AIAA Paper 2006-0102, 01/09/2006

Analysis of Jet Effects on Co-Flow Jet Airfoil Performance with Integrated Propulsion System

Gecheng Zha
Wei Gao
Dept. of Mechanical and Aerospace Engineering
University of Miami
Coral Gables, FL 33124
E-mail: Gzha@miami.edu

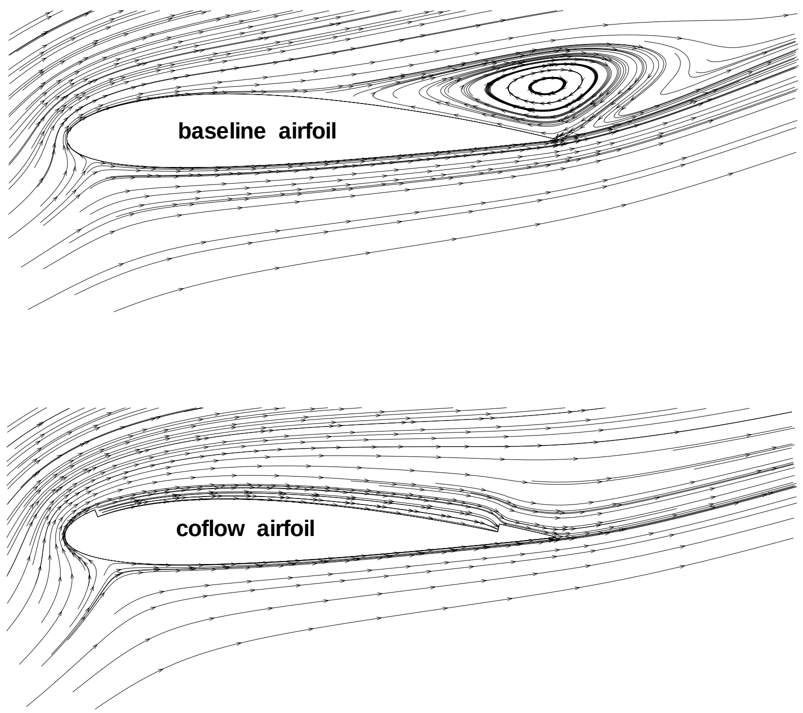
Overview of Airfoil Flow Control

- Rotating Cylinder at LE and TE
- Circulation Control Airfoil, Coanda Effect (IBF)
- Synthetic Jet, Pulsed Jet
- Externally Blown Flaps
- Upper Surface Blowing
- Co-Flow Jet Airfoil (2005)

Co-Flow Jet(CFJ) Airfoil

• AIAA Book Series, 2006, AIAA J. of Aircraft, 2006

• AIAA Paper: 2004-2208,2005-1260, 2006-1060, 2006-0102, 2006-1061, NASA/CP-2005-213506, 2005



CFJ Airfoil

- **Highly Effective**: High Lift, Low Drag, High Stall Margin
- **Energy Efficient**: Small Penalty to Propulsion System
- **Easy Implementation**

Objectives:

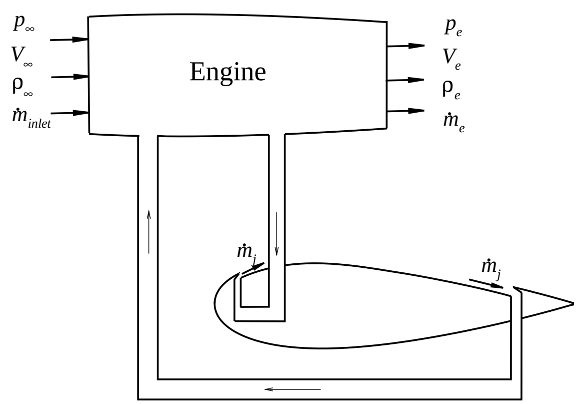
Control Volume Analysis with Integrated Propulsion System

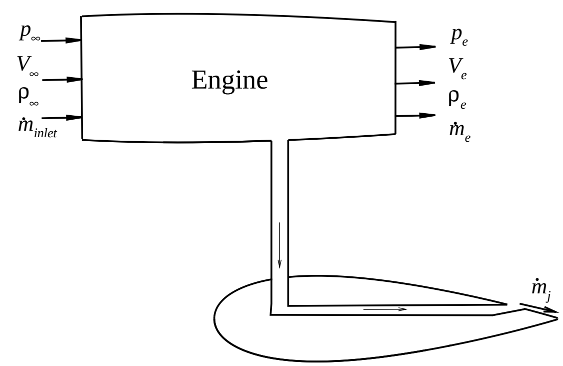
- Jet Ducts Effect
- Suction Effect

Strategies: CFD, Wind Tunnel, Analysis

Q1: What is the equivalent drag?

Q2: Where is better for jet suction, on airfoil or engine?

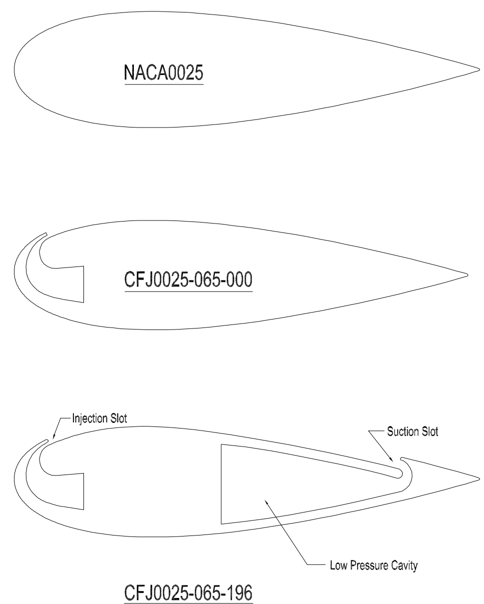




CFJ Airfoil, injection-suction

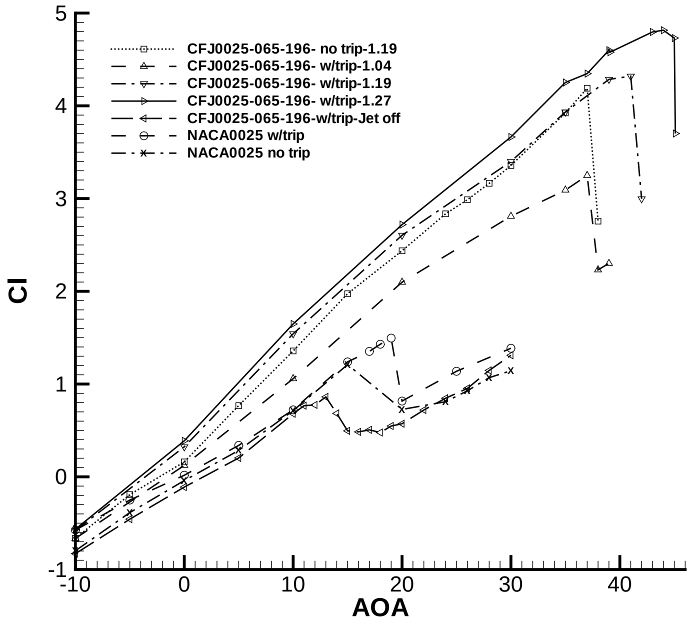
CC Airfoil, injection only

CFJ Airfoil Geometry

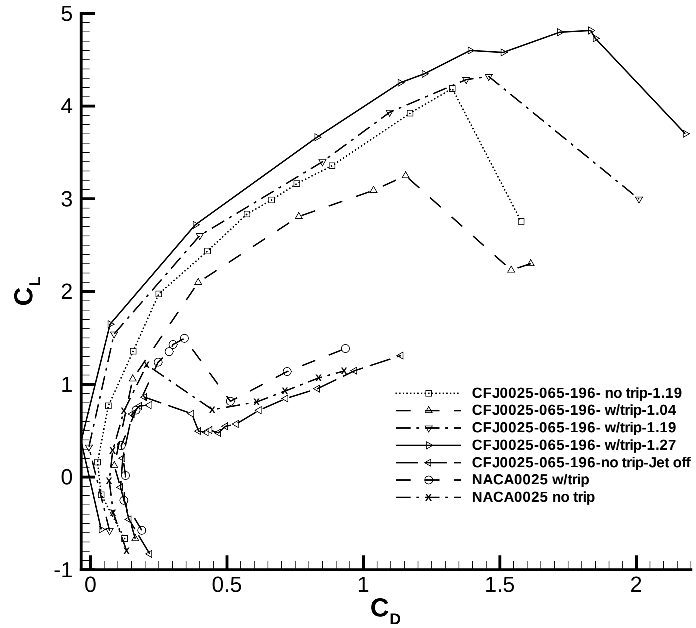


Baseline NACA0025, CFJ0025-065-000, CFJ0025-065-196,

Wind Tunnel Test Results, CFJ0026-065-196 airfoil

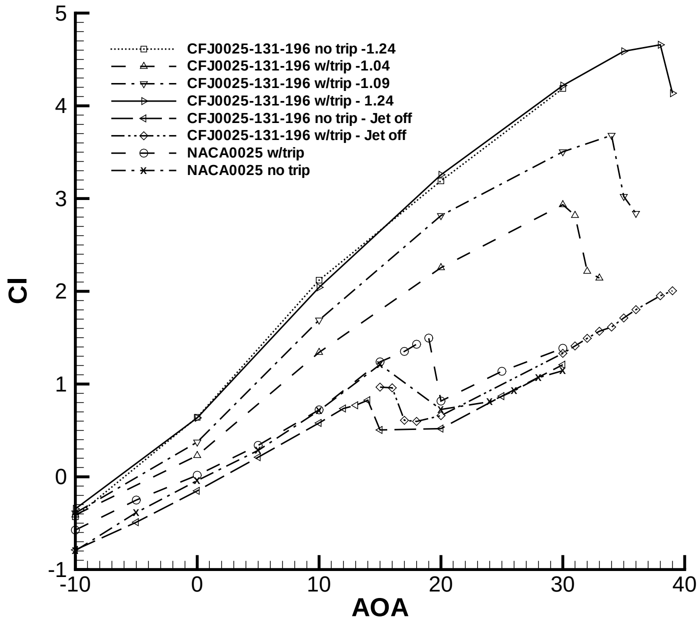


Measured Lift vs AoA

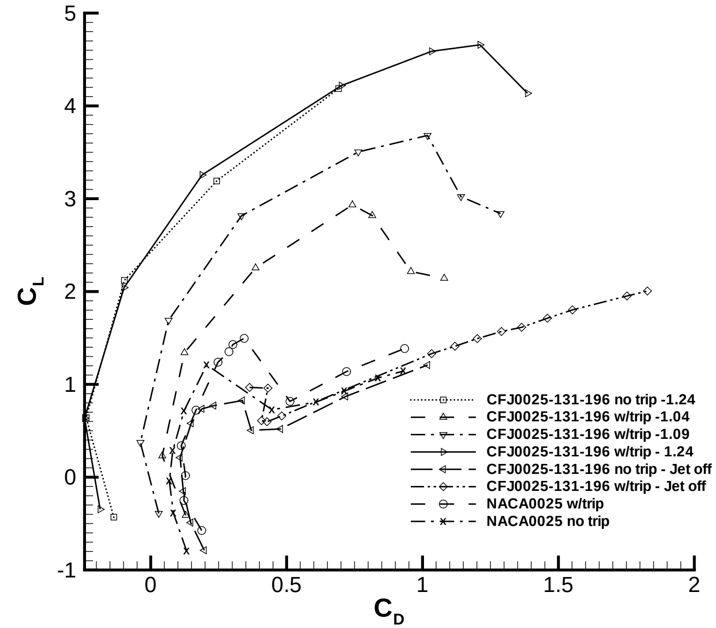


Measured Drag Polar

Wind Tunnel Test Results, CFJ0026-131-196 airfoil

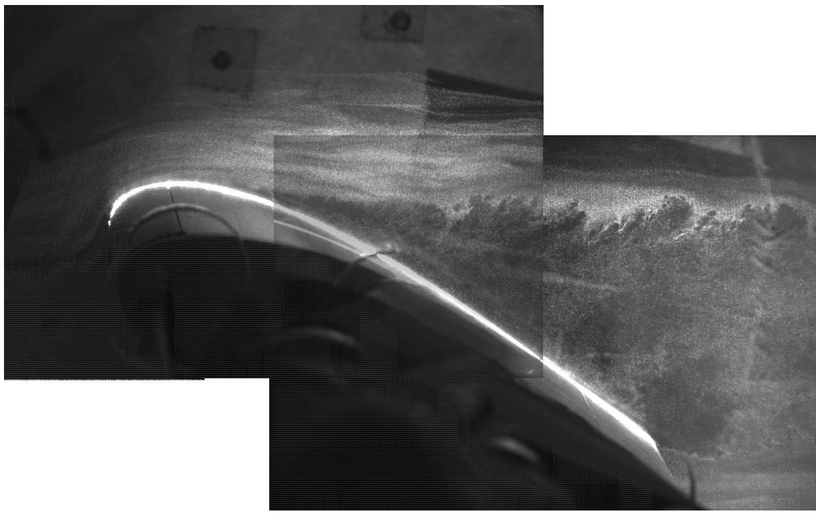


Measured Lift vs AoA

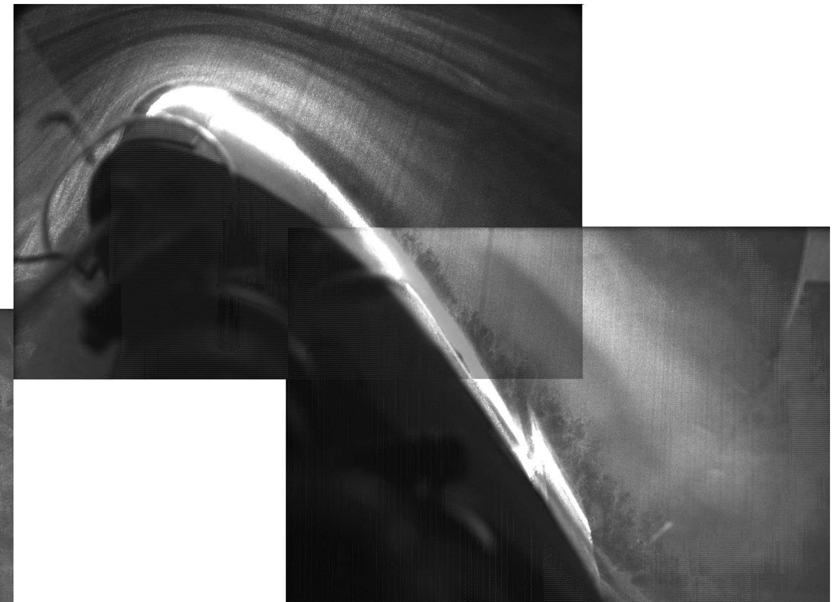


Measured Drag Polar

Wind Tunnel Test Results

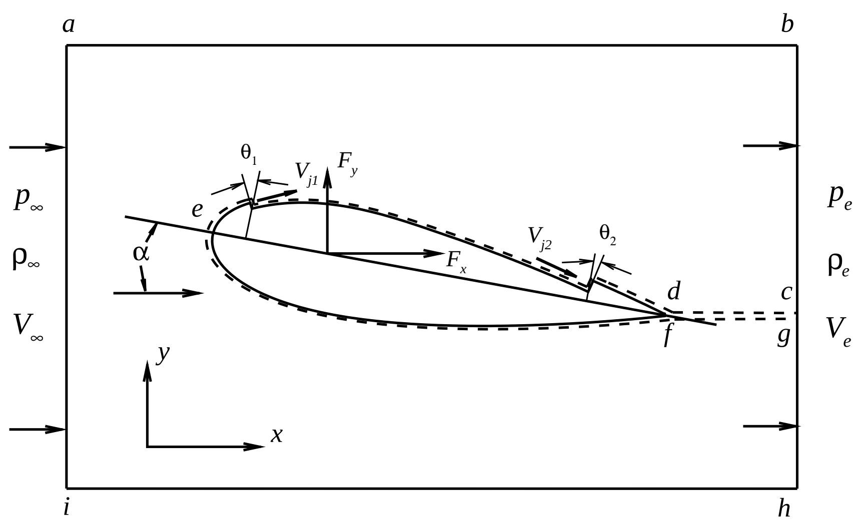


baseline airfoil, AoA $=20^0$



CFJ0025-065-196 airfoil, AoA$=43^0$

Control Volume



Momentum equation

$$\sum \mathbf{F} = \int \int_s \rho \mathbf{V} \cdot d\mathbf{S} \cdot \mathbf{V} \tag{1}$$

$$(p_{j1}A_{j1})_x - (p_{j2}A_{j2})_x + R_x = \int_h^b \rho V_e \cdot dy \cdot V_e - \int_i^a \rho V_\infty \cdot dy \cdot V_\infty - \dot{m}_{j1}u_{j1} + \dot{m}_{j2}u_{j2} \tag{2}$$

F_{xcfj}: duct reaction force in x-direction

$$F_{xcfj} = (\dot{m}_{j1}u_{j1} + (p_{j1}A_{j1})_x) - \gamma(\dot{m}_{j2}u_{j2} + (p_{j2}A_{j2})_x)$$
$$= (\dot{m}_j V_{j1} + p_{j1}A_{j1}) * cos(\theta_1 - \alpha) - \gamma(\dot{m}_j V_{j2} + p_{j2}A_{j2}) * cos(\theta_2 + \alpha) \tag{3}$$

$$D = R'_x - F_{xcfj} = \int_i^a \rho V_\infty \cdot dy \cdot V_\infty - \int_h^b \rho V_e \cdot dy \cdot V_e \tag{4}$$

$R'_x = -R_x$: surface integral of pressure and shear stress

Mass Conservation:

$$\dot{m}_{j1} = \dot{m}_{j2} \tag{5}$$

and

$$\int_i^a \rho V_\infty \cdot dy = \int_h^b \rho V_e \cdot dy \tag{6}$$

Drag becomes:

$$D = R'_x - F_{xcfj} = \int_h^b \rho V_e (V_\infty - V_e) dy \tag{7}$$

or

$$C_D = C_{Drake} \tag{8}$$

Lift

$$L = R'_y - F_{y_{cfj}} \tag{9}$$

R'_y: Surface pressure and shear stress integral in y-direction

$$F_{y_{cfj}} = (\dot{m}_{j1} v_{j1} + (p_{j1} A_{j1})_y) - \gamma(\dot{m}_{j2} v_{j2} + (p_{j2} A_{j2})_y)$$

$$= (\dot{m}_j V_{j1} + p_{j1} A_{j1}) * sin(\theta_1 - \alpha) + \gamma(\dot{m}_j V_{j2} + p_{j2} A_{j2}) * sin(\theta_2 + \alpha) \tag{10}$$

Airfoil with Jet Injection Only

Mass Conservation

$$\int_i^a \rho V_\infty \cdot dy + \dot{m}_j = \int_h^b \rho V_e \cdot dy \tag{11}$$

Momentum Equation

$$D_{windtunnel} = R'_x - (\dot{m}_j u_j + (p_j A_j)_x)$$

$$= R'_x - (\dot{m}_j V_{j1} + p_{j1} A_{j1}) * cos(\theta_1 - \alpha)$$

$$= \int_h^b \rho V_e (V_\infty - V_e) dy - m_j V_\infty \tag{12}$$

$$C_{D windtunnel} = C_{D rake} - C_\mu \frac{V_\infty}{V_j} \tag{13}$$

Equivalent Drag (Actual Drag)

Assume drawing in flow from engine inlet (ei),

$$D_{equiv} = R'_x - (\dot{m}_j u_j + (p_j A_j)_x) + \dot{m}_j V_{ei} + p_{ei} A_{j\,ei} \tag{14}$$

$$D_{equiv} = D_{windtunnel} + \dot{m}_j V_{ei} + p_{ei} A_{j\,ei} \tag{15}$$

$$\rho_{ei} V_{ei} A_{j\,ei} = \dot{m}_j \tag{16}$$

$$p_{ei} A_{j\,ei} = \frac{\dot{m}_j V_{ei}}{\gamma M_{ei}^2} \tag{17}$$

$$C_{D\,equiv} = C_{D\,windtunnel} + C_\mu \frac{V_{ei}}{V_j} + C_\mu \frac{V_{ei}}{V_j \gamma M_{ei}^2} \tag{18}$$

Lift

$$L = R'_y - (\dot{m}_{j1} v_{j1} + (p_{j1} A_{j1})_y) = R'_y - (\dot{m}_j V_{j1} + p_{j1} A_{j1}) * sin(\theta_1 - \alpha) \tag{19}$$

The equivalent drag used by Jones(2005) and Wilson(1979):

$$C_{Dequiv} = C_{Dwindtunnel} + C_\mu \frac{V_\infty}{V_j} + C_\mu \frac{V_j}{2V_\infty} \tag{20}$$

Using Eq.(13),

$$C_{Dequiv} = C_{Drake} + C_\mu \frac{V_j}{2V_\infty} \tag{21}$$

Power Required for Jet

CFJ airfoil with injection-suction:

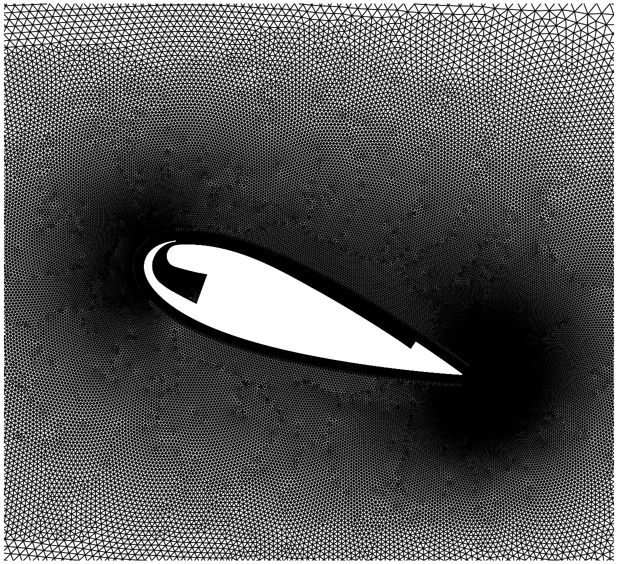
$$P_{cfj} = V_\infty F_{xcfj} = V_\infty [(\dot{m}_j V_{j1} + p_{j1} A_{j1}) * cos(\theta_1 - \alpha)$$

$$-(\dot{m}_j V_{j2} + p_{j2} A_{j2}) * cos(\theta_2 + \alpha)] \quad (22)$$

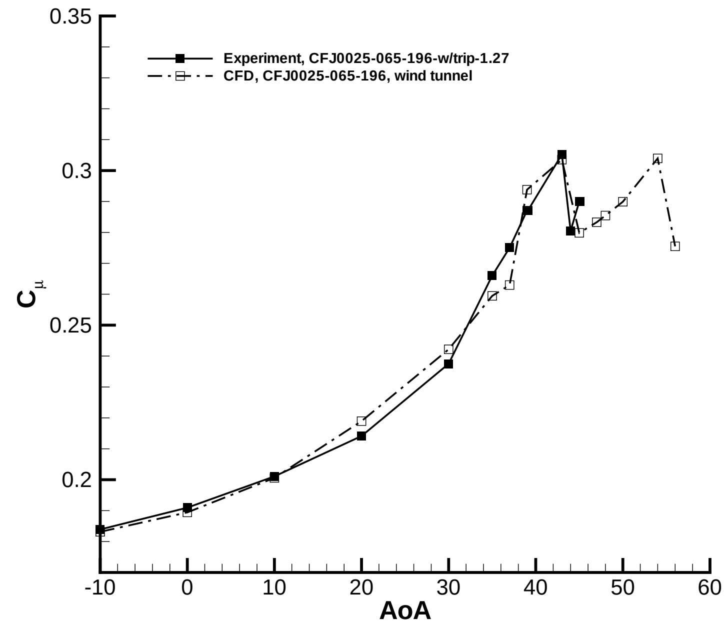
Airfoil with injection only :

$$P_{inj\ only} = V_\infty F_{xinj\ only} = V_\infty [(\dot{m}_j V_{j1} + p_{j1} A_{j1}) * cos(\theta_1 - \alpha)$$

$$-(\dot{m}_j V_{ei} + p_{ei} A_{j\,ei})] \quad (23)$$

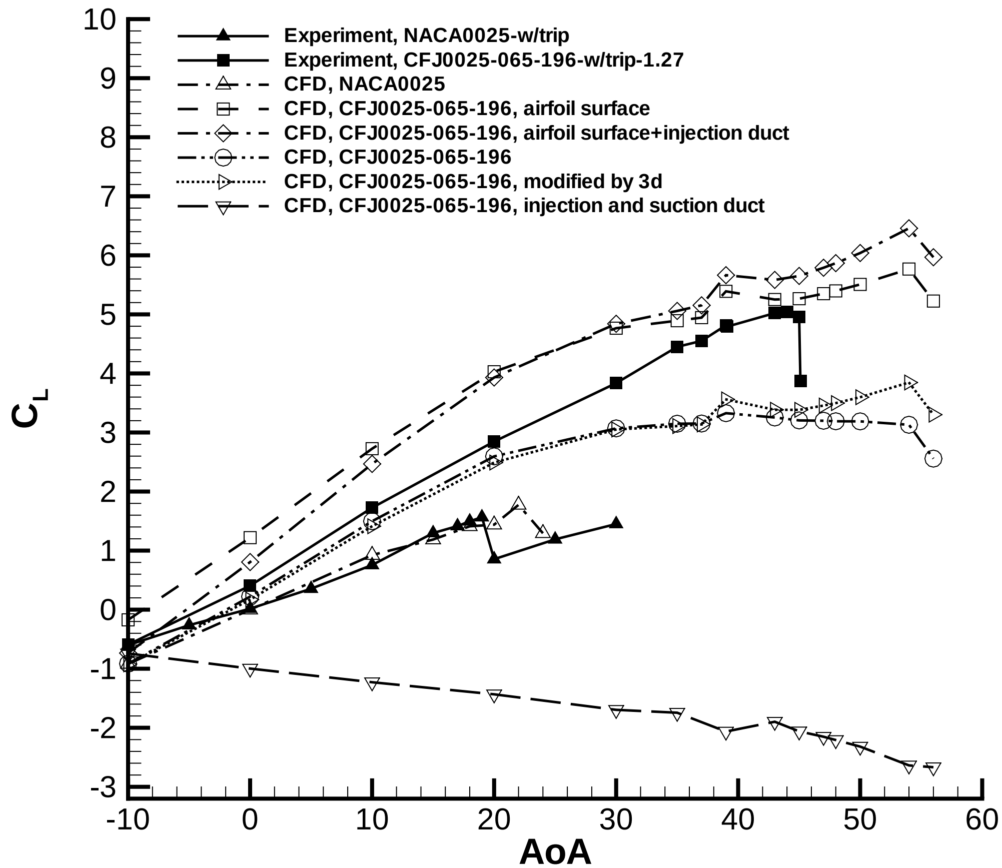


2D Mesh

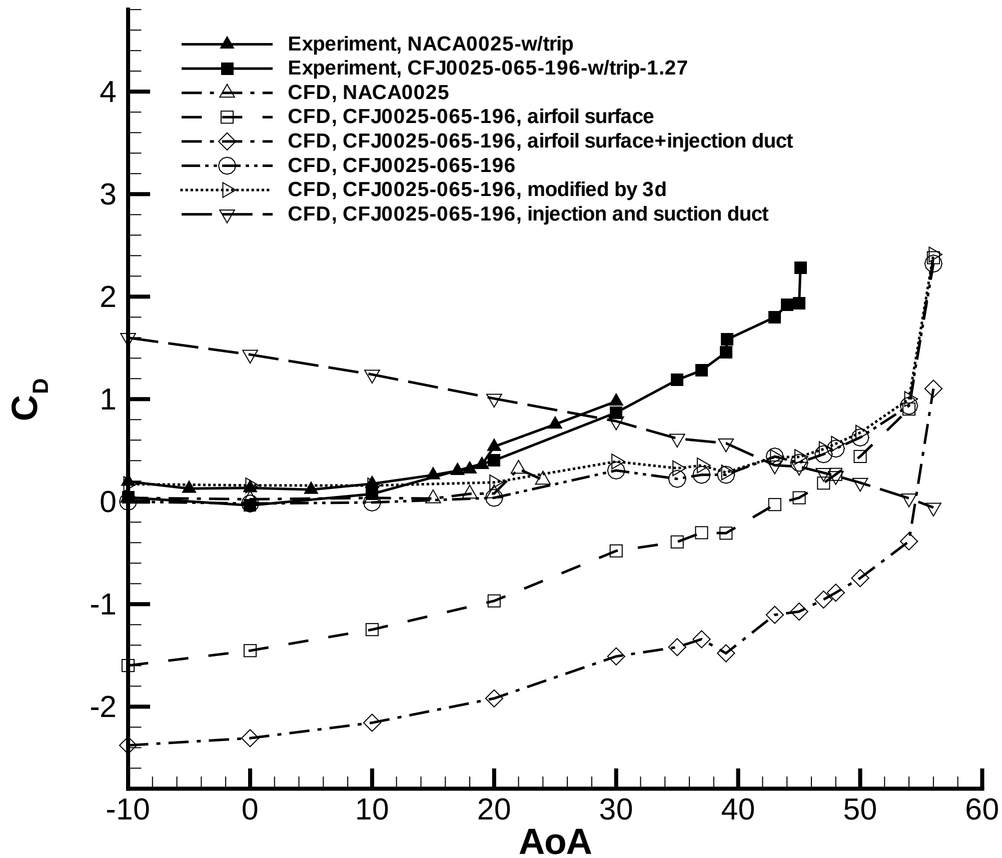


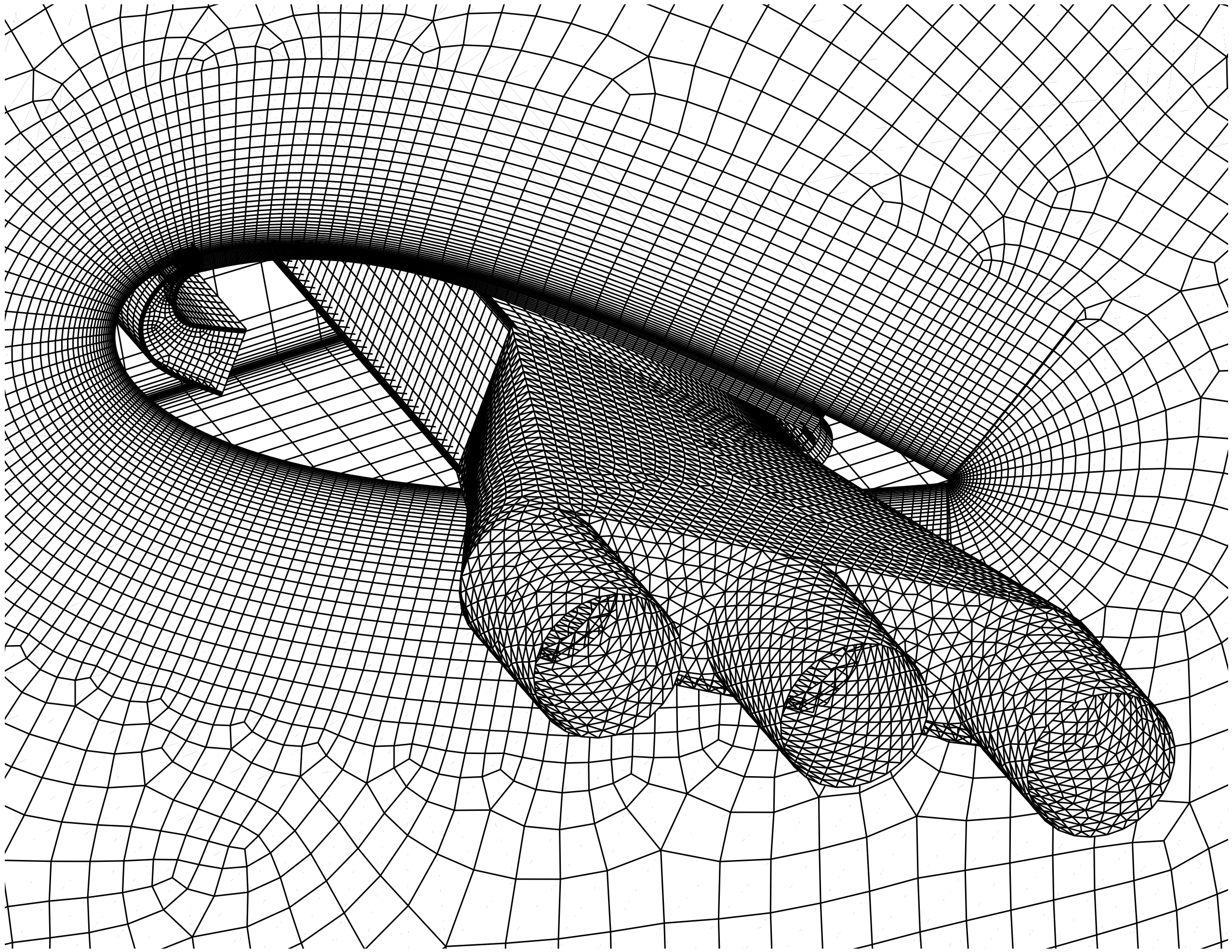
0.35
0.3
0.25
0.2
C_μ
Experiment, CFJ0025-065-196-w/trip-1.27
CFD, CFJ0025-065-196, wind tunnel
-10
0
10
20
30
40
50
60
AoA

Computed lift coefficient

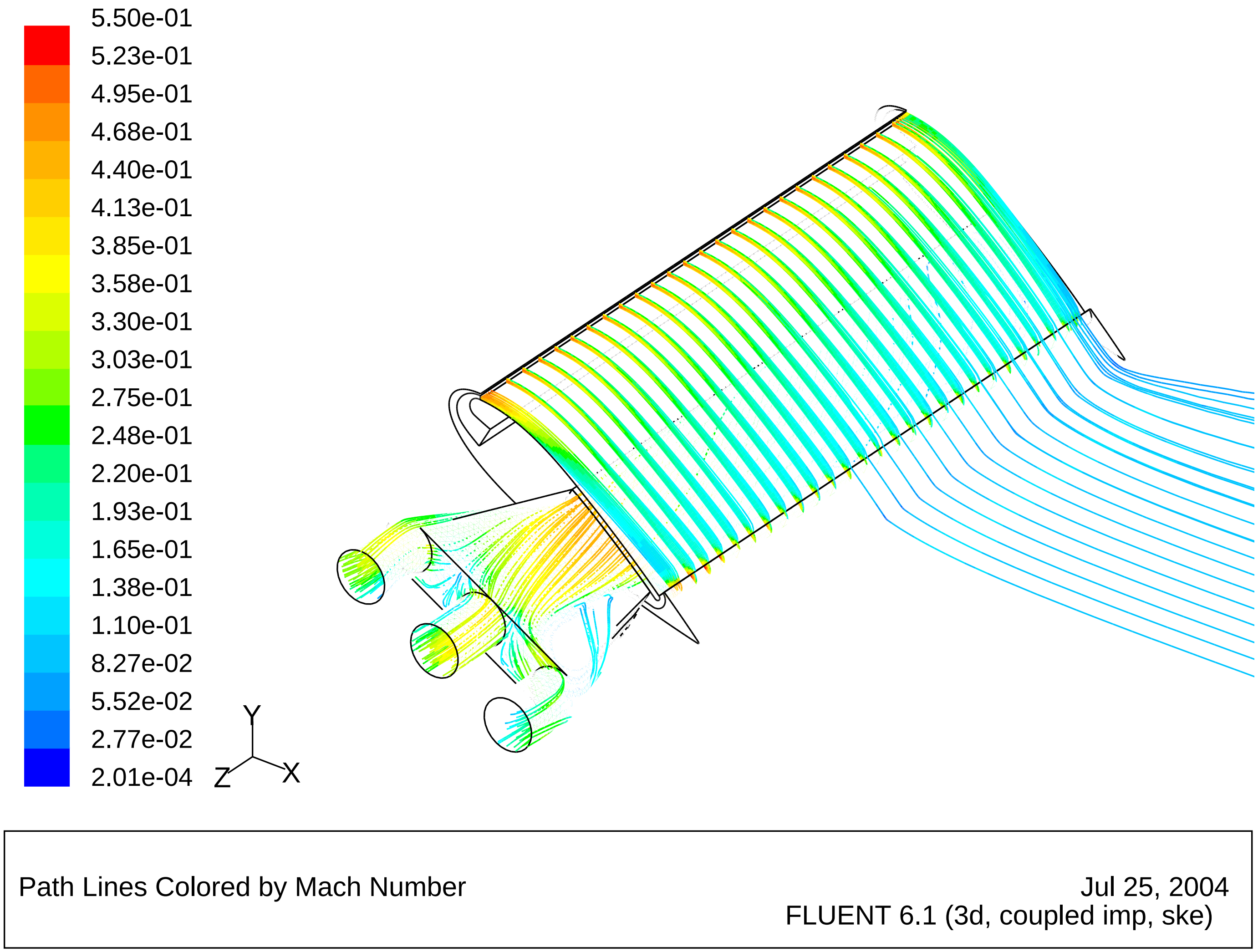


Computed drag coefficient

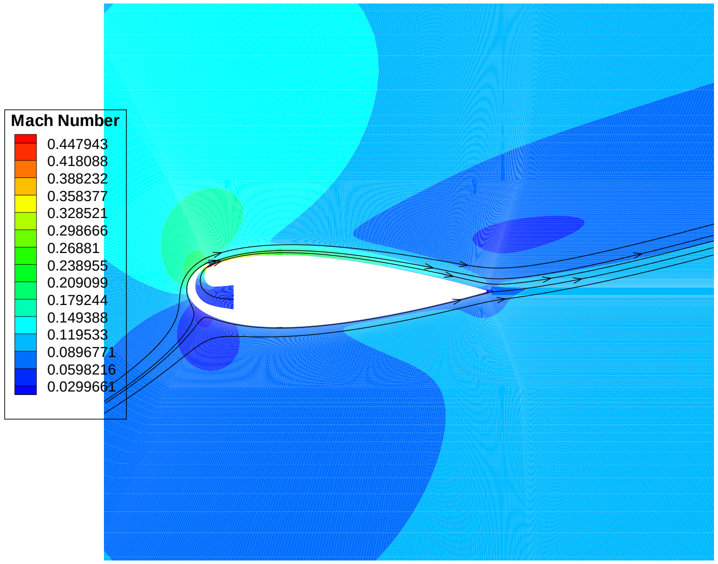




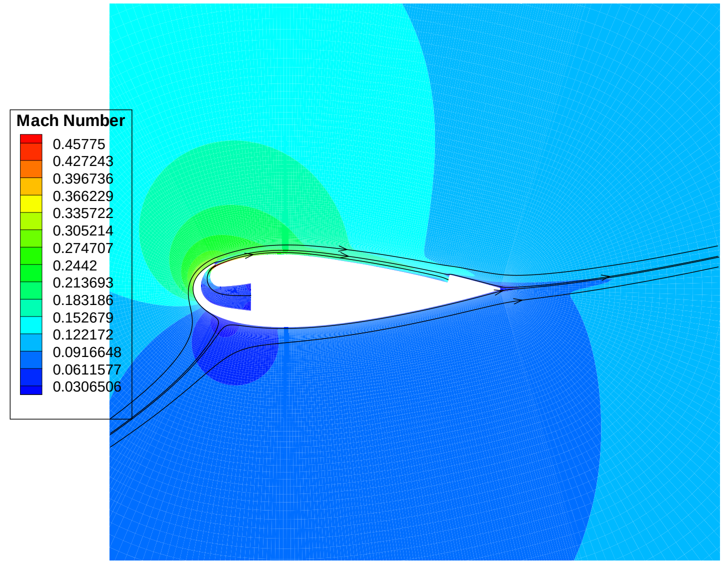
3D mesh of the CFJ airfoil inside the wind tunnel with secondary flow suction duct



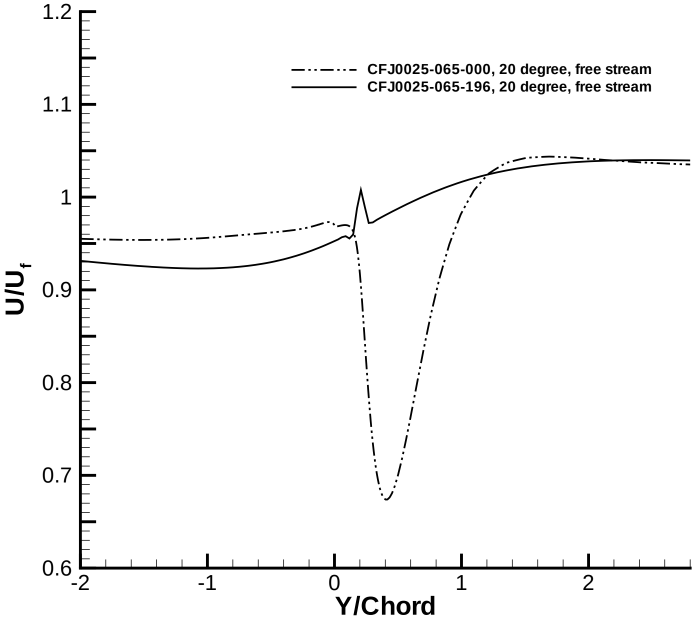
Streamlines released from the injection jet at AoA=30^0,
CFJ0026-131-192 airfoil



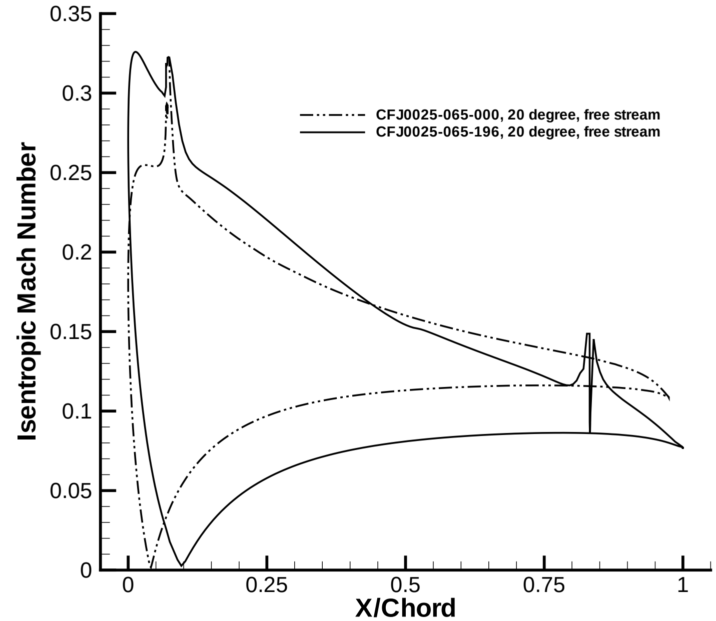
CFJ0025-065-000 airfoil, AoA=20°



CFJ0025-065-196 airfoil, AoA=20°



Wake Profile, AoA=20°



Surface Isentropic Mach number, AoA=20°

Airfoil	C_μ	C_L	R'_y	F_y inj.	F_y suc.
CFJ0025-065-196	0.208	2.36	3.78	-0.095	-1.33
CFJ0025-065-000	0.217	1.66	1.76	-0.1	0

Table 1: Comparison of lift coefficient and its breakdowns for the two CFJ airfoils at AoA=20°.

Airfoil	C_D	R'_x	F_x inj.	F_x suc.	C_D equiv
CFJ0025-065-196	-0.017	-1.03	-0.93	1.94	-0.017
CFJ0025-065-000	0.17	1.14	-0.97	3.43	3.6 (present), 0.7(Jo

Table 2: Comparison of drag coefficient and its breakdowns for the two CFJ airfoils at AoA=20°..

Airfoil	Power Required
CFJ0025-065-196	1
CFJ0025-065-000	2.4

Table 3: Comparison of the power required to pump the jet for the two CFJ airfoils at AoA=20°..

A1: For CFJ Airfoil, $D_{equiv} = D_{windtunnel}$

For Airfoil with injection only,

$$C_{D equiv} = C_{D windtunnel} + C_{\mu} \frac{V_{ei}}{V_j} + C_{\mu} \frac{V_{ei}}{V_j \gamma M_{ei}^2} \tag{24}$$

A2: Suction on airfoil is better than suction on engine.

Conclusions

- Jet injection reduce drag, increase lift if downward, decrease drag if upward
- Jet suction increase drag and decrease lift
- Jet suction is necessary as long as jet injection is used.
- For CFJ airfoil, the wind tunnel measured drag is the actual drag.
- Jet suction on airfoil surface is more beneficial than jet suction on engine inlet
- For CFJ airfoil, jet suction penalty is off set by higher circulation, lower drag due to stronger LE suction.
- The airfoil with injection only needs to add suction drag. The equivalent drag is significantly larger than the measured drag and the CFJ airfoil drag.

- Compared with the airfoil with injection only, the CFJ airfoil has higher lift, higher stall margin, lower drag and lower energy expenditure.

- For the CFJ0025-065-196 airfoils, the RANS model predict lift and drag fairly well when AoA $\leq 20^\circ$, significantly under-predicts lift and drag when AoA is higher.

- The jet ducts force contributions from control volume analysis agree well with 3D CFD calculation.