}{\frac{1}{2}\rho_\infty {V_\infty}^2 S} \tag{6}$$

CFJ Pumping Power and Power Coefficient

$$P = \frac{\dot{m} C_p T_{t2}}{\eta} (\Gamma^{\frac{\gamma-1}{\gamma}} - 1) \tag{7}$$

Pumping efficiency $\eta = 0.85$

$$P_c = \frac{P}{\frac{1}{2}\rho_\infty V_\infty^3 S} \tag{8}$$

Aerodynamic efficiency

$$(\frac{L}{D})_c = \frac{L}{D + \frac{P}{V_\infty}} \tag{9}$$

L/D is pure aerodynamic parameter for the ratio of lift to drag.

Range Estimate for Electric Aircraft

$$
\begin{aligned}
R &= E_c \cdot \eta \cdot \frac{1}{g} \cdot (\frac{L}{D})_c \cdot \frac{W_b}{W} \\
&= E_c \cdot \eta \cdot \frac{1}{g} \cdot (\frac{L}{D})_c \cdot (1 - \frac{W_p}{W} - \frac{W_s}{W}) \\
&= E_c \cdot \eta \cdot \frac{1}{g} \cdot (\frac{L}{D})_c \cdot (1 - \frac{W_p}{W} - SF) \qquad (10)
\end{aligned}
$$

SF: structure factor=0.45. Propeller efficiency $\eta = 0.75$

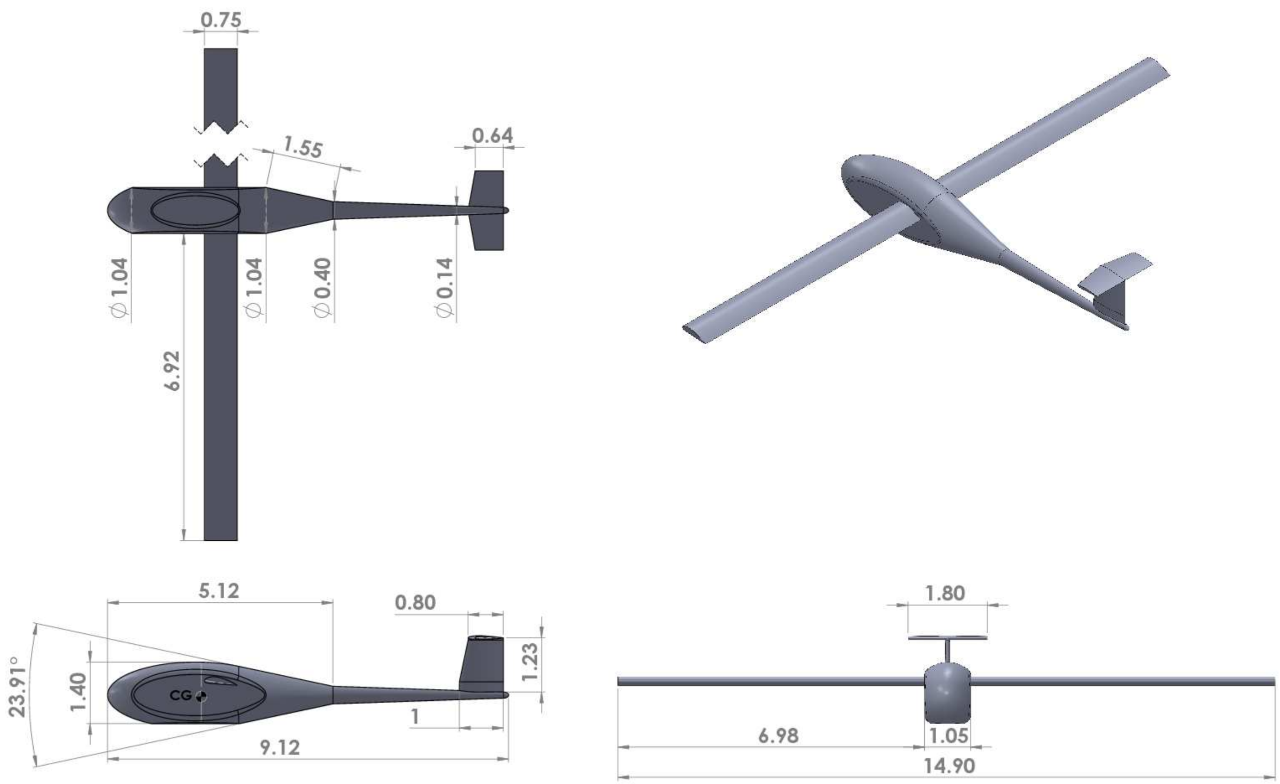
Compact size tends to have smaller SF.

If payload and SF are same, increase W $->$ increase R.

CFJ-EA Mission Requirements

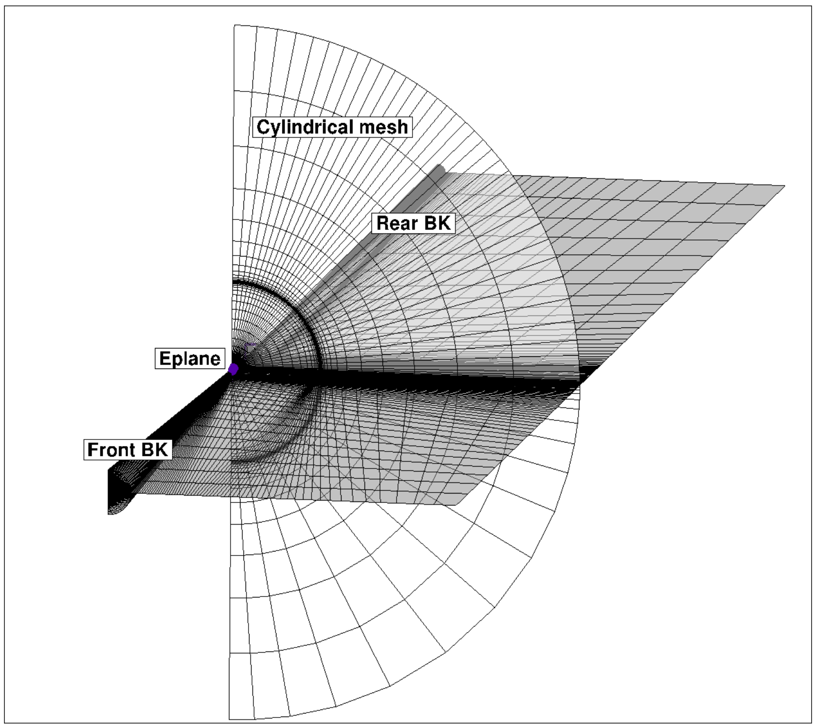
- 4 Passengers, $R \approx 300nm$, Altitude=1524m (5000ft)
- Cruise Speed, Mach=0.15, 51m/s (114miles/h)
- Takeoff distance $\approx 610m(2000ft)$
- Wing Span=15m, $(L/D)_c \geq 24$

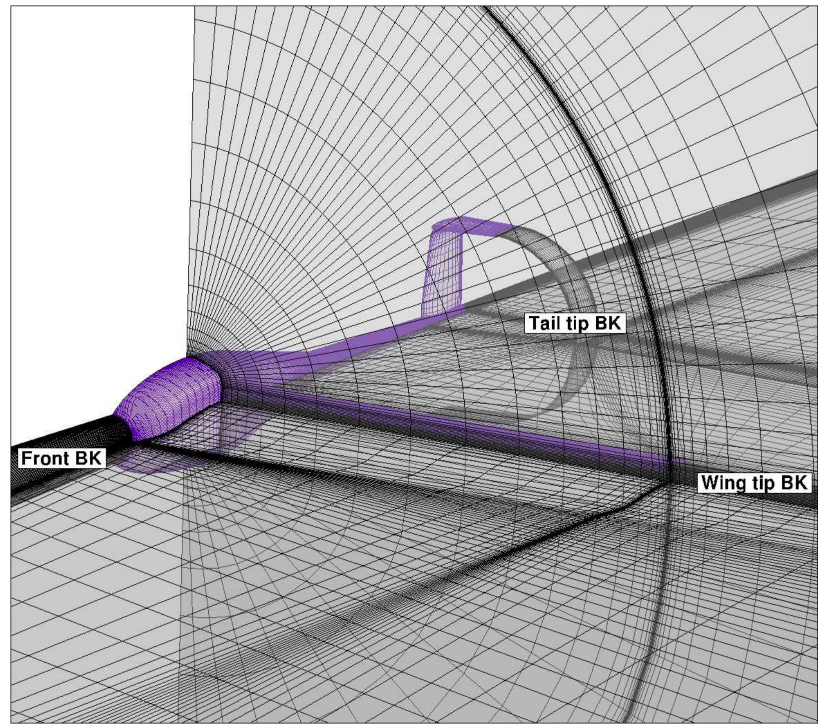
CFJ Electric Airplane Configuration (m),AR=21.5



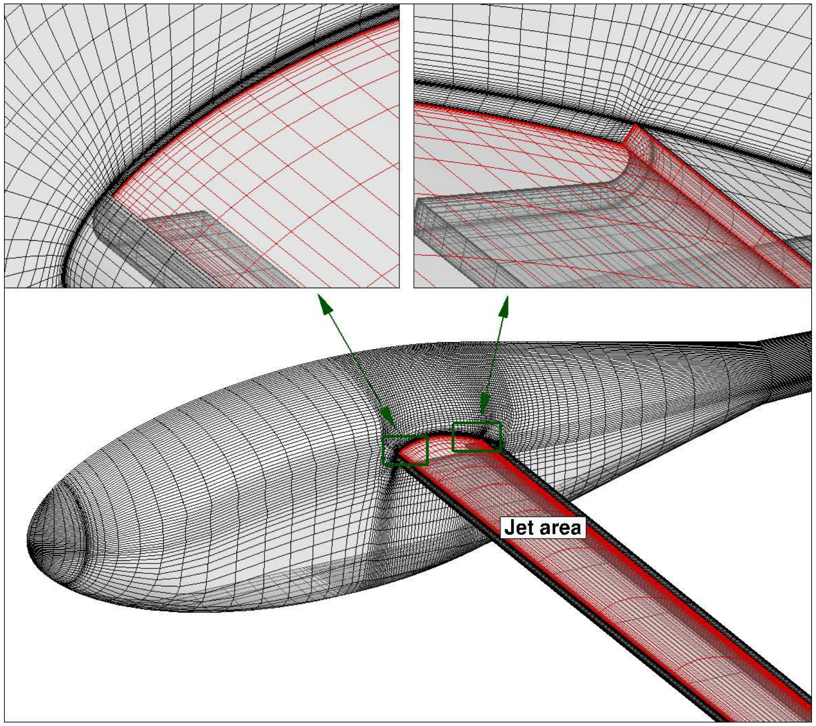
Cruise:Wing AoA=5°; Takeoff/Landing: Wing AoA=25°, Fuselage rotates 5°, Wing rotates 15°

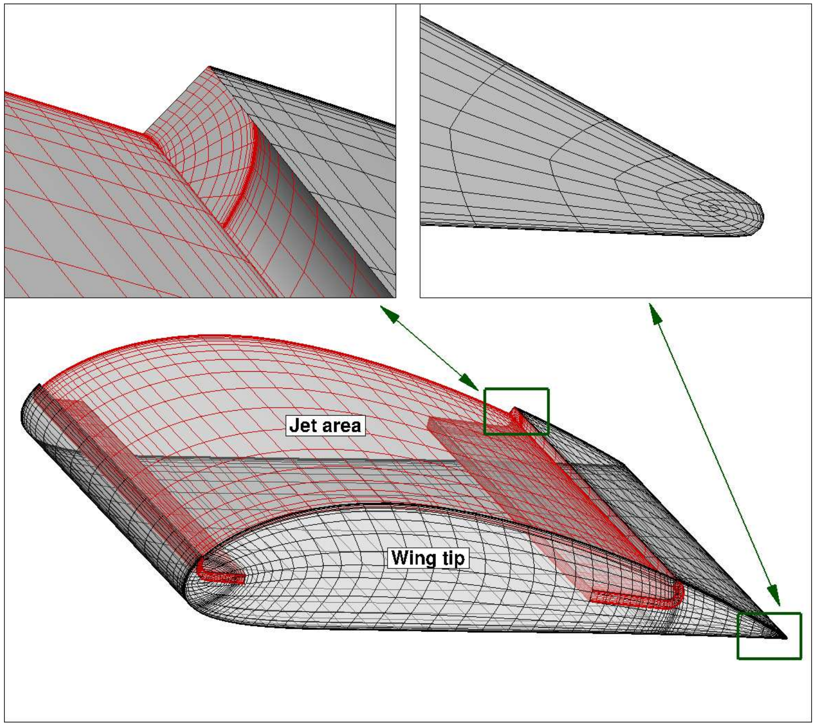
Mesh, 10.4M points, shown every other line



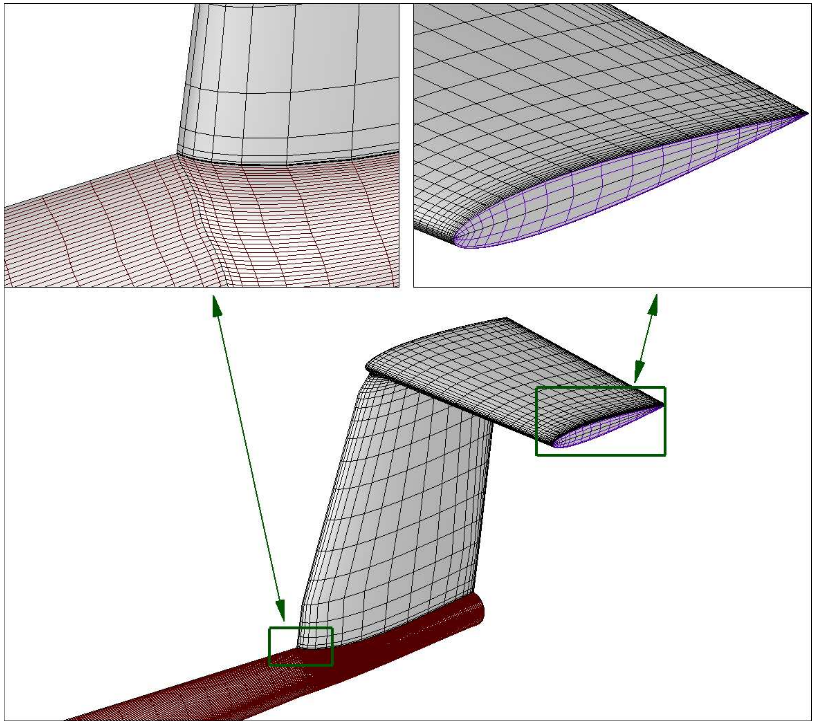


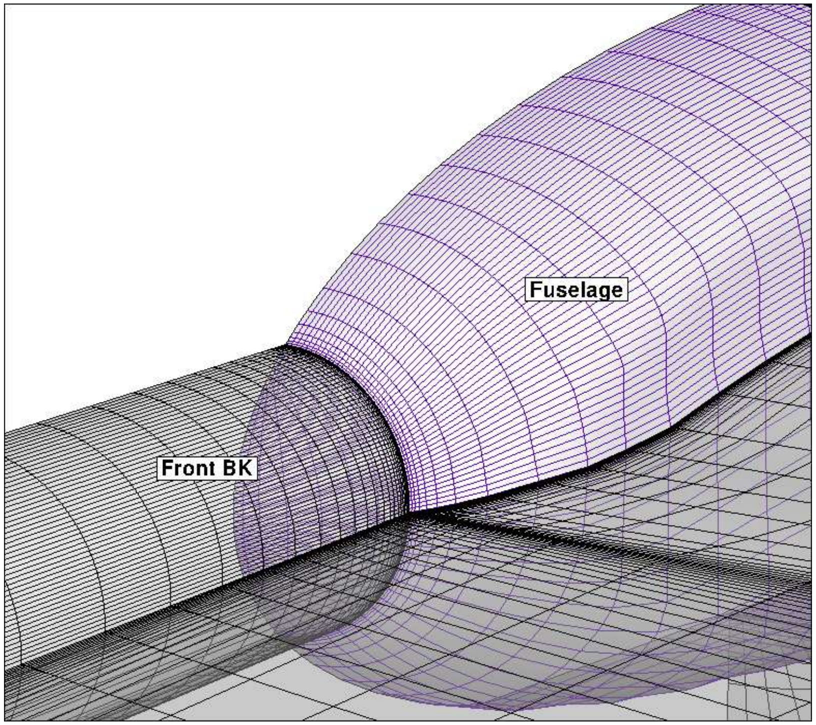
Mesh, 225 blocks



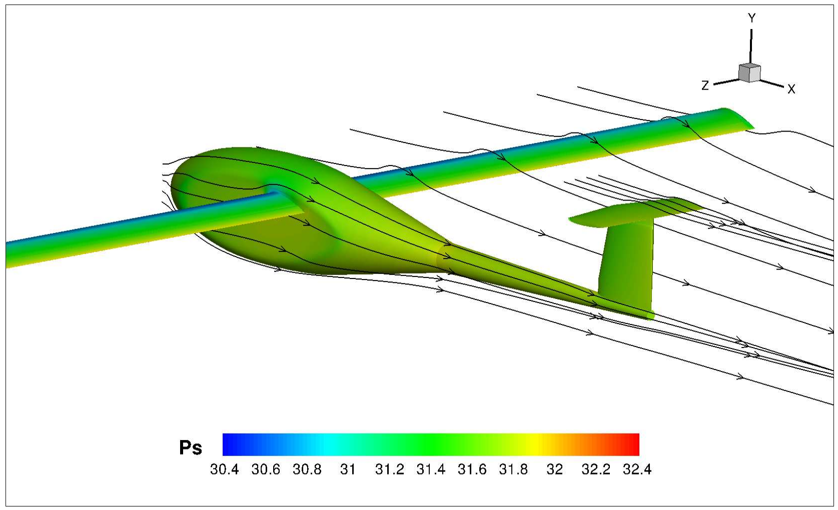


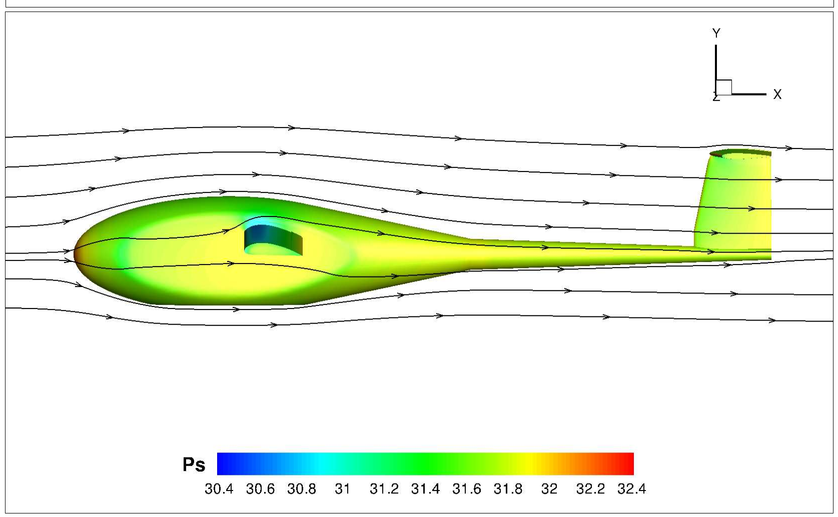
Mesh



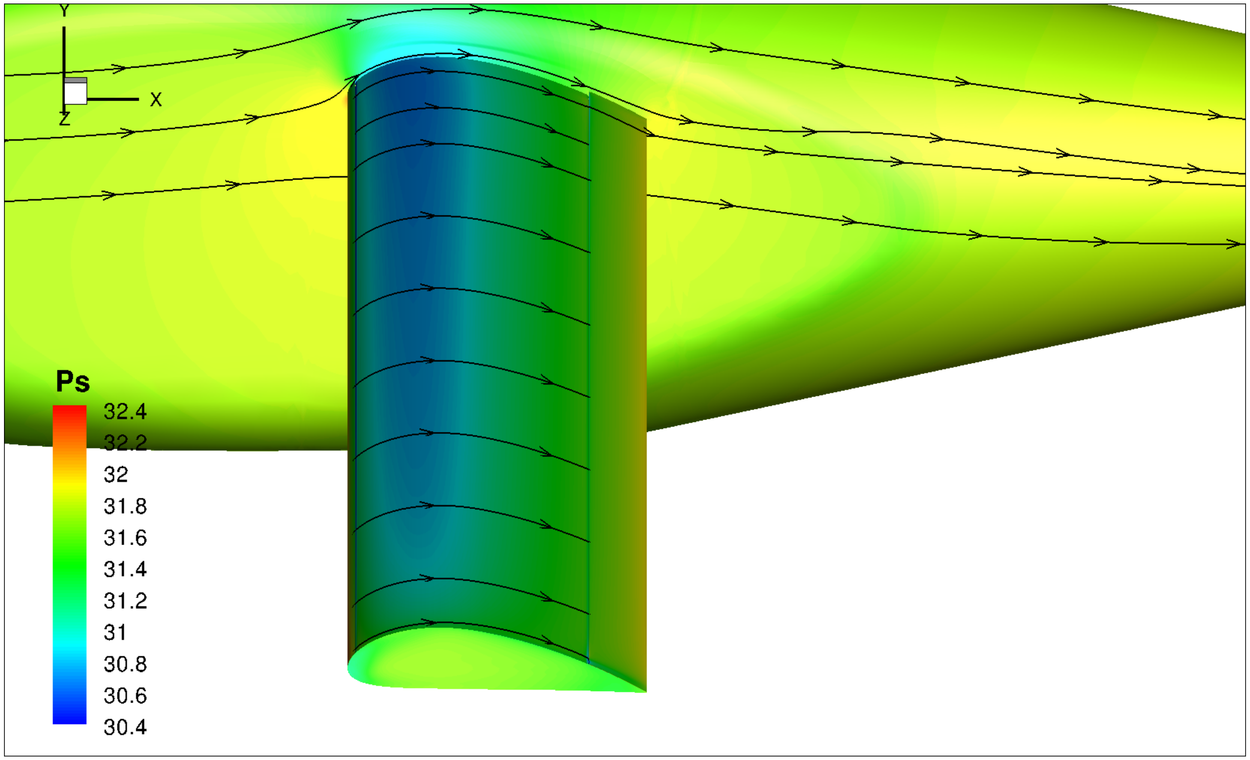


Surface Pressure Contours, Cruise, $C_\mu = 0.04$

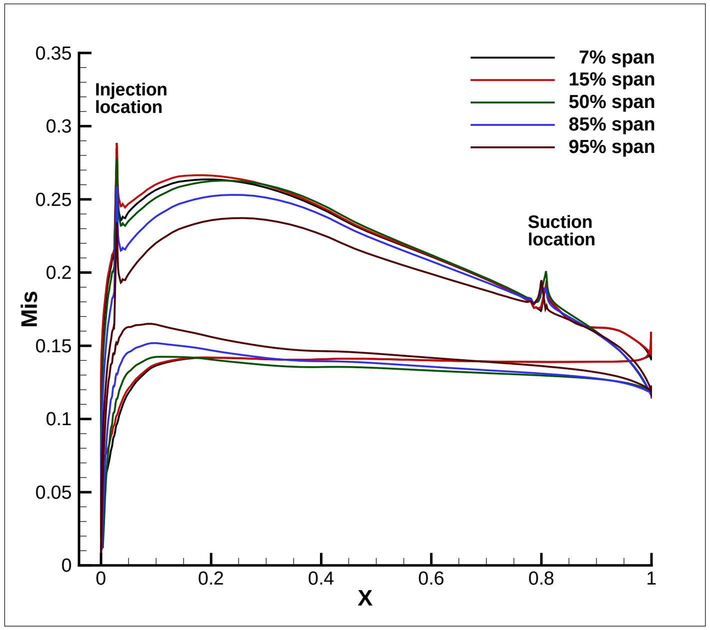


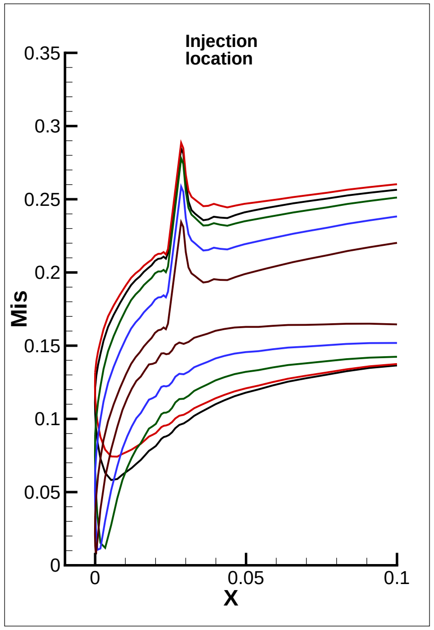


Surface Pressure Contours, Cruise, $C_L = 1.3$

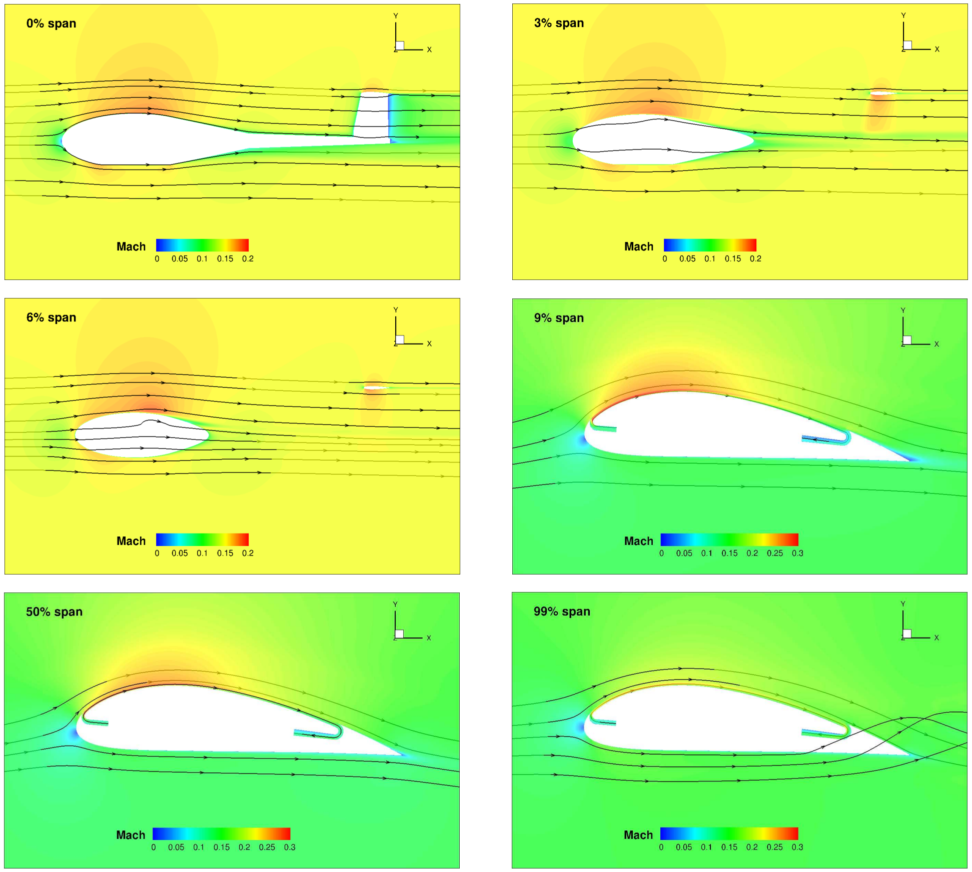


Isentropic Mach distributions at different span, Cruise, (L/D)c=24



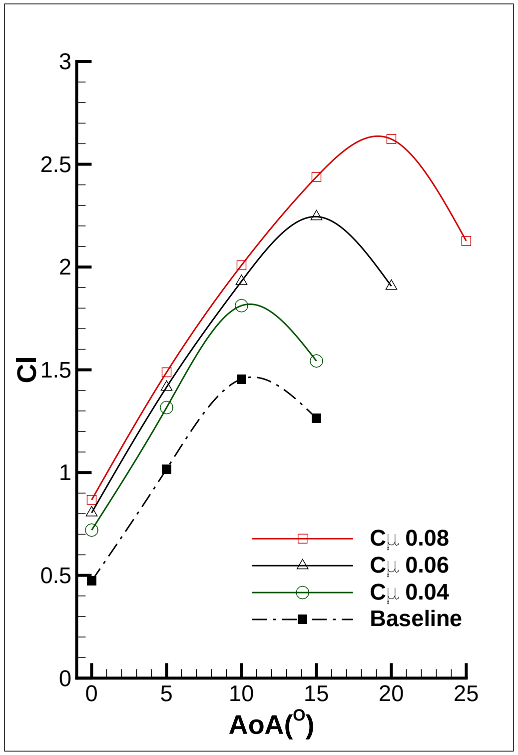


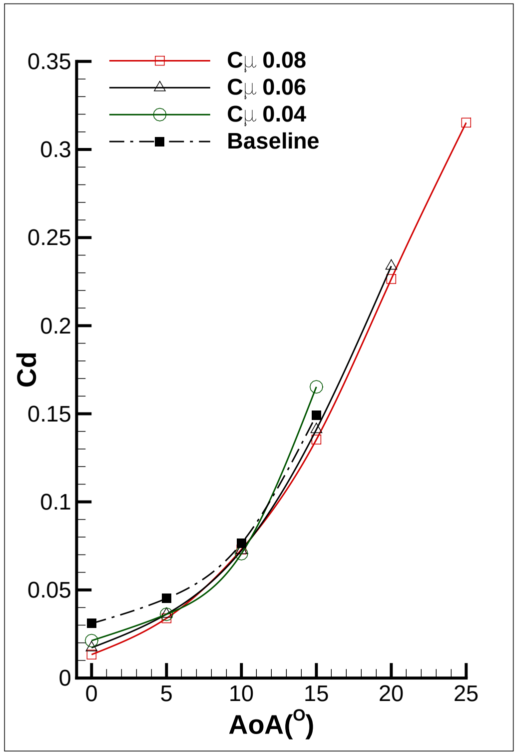
Isentropic Mach contours at different span, Cruise. L/D=36

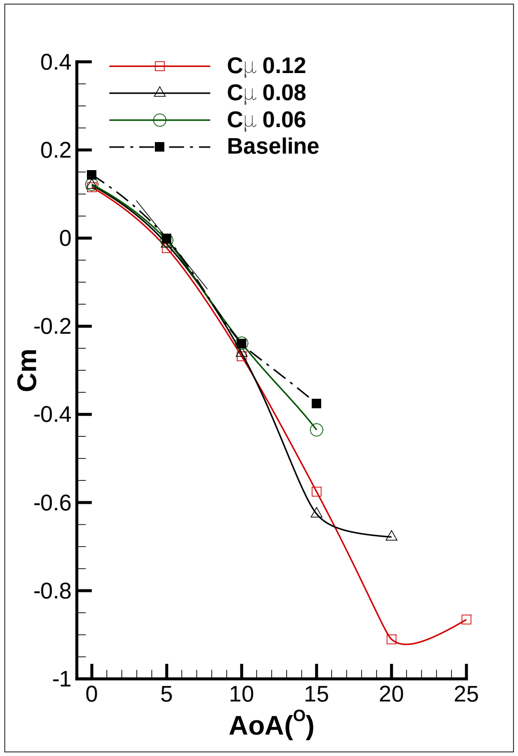


CFJ-NACA 6421 airfoil, slots location: 2%C,80%C; injection/suction slot size: 0.65%C, 1.30%C

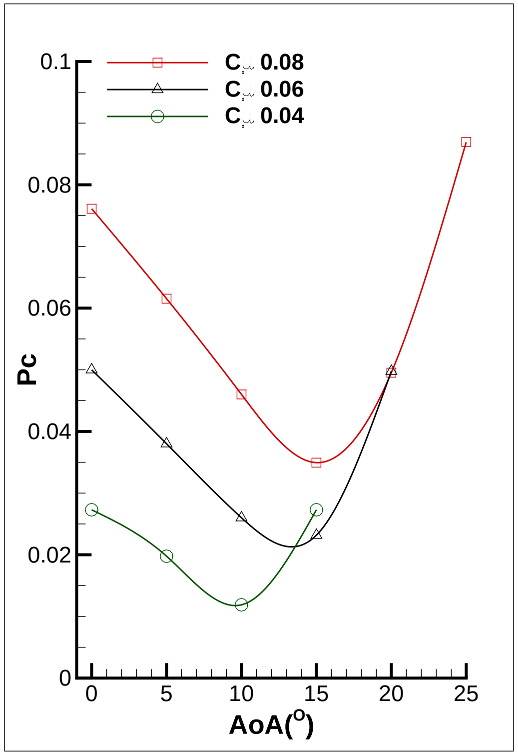
C_L, C_D, C_M vs AoA ($C_\mu = 0.04 - 0.08$)

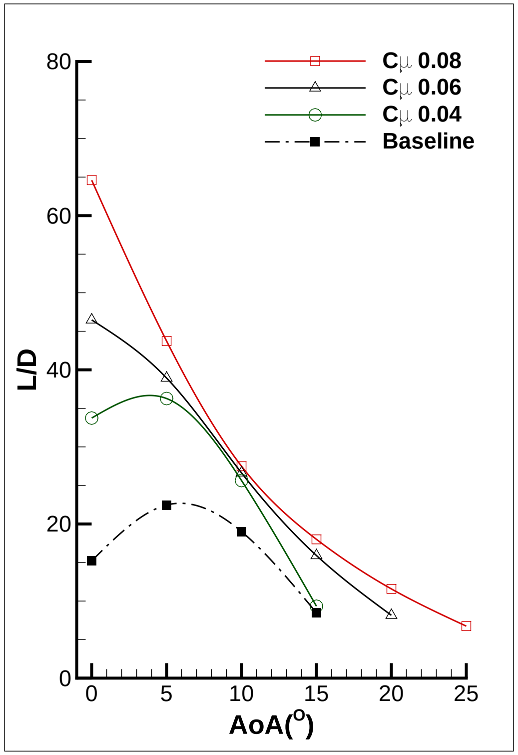


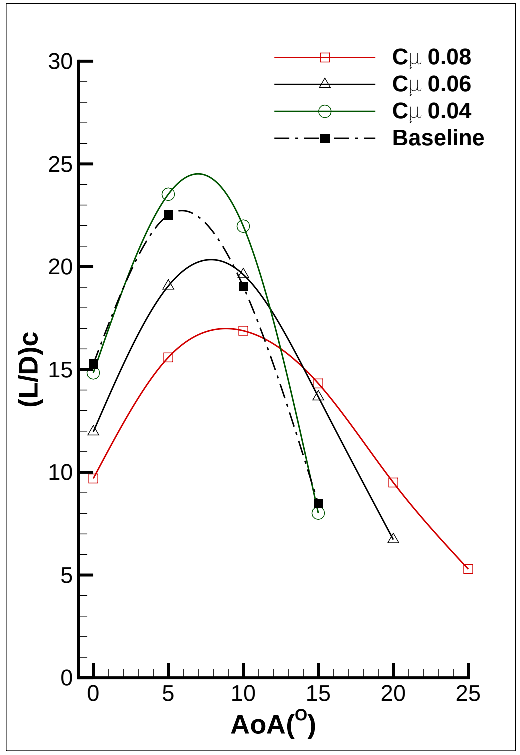




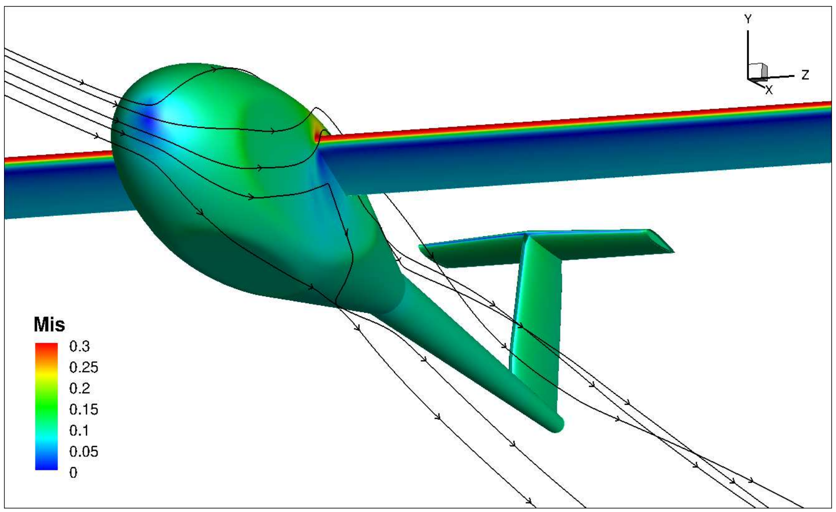
$P_c, L/D, (L/D)_c$ vs AoA ($C_\mu = 0.04 - 0.08$)

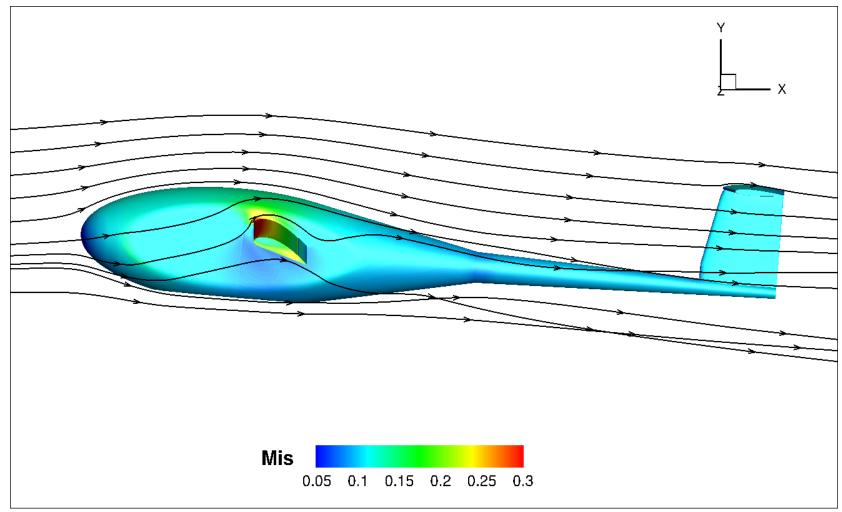




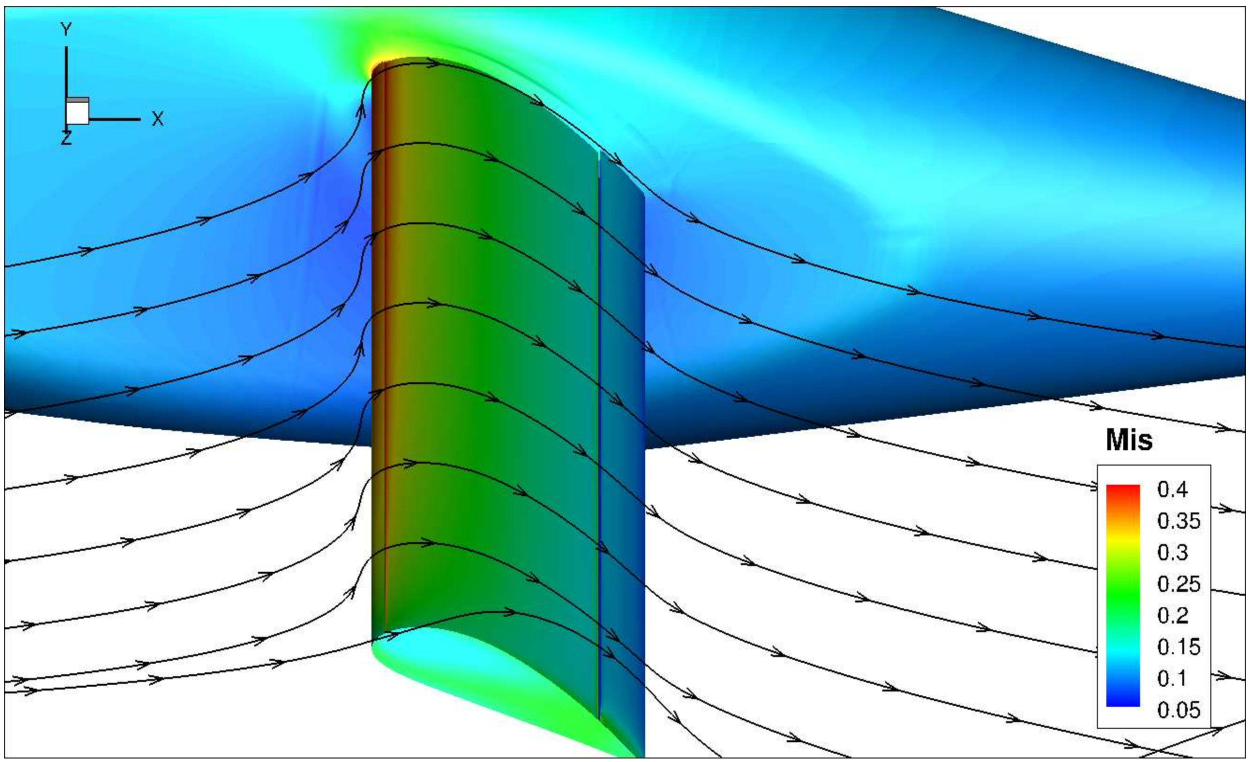


Takeoff Isentropic Mach contours, AoA=25° $C_\mu = 0.24$

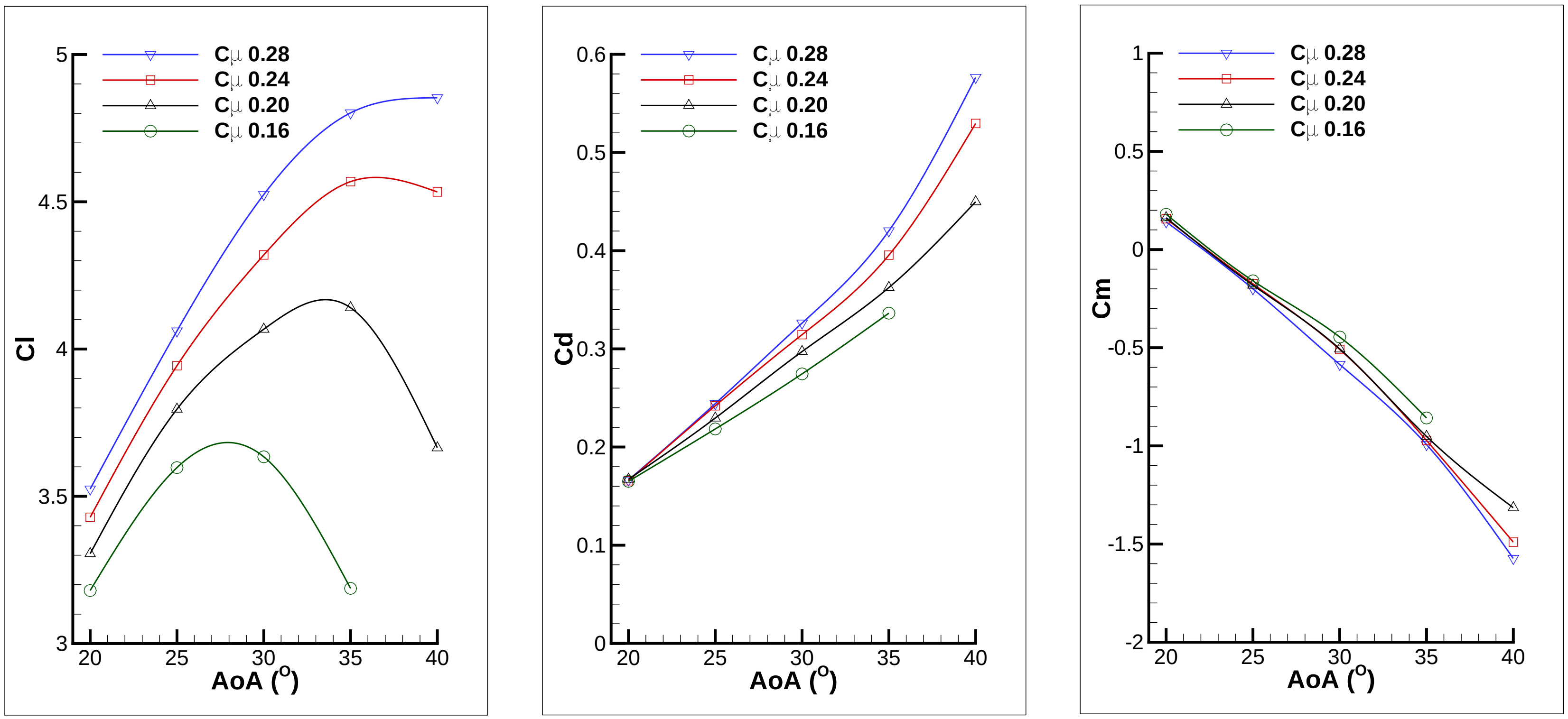




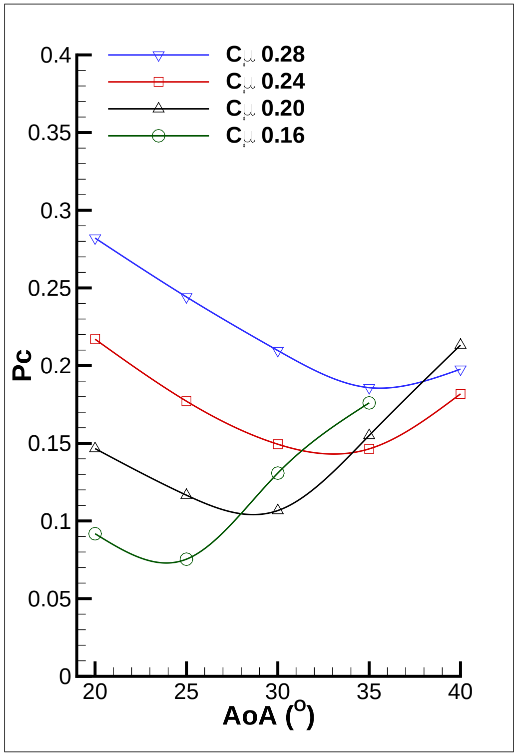
Takeoff Isentropic Mach contours, AoA=25° $C_L =$ 3.9

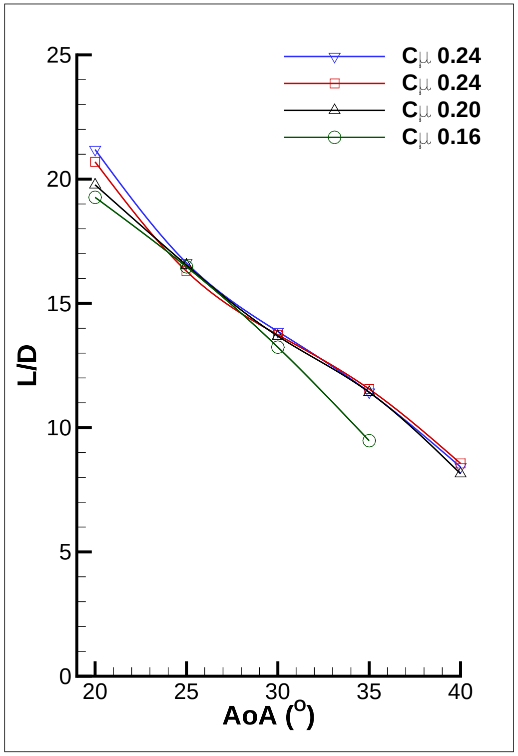


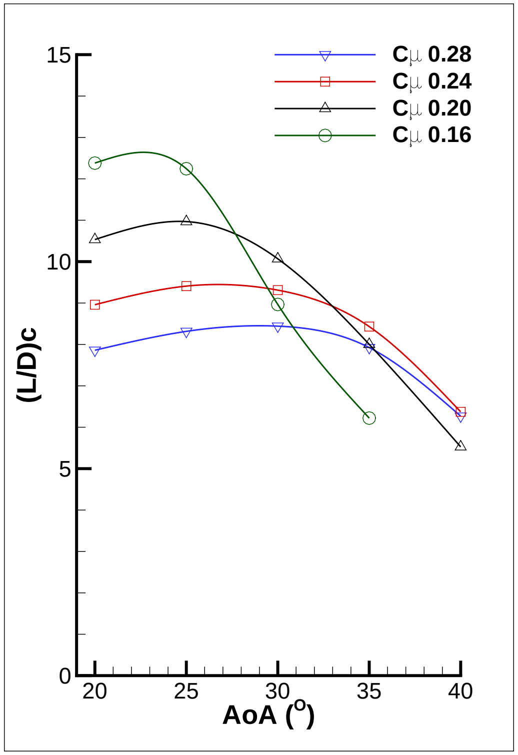
C_L, C_D, C_M vs AoA ($C_\mu = 0.16 - 0.28$), Takeoff



$P_c, L/D, (L/D)_c$ vs AoA ($C_\mu = 0.16 - 0.28$), Take-off







Comparison of Performance

Aircraft	Cesna 172	Antares 20E	E-Genius	Taurus G4	CFJ Eplane
Geometry					
Wing span (m)	11.00	20.00	16.90	21.36	14.90
Wing area (m2)	16.20	12.60	14.56	20.30	10.44
AR	7.3	31.7	19.6	22.5	21.3
Length (m)	8.28	7.40	8.10	7.40	9.12
Cruise data					
Nb of passengers	4	1	2	4	4
CL	0.32	0.38	0.57	0.50	1.31
CD	0.046	0.013	0.020	0.018	0.036
Pc	N/A	N/A	N/A	N/A	0.014
L/D	9	30	26	28	36
L/Dc	9	30	26	28	24
Velocity (m/s)	63	51	45	51	51
Weight					
Max TO weight (kg)	1,111	660	950	1,496	1,896
Structure ratio	0.69	0.70	0.47	0.39	0.45
Structure weight (kg)	767.0	460.0	760.0	632.0	853.0
Passenger + payload (kg)	250.0	140.0	182.0	364.0	364.0
Battery weight (kg)	N/A	60.0	310.0	500.0	678.5
Aircraft	**Cesna 172**	**Antares 20E**	**E-Genius**	**Taurus G4**	**CFJ Eplane**
Propulsion / Battery					
Propulsion eff (%)	39	73	73	73	73
Pump efficiency (%)	N/A	N/A	N/A	N/A	85
Battery specific E (Wh/Kg)	N/A	136	180	180	250
Energy available (kWh)	2,212.0	8.2	56.0	90.0	169.6
Propeller power cruise (kW)	251.6	15.2	17.6	32.0	35.7
CFJ power cruise (kW)	N/A	N/A	N/A	N/A	10.34
Total power drawn cruise (kW)	251.6	15.2	17.6	32.0	46.0
Performance					
Range (nm)	700	43	216	250	292
nm*passenger/S	172.8	3.4	29.7	49.3	112.4
mpg*passengers	57.5	236.8	350.7	505.1	313.2
Crusie time (h)	5.7	0.4	2.5	2.5	2.9
Projected range in 20 year (nm)	700	298	1512	1750	2046
Wing loading (kg/m2)	68.6	52.9	61.8	69.6	182.3
TO CL	2.0	1.6	1.8	1.8	3.5
TO distance (ft)	1700	1900	1700+	2000	2000

Conclusions

- Compact 4 passenger GA-EA using CFJ is feasible.

- (L/D)c=24, L/D=36, cruise C_L=1.3, Max C_L=4.8.

- R=292nm; V= 51m/s(M=0.15), Wing span=14.9m, wing area=10.44m^2, AR=21.5, Structure factor=0.45, $S_{TO} =$ 610m(2000ft).

- Wing loading=182kg/m^2, 3 times higher than conventional design.

- PMS= Passenger*Miles/S=112.4, 2.3-3.8 times higher than SoA EA design.

- A same wing size CFJ-EA will have 2-3 times the range of a conventional EA.

- Better performance expected with design optimization.

- Same concept applicable to conventional GA and high altitude airplane to reduce size.