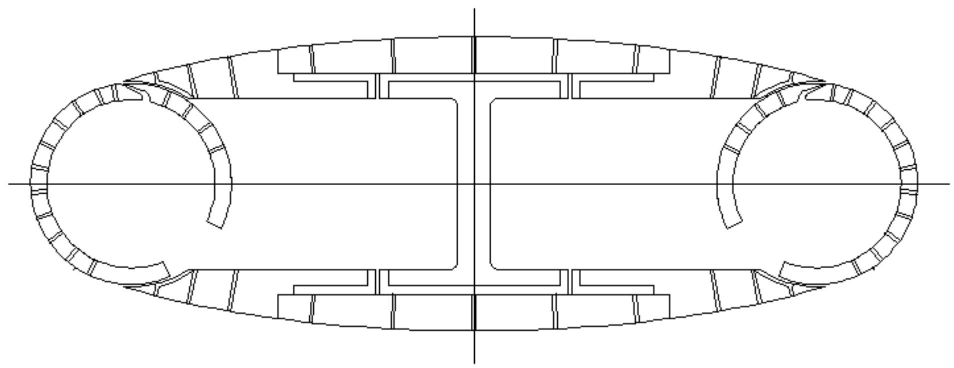
APPLICATION OF CFD ON A BLUNT ELLIPTICAL AIRFOIL

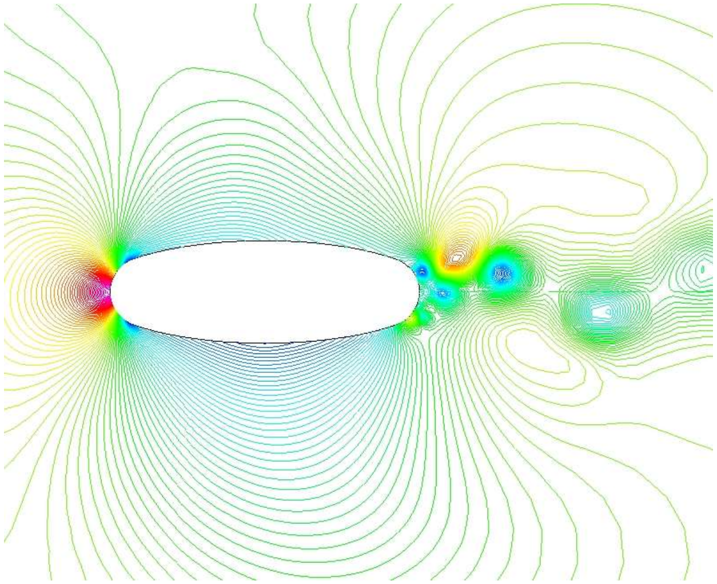


Cristina Bhamburkar

6/16/2009

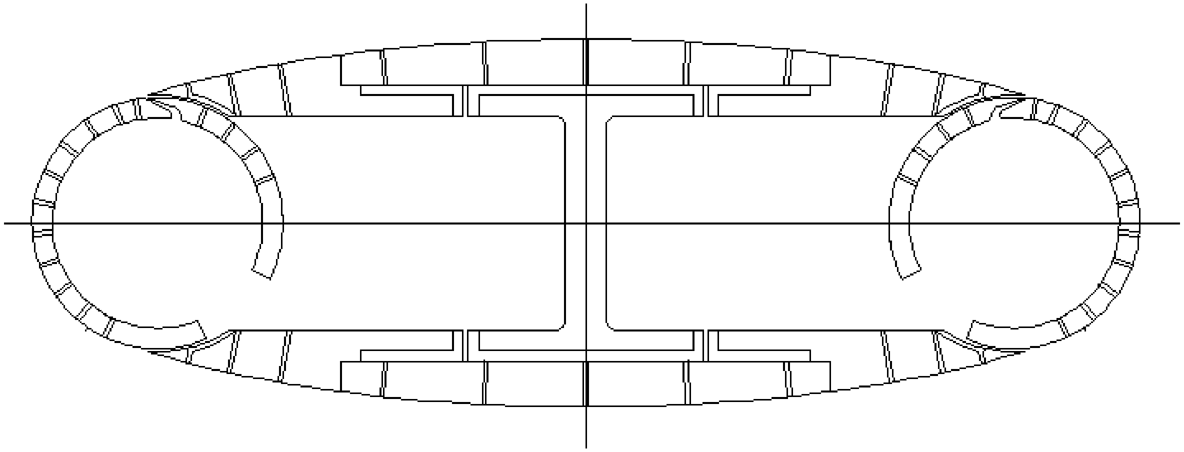
Outline

- Setup
- Results
  - Code Validation
    - Baseline Flow
    - Active Flow Control
    - Time averaged behavior
  - Code Issues
    - Turbulence Models
    - Time dependent behavior
- Comparisons
  - Time averaged behavior compared to results from the Aerodynamics Laboratory
  - Experimental results are not performed in this paper
- Conclusions

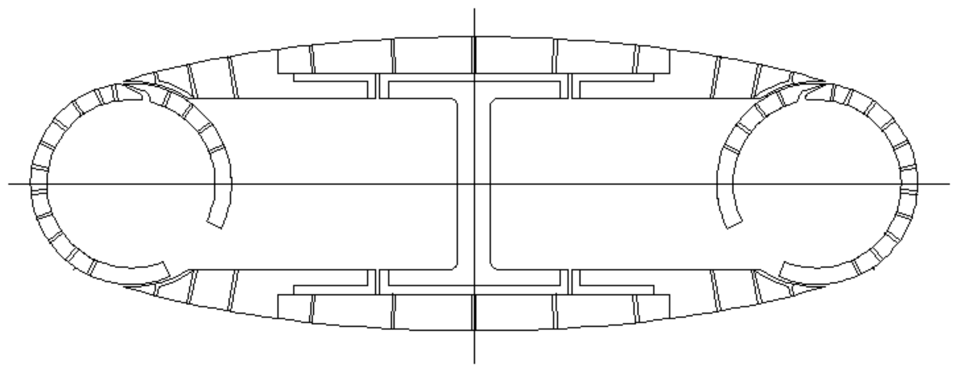


Setup

- 2D elliptical airfoil model
  - Circular cylinders at leading and trailing edges
    - Cylinders can be rotated
  - Circular cylinders are fitted with slots
    - Slot widths can be varied
  - Allows various options for active flow control experiments
- The chord length of the airfoil is approximately 27cm
- Roughness strips are placed at 3cm (11% chord)
  - On upper and lower surfaces

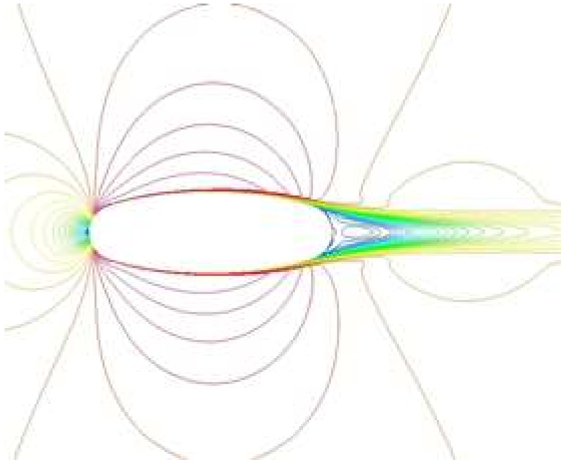


Baseline Flow

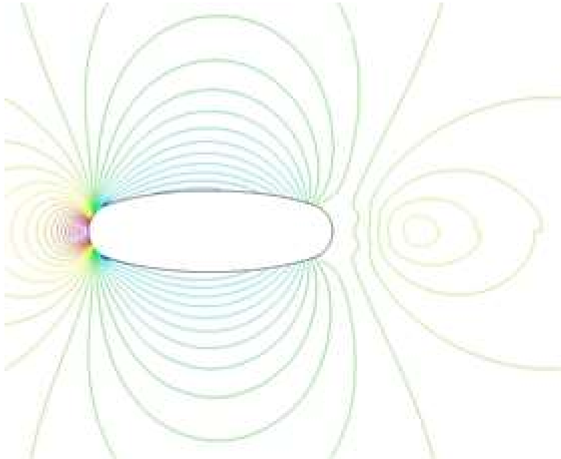


Velocity + Pressure Contours

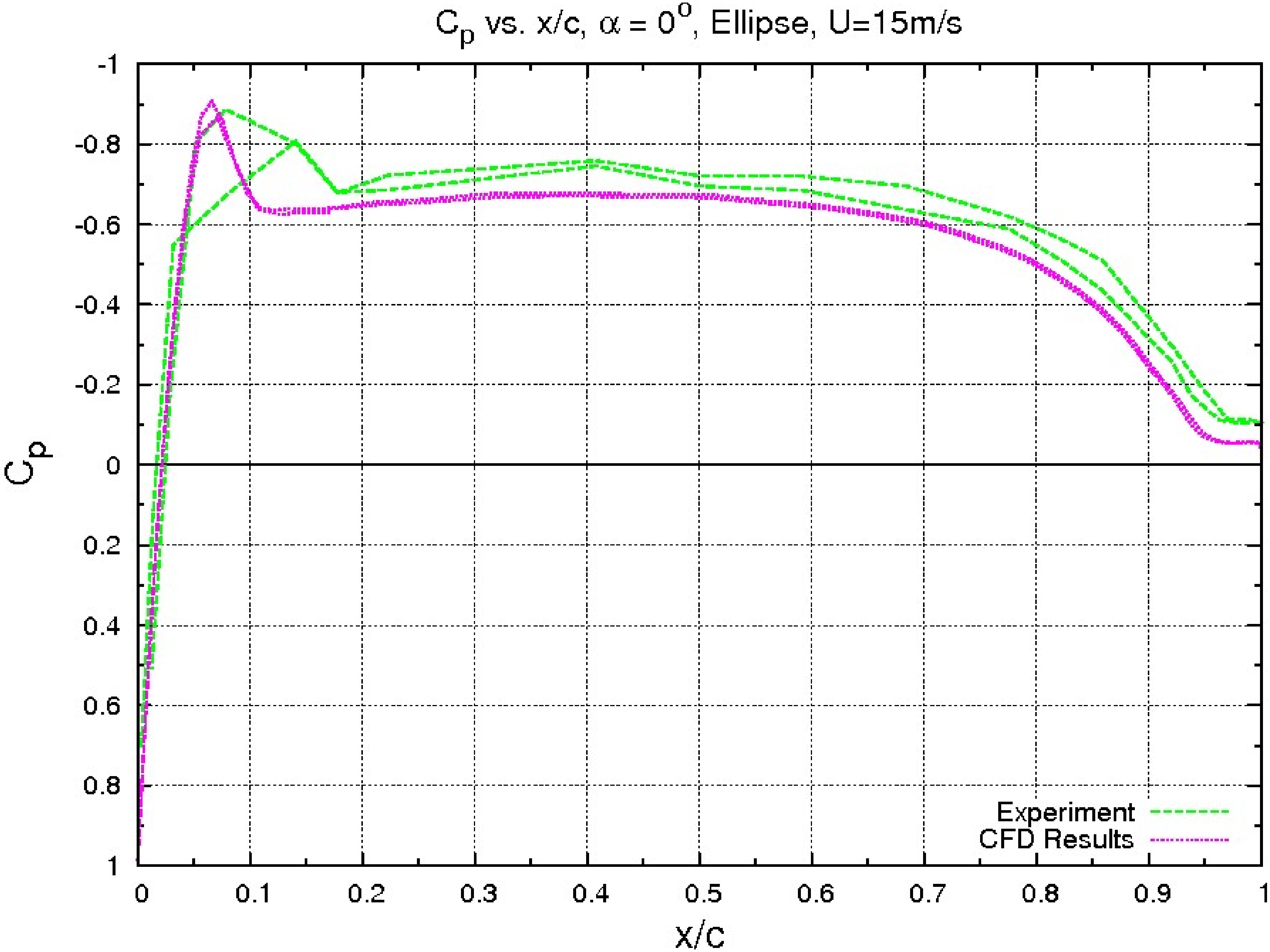
- Baseline solution
  - angle of attack was varied from 0 to 20 degrees
- Contour plots generated
  - contours are lines of constant magnitude
- Velocity contours
  - blue lines – zero velocity
  - red lines – high velocity
- Pressure contours
  - blue lines – low pressure
  - red lines – high pressure
- Pressure coefficient vs. x/c



Velocity



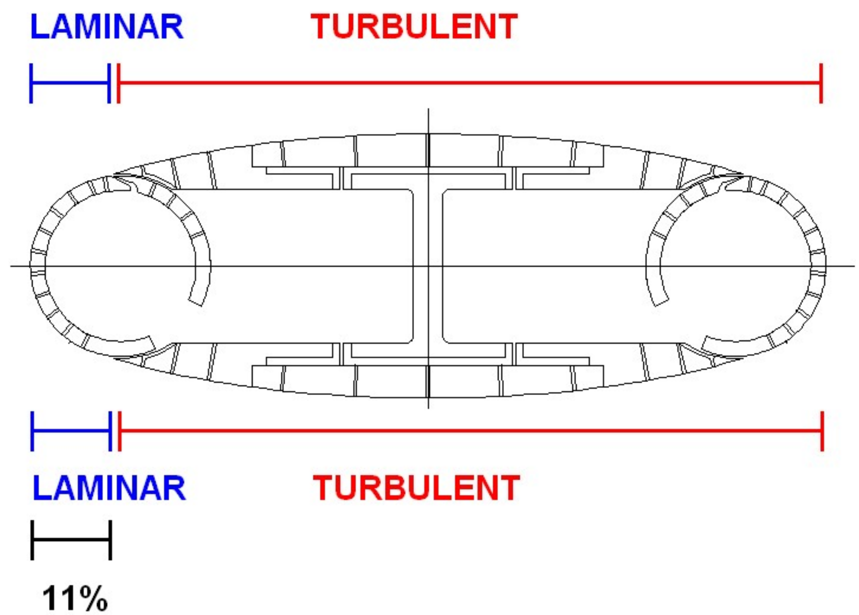
Pressure

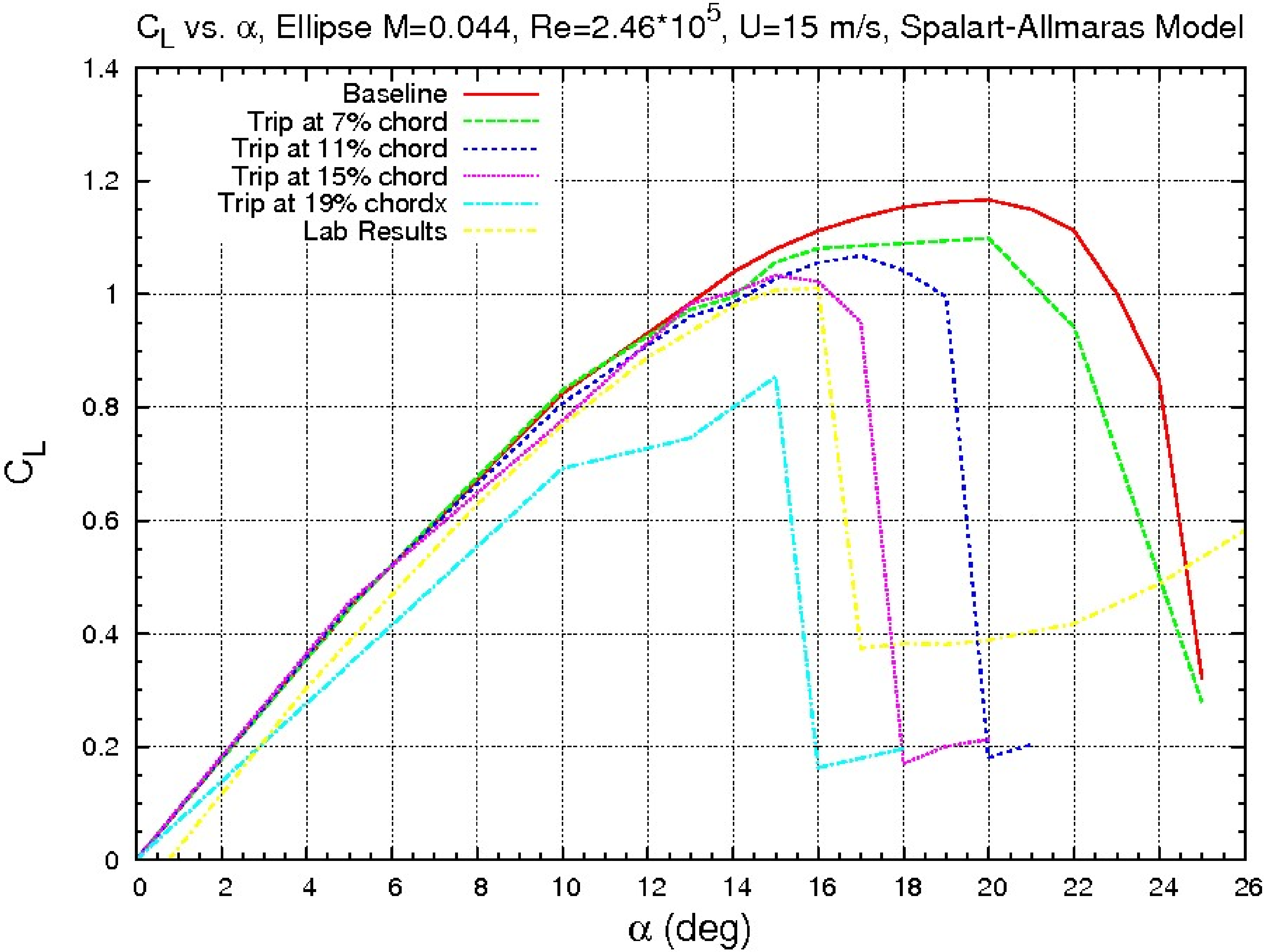


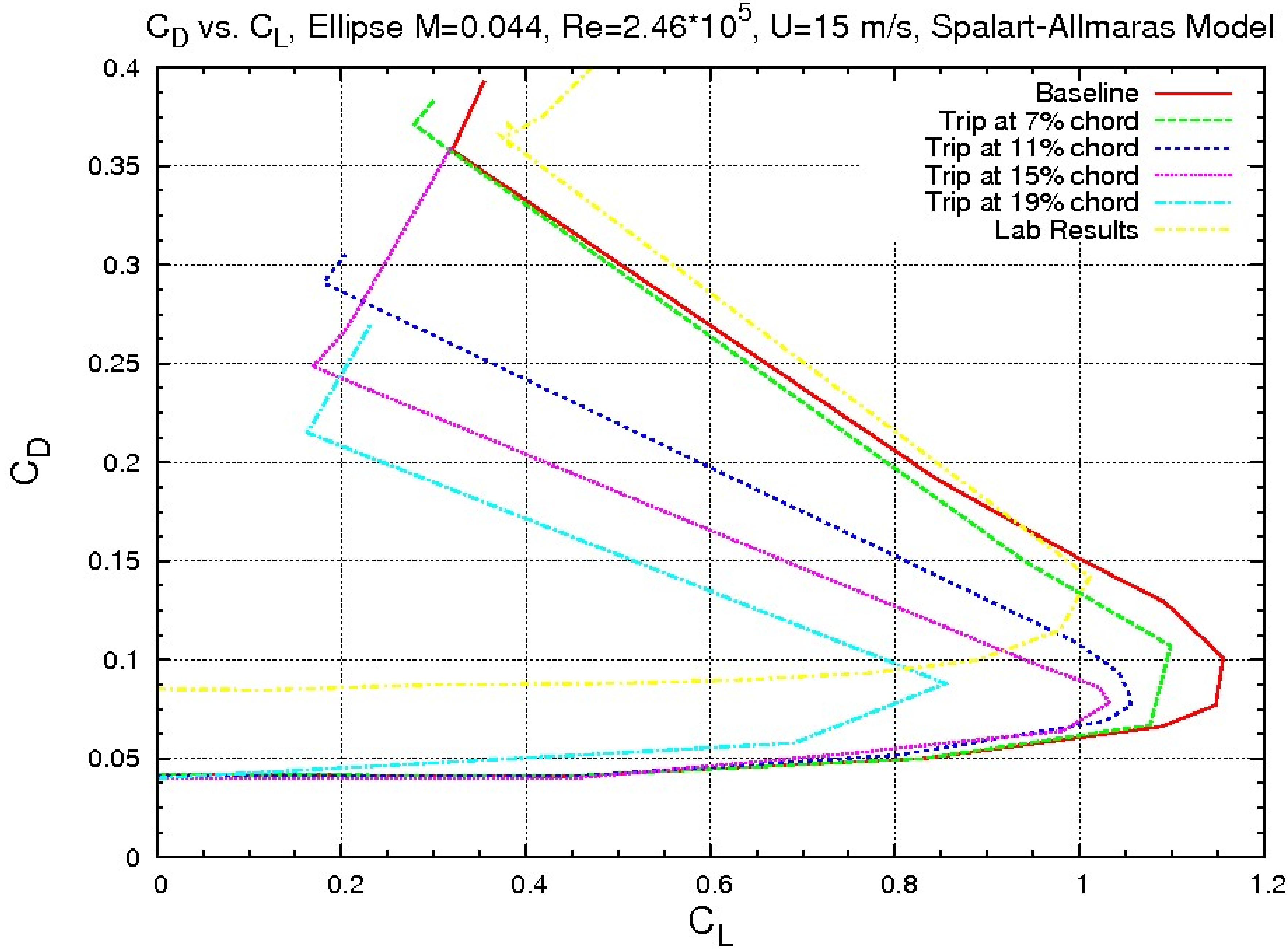
C_p vs. x/c, $\alpha = 0^o$, Ellipse, U=15m/s
C_p
x/c
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Experiment
CFD Results

Comparison of Trip Locations

- A trip is simulated by defining a laminar region at the leading edge
- The grid points outside this region were run turbulent
- Laminar-turbulent transition is simulated at
  - 7%, 11%, 15%, 19% chord
- In the lab, the ellipse is tripped at 11% chord



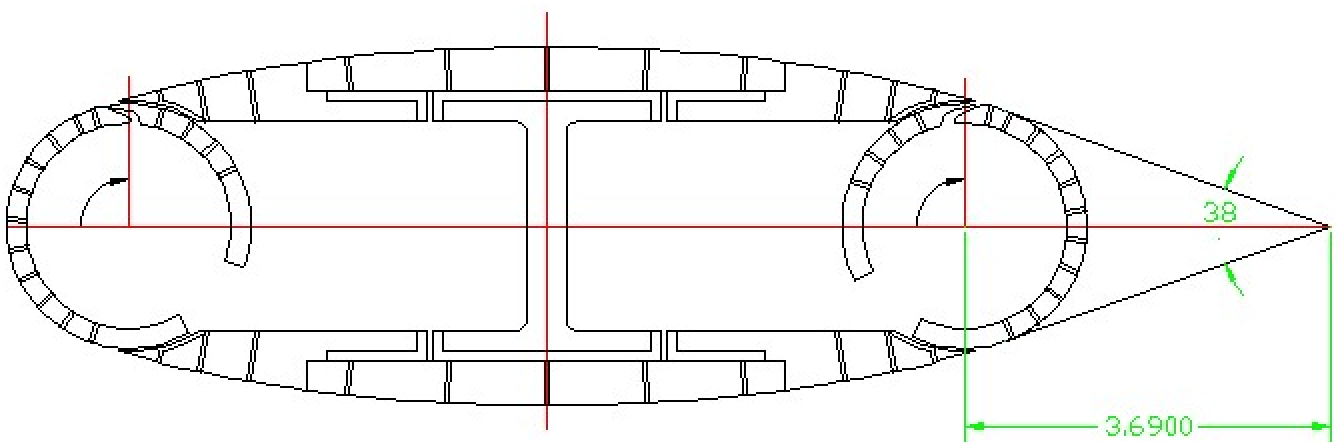

C_L vs. α, Ellipse M=0.044, Re=2.46*10^5, U=15 m/s, Spalart-Allmaras Model
Baseline
Trip at 7% chord
Trip at 11% chord
Trip at 15% chord
Trip at 19% chordx
Lab Results
C_L
α (deg)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
0
2
4
6
8
10
12
14
16
18
20
22
24
26

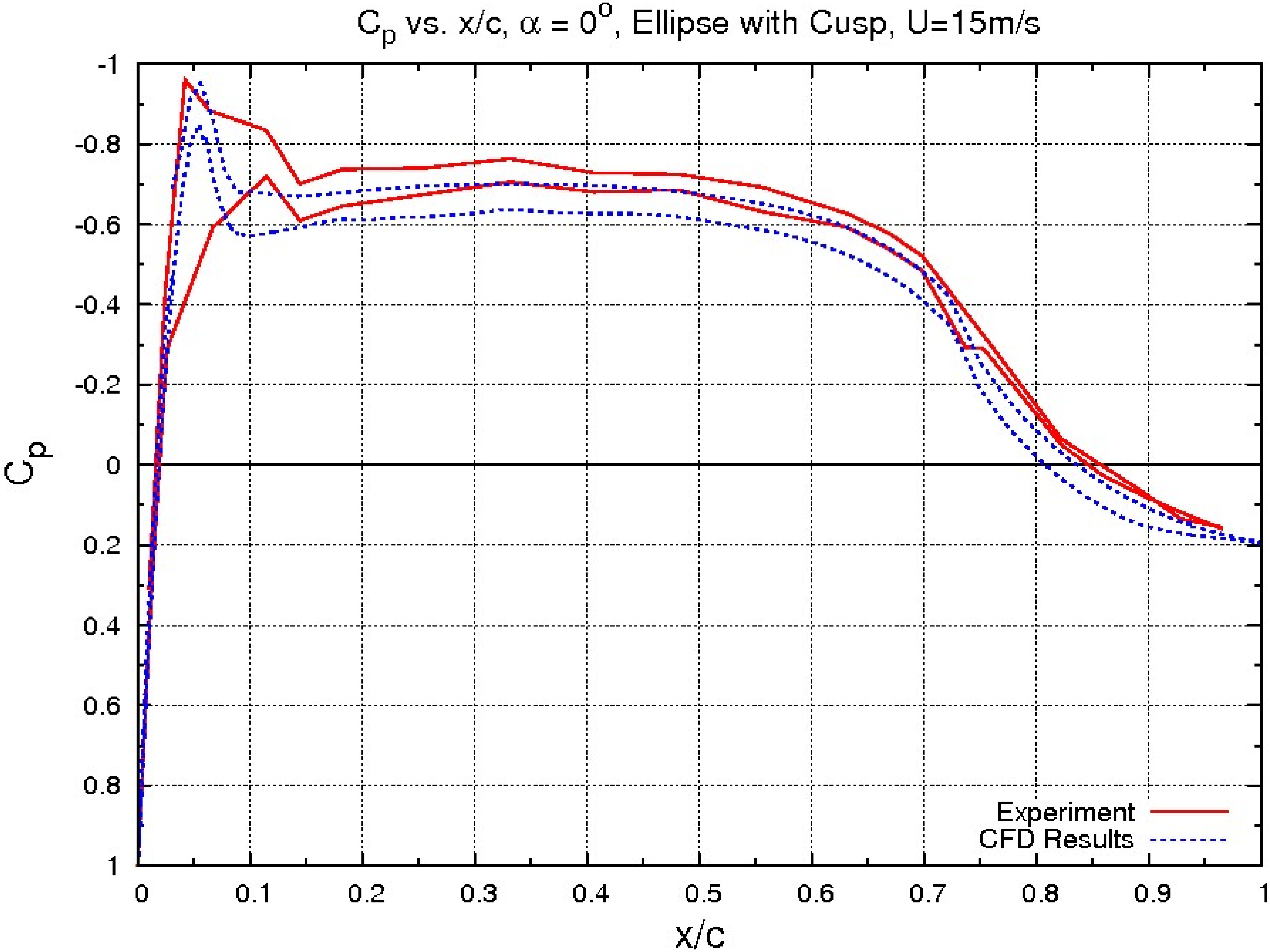


C_D vs. C_L, Ellipse M=0.044, Re=2.46*10^5, U=15 m/s, Spalart-Allmaras Model
Baseline
Trip at 7% chord
Trip at 11% chord
Trip at 15% chord
Trip at 19% chord
Lab Results
C_D
C_L
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.2
0.4
0.6
0.8
1
1.2

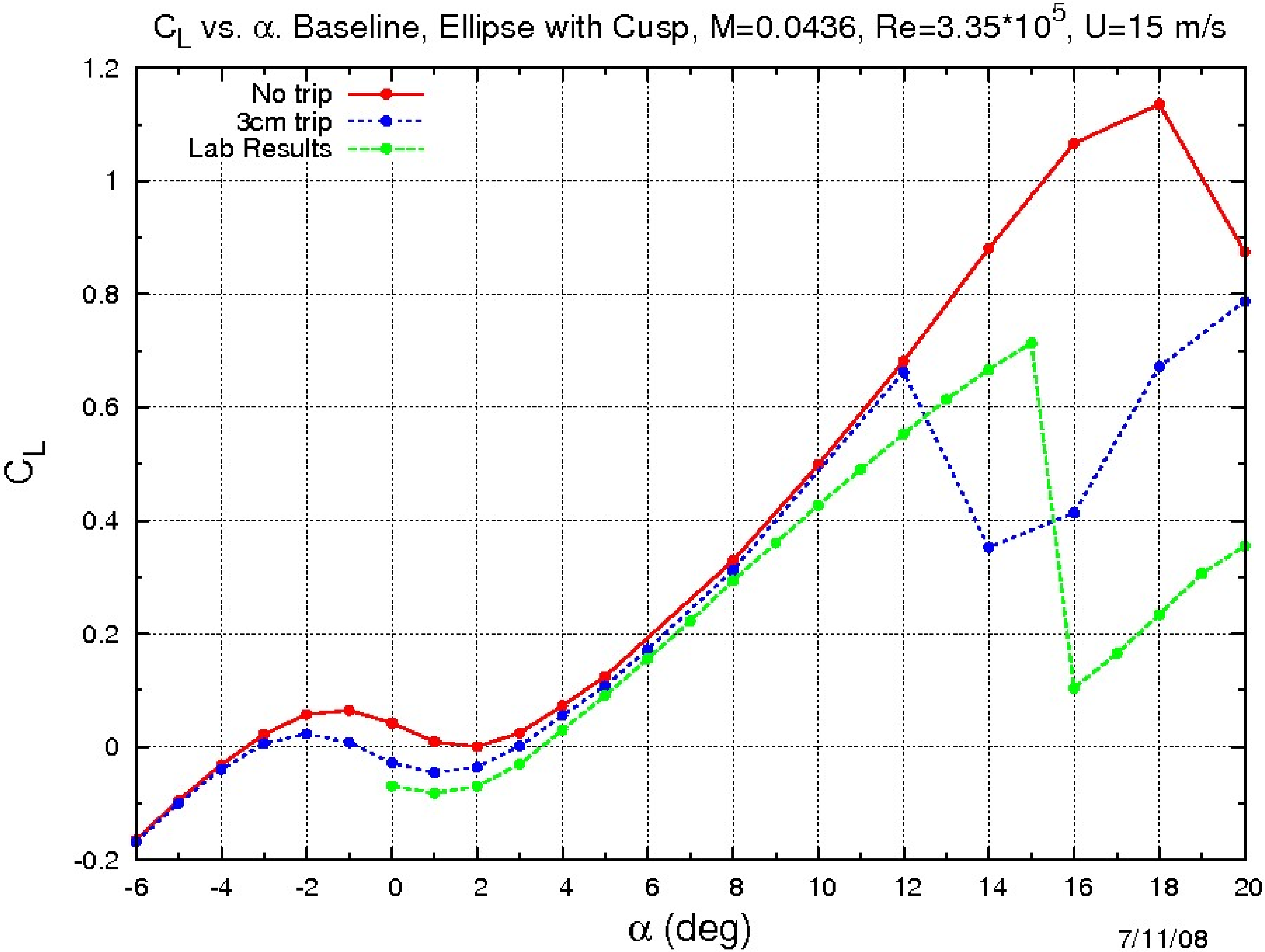
Ellipse with a Cusp

- A triangular cusp was added to the trailing edge
- The cusp enforces the Kutta condition
  - drastically changes the behavior of the airfoil
- The height is approximately 3.69”
- The two sides make a 38 degree angle



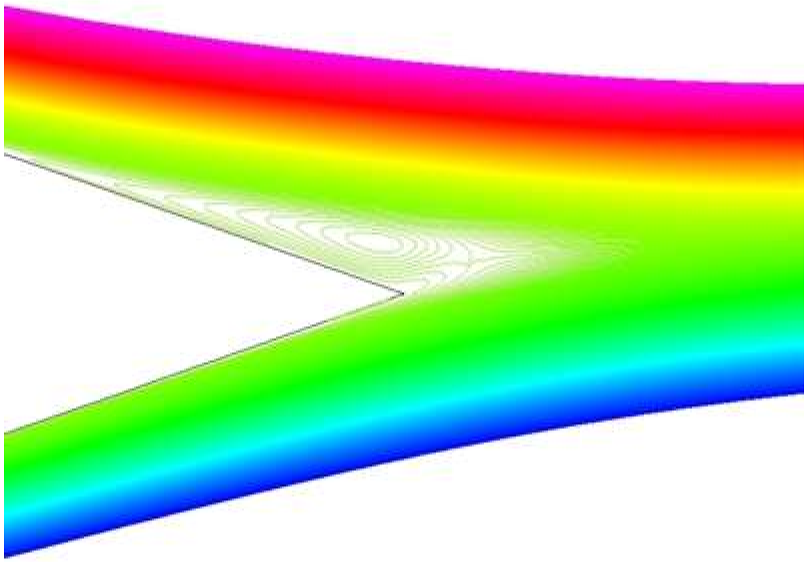


C_p vs. x/c, α = 0^o, Ellipse with Cusp, U=15m/s
C_p
x/c
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Experiment
CFD Results


C_L vs. α. Baseline, Ellipse with Cusp, M=0.0436, Re=3.35*10^5, U=15 m/s
No trip
3cm trip
Lab Results
C_L
α (deg)
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-6
-4
-2
0
2
4
6
8
10
12
14
16
18
20
7/11/08

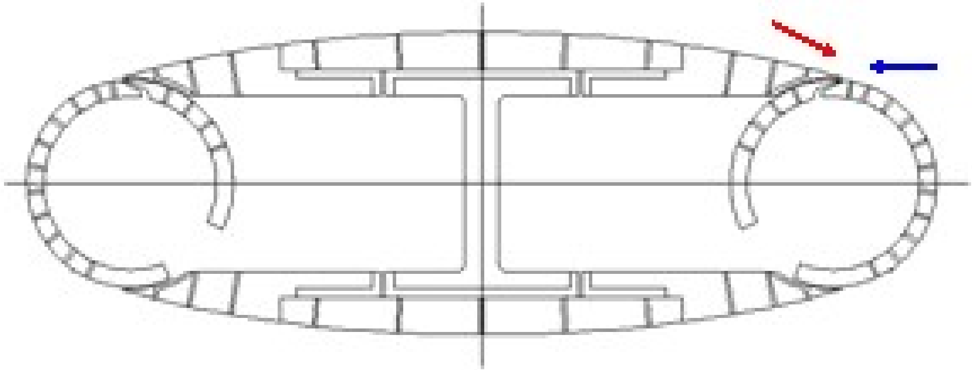
Cusp Observations

- About the geometry
  - High thickness ratio
  - High trailing edge angle
- At low angles of attack the boundary layer switches from one side to the other
  - There is growth at the upper surface
  - There is attached flow at the lower surface
- Suction is so strong that it produces a negative lift-curve slope

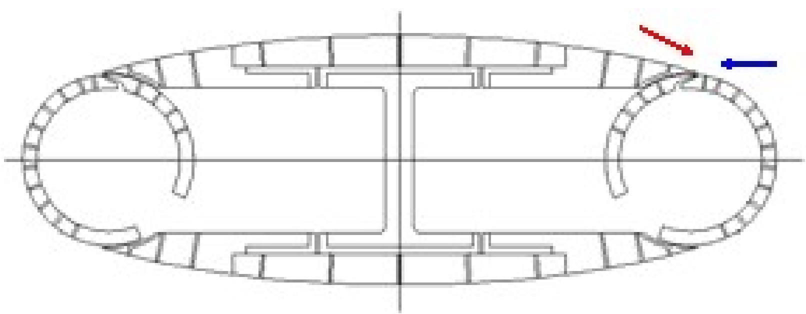


Streamlines, AOA = 2 degrees

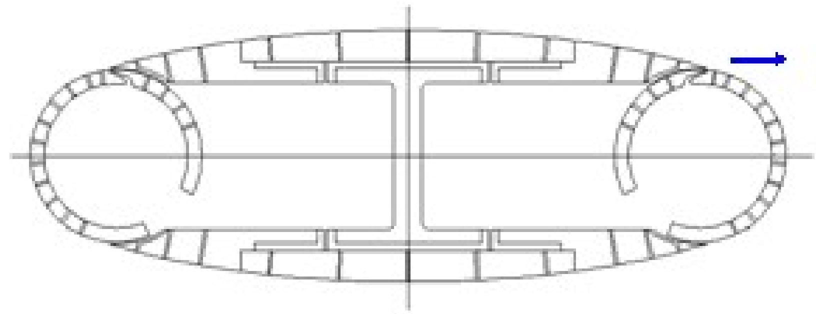
Active Flow Control



Trailing Edge Blowing and Suction



Suction Upstream and Downstream

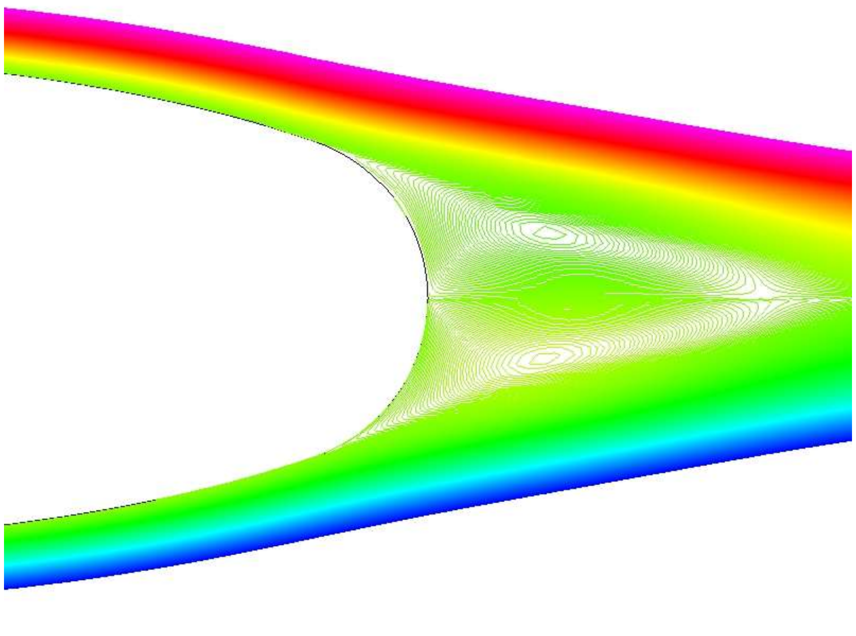


Blowing Downstream

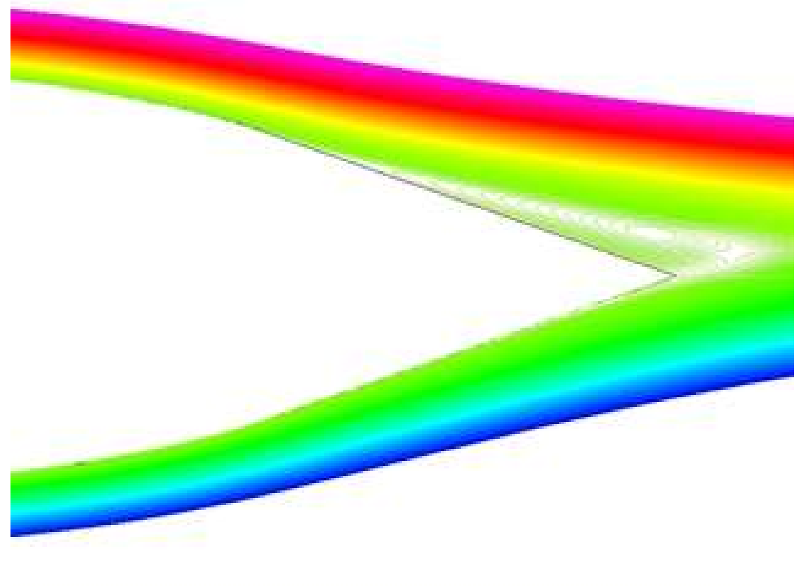
- Slot is pointed either upstream or downstream
- Slot width was varied from 15/1000 inch to 90/1000 inch
- Momentum coefficient was varied between 0% and 8%

$$C_\mu = \rho_J U_J^2 h / (\tfrac{1}{2} \rho_\infty U_\infty^2 c)$$

Steady Blowing, Streamlines

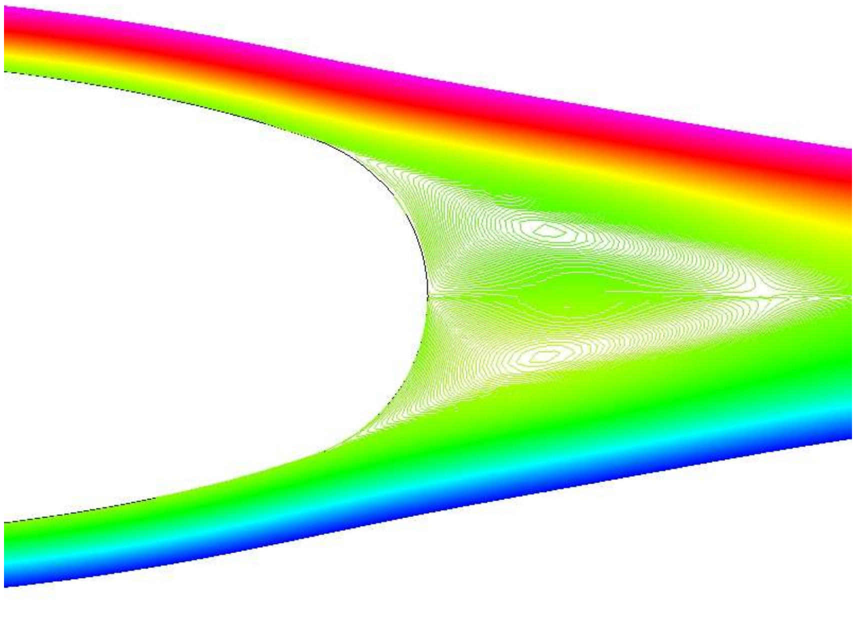


C_μ = 1%, h=15/1000 inch

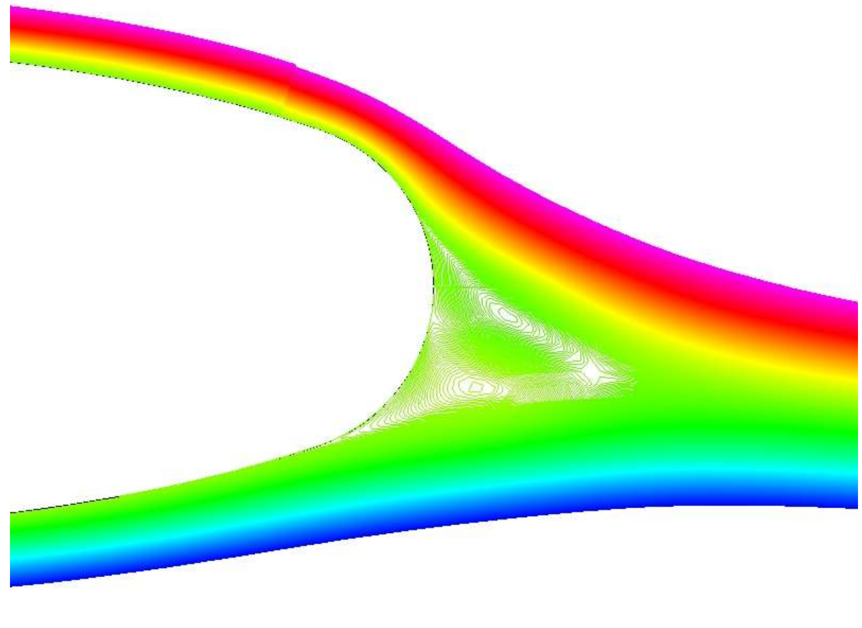


C_μ = 1%, h=15/1000 inch

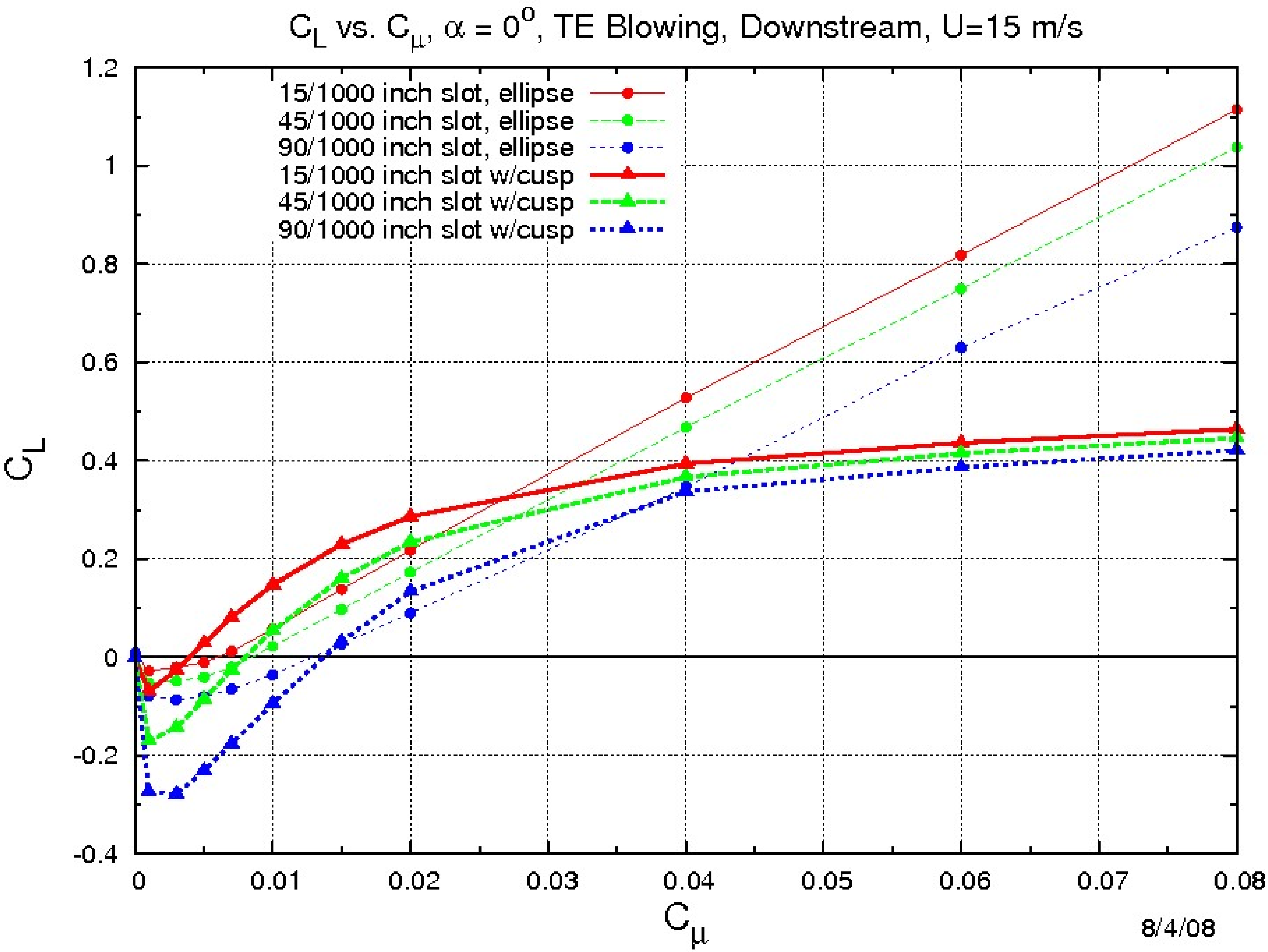
Steady Blowing, Streamlines



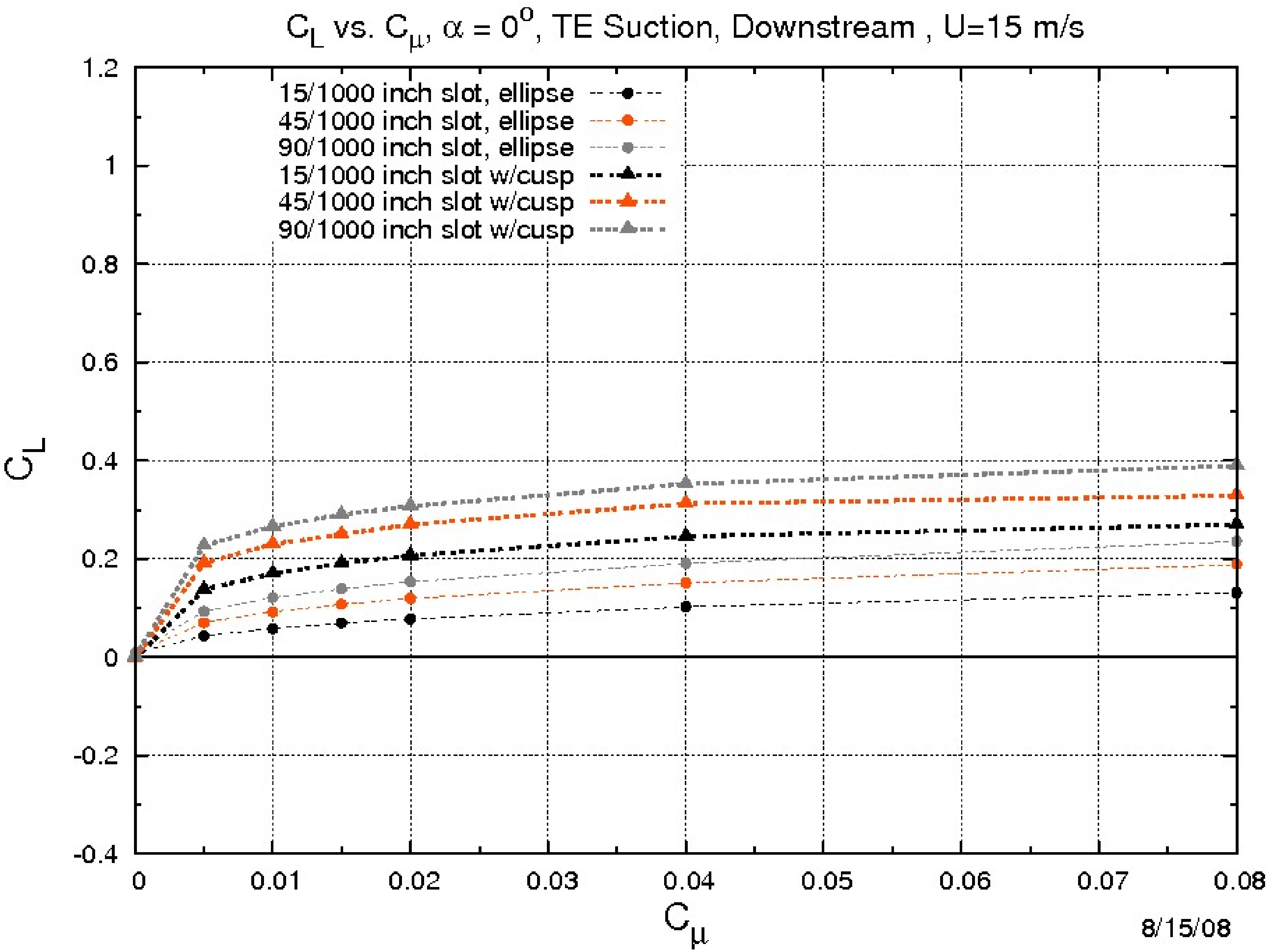
C_μ = 1%, h=15/1000 inch



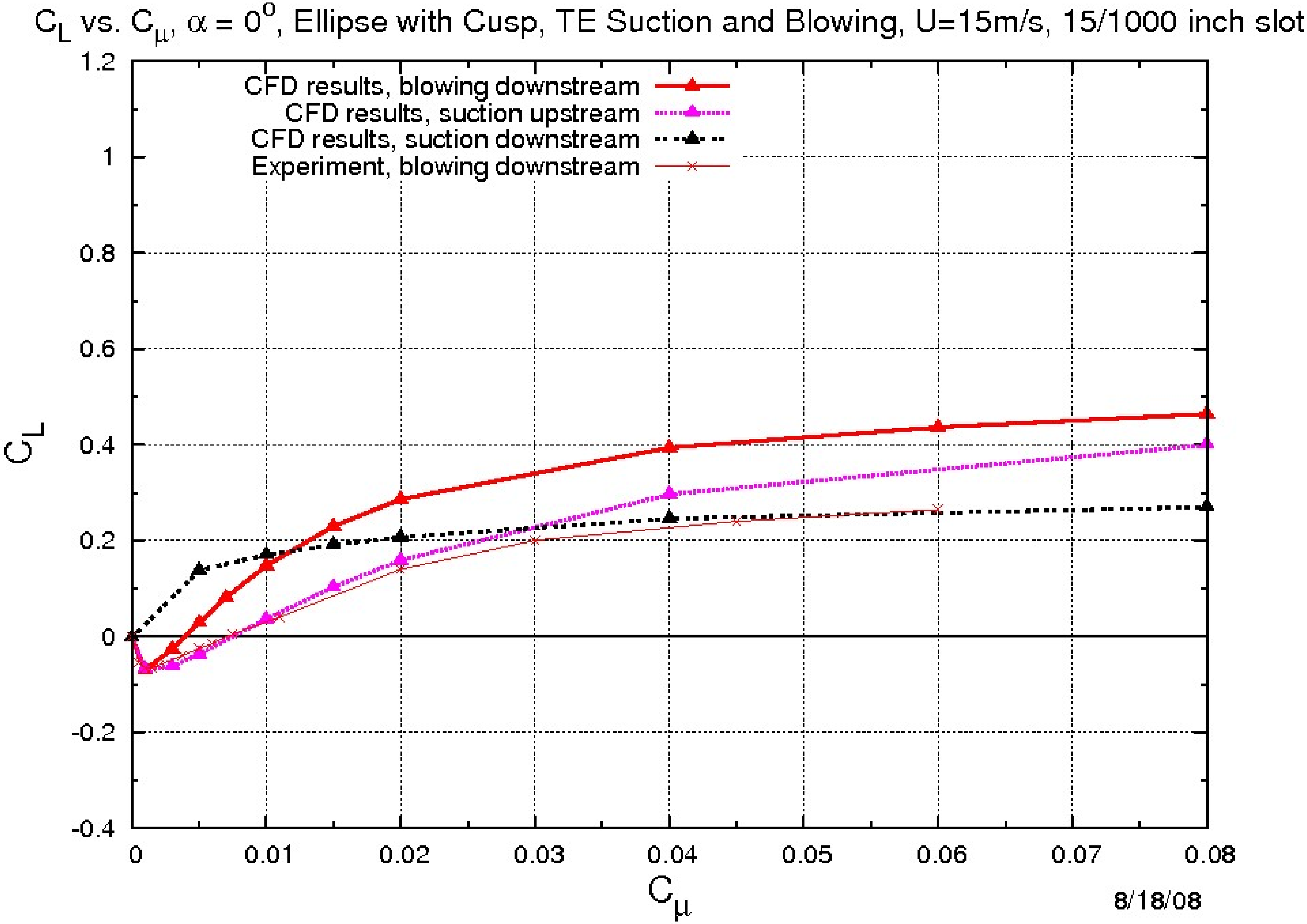
C_μ = 8%, h=15/1000 inch



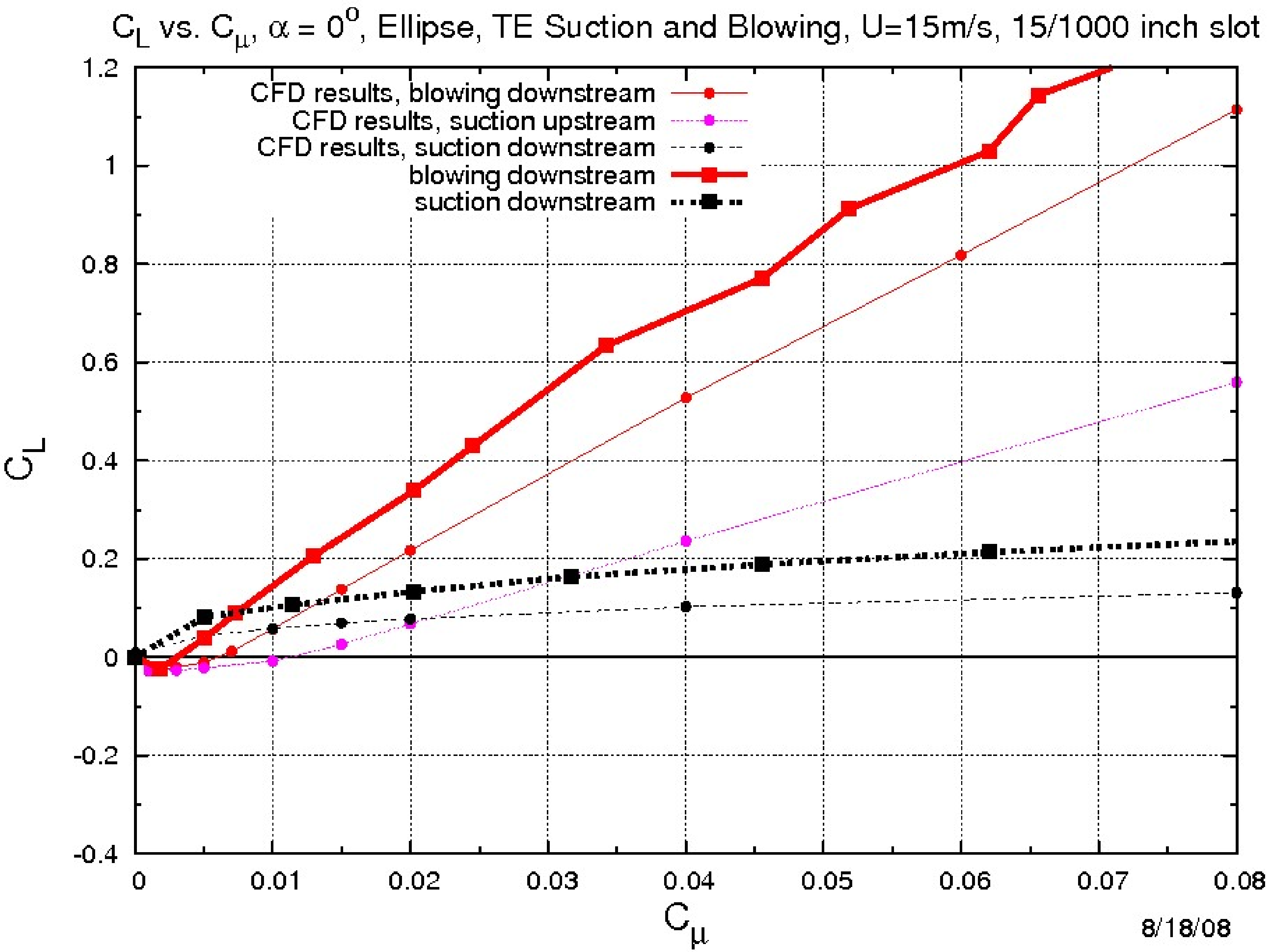
C_L vs. C_μ, α = 0°, TE Blowing, Downstream, U=15 m/s
15/1000 inch slot, ellipse
45/1000 inch slot, ellipse
90/1000 inch slot, ellipse
15/1000 inch slot w/cusp
45/1000 inch slot w/cusp
90/1000 inch slot w/cusp
C_L
C_μ
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
8/4/08



C_L vs. C_μ, $\alpha = 0^o$, TE Suction, Downstream , U=15 m/s
15/1000 inch slot, ellipse
45/1000 inch slot, ellipse
90/1000 inch slot, ellipse
15/1000 inch slot w/cusp
45/1000 inch slot w/cusp
90/1000 inch slot w/cusp
C_L
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
C_μ
8/15/08



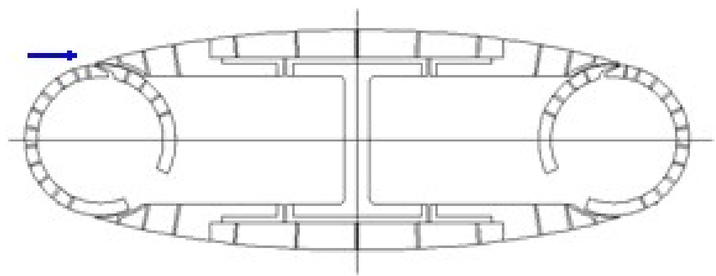
C_L vs. C_μ, α = 0°, Ellipse with Cusp, TE Suction and Blowing, U=15m/s, 15/1000 inch slot
CFD results, blowing downstream
CFD results, suction upstream
CFD results, suction downstream
Experiment, blowing downstream
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
C_L
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
C_μ
8/18/08



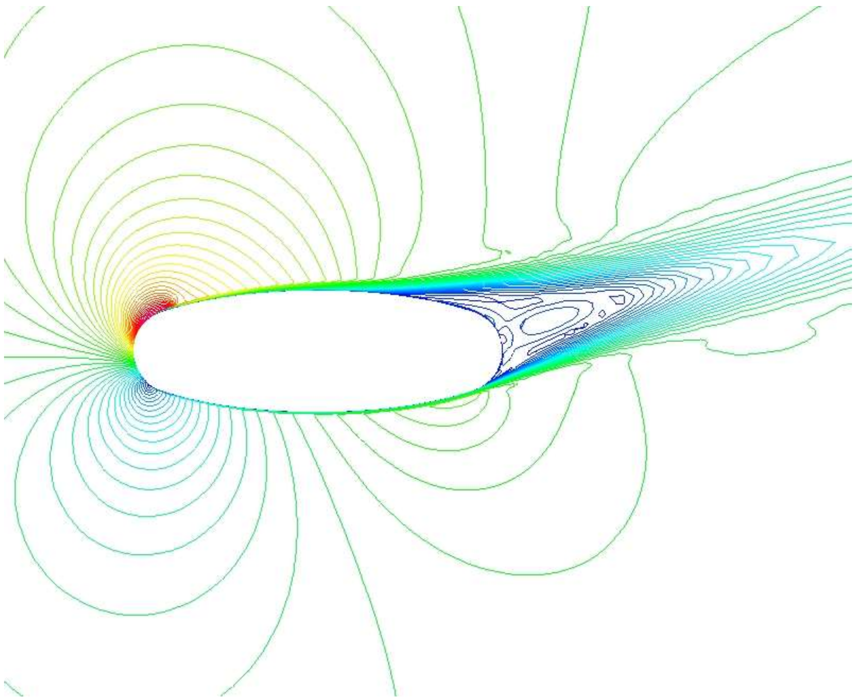
C_L vs. C_μ, α = 0°, Ellipse, TE Suction and Blowing, U=15m/s, 15/1000 inch slot
CFD results, blowing downstream
CFD results, suction upstream
CFD results, suction downstream
blowing downstream
suction downstream
C_L
C_μ
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
8/18/08

Leading Edge Suction

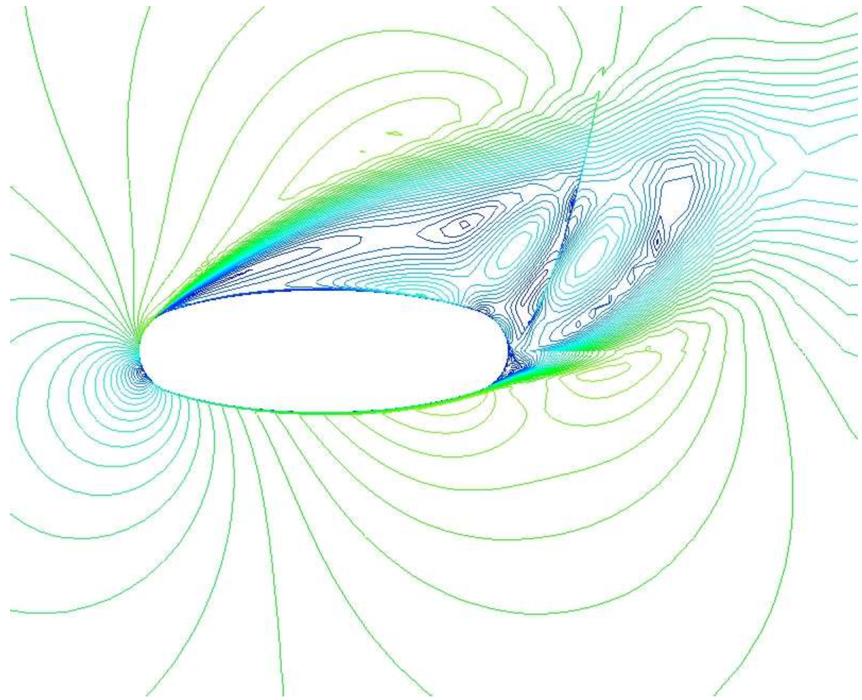
- Effects of steady suction
  - Significantly delays stall
  - Significantly increases lift
- Steady suction hysteresis
  - How will the airfoil stall if steady suction is turned off?
  - How will the airfoil recover from stall if suction is turned on?



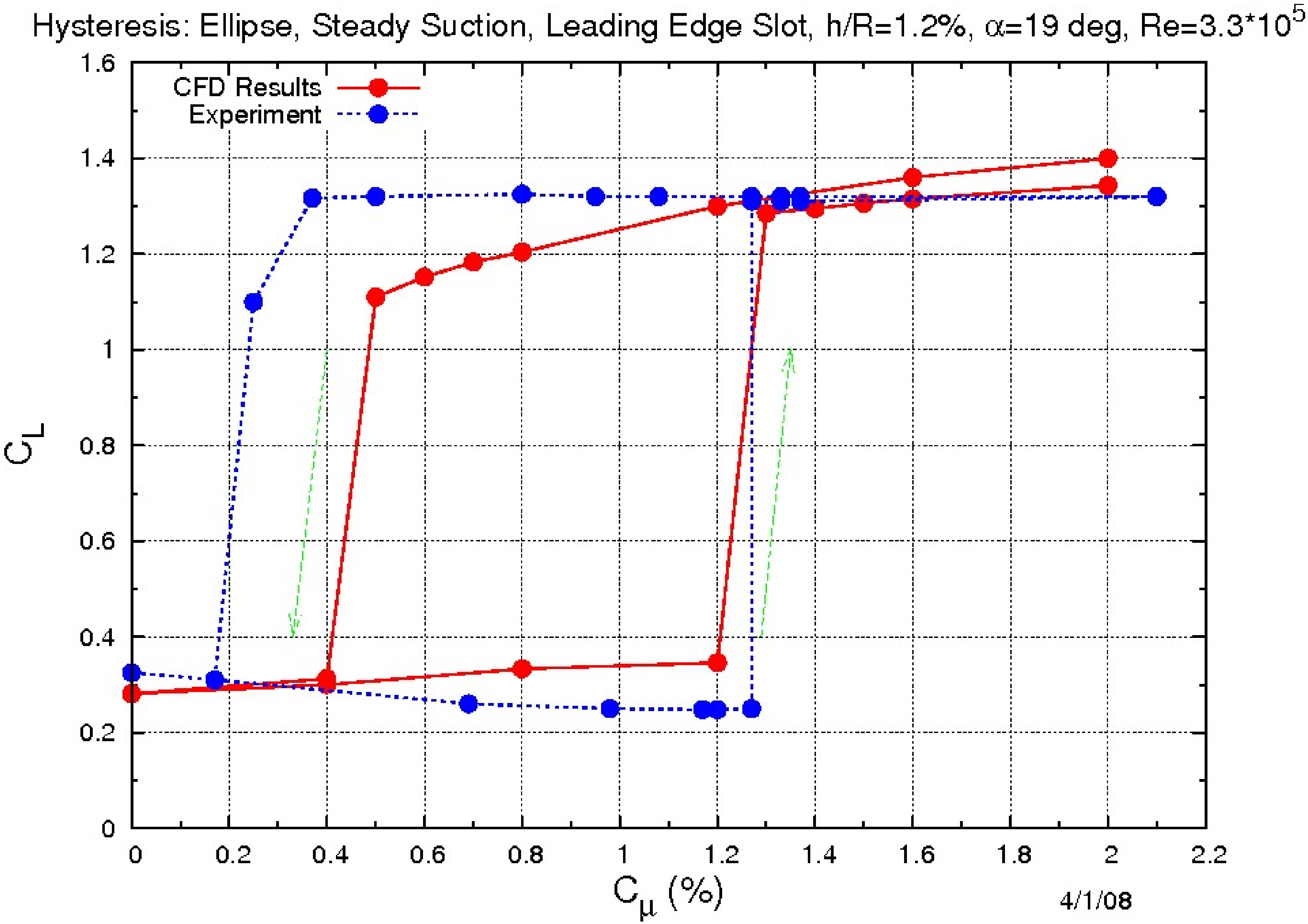
With and Without Suction

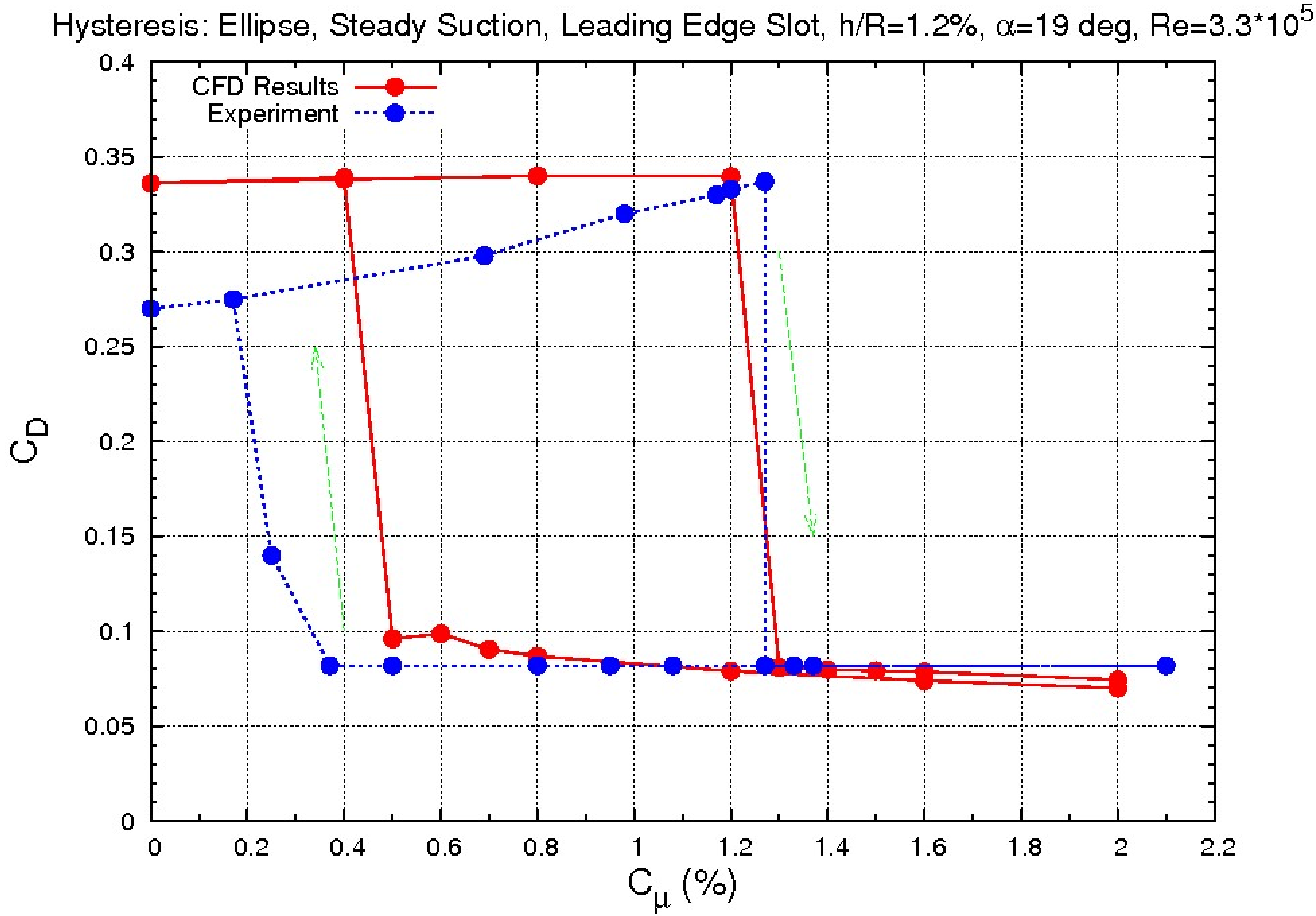


α = 19 degrees, C_{μ} = 2%



α = 19 degrees, C_{μ} = 0%


Hysteresis: Ellipse, Steady Suction, Leading Edge Slot, h/R=1.2%, α=19 deg, Re=3.3*10^5
CFD Results
Experiment
C_L
C_μ (%)
4/1/08
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
2.2

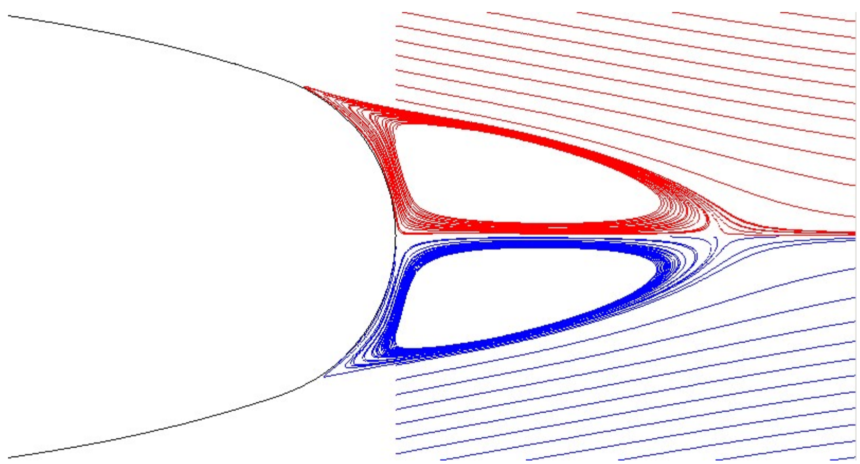


Hysteresis: Ellipse, Steady Suction, Leading Edge Slot, h/R=1.2%, α=19 deg, Re=3.3*10^5
CFD Results
Experiment
C_D
C_μ (%)
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
2.2

Time Accurate Results

Zero Angle of Attack

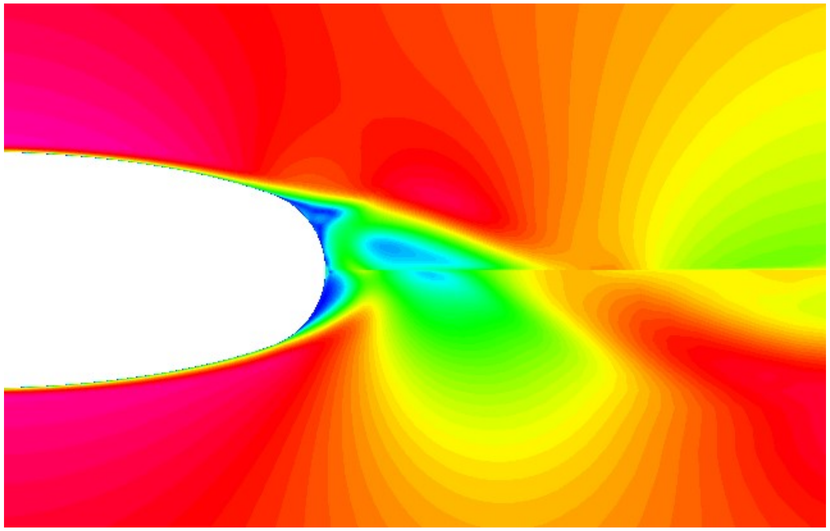
- Theory
  - Blunt trailing edge
  - Similar to circular cylinder
  - Solution oscillates
- CFD
  - Solution is steady
  - Spalart-Allmaras model
  - Flow field is characteristic of low Reynolds numbers Re = 3000



dt = 0.01 ncyc = 8

Zero Angle of Attack

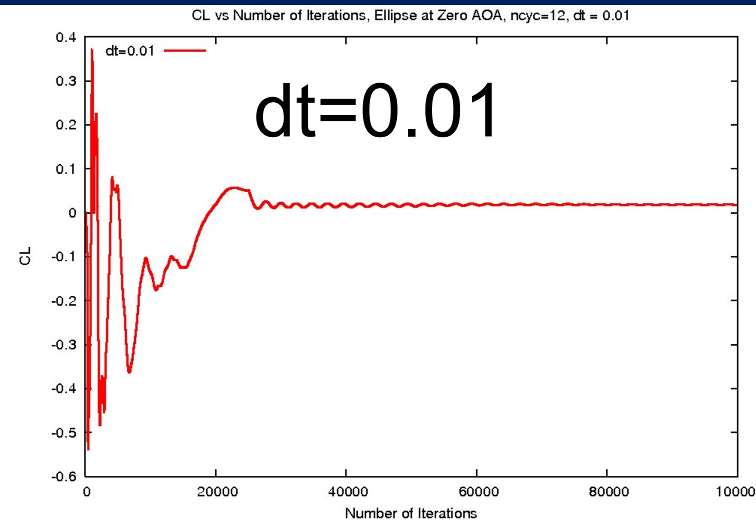
- Is the time step too low?
  - dt was increased to 1.00
  - Solution oscillates
- Poor solution
  - Residuals were high
  - Oscillations too large
  - Solution not resolved at boundaries

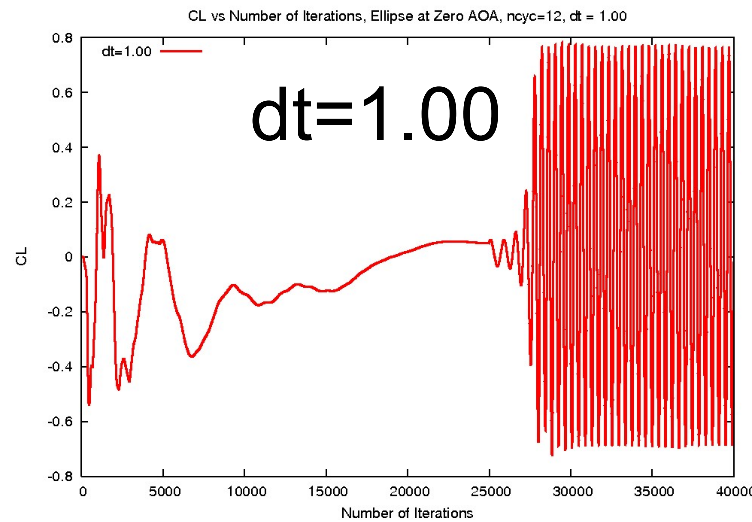


dt = 1.00 ncyc = 8

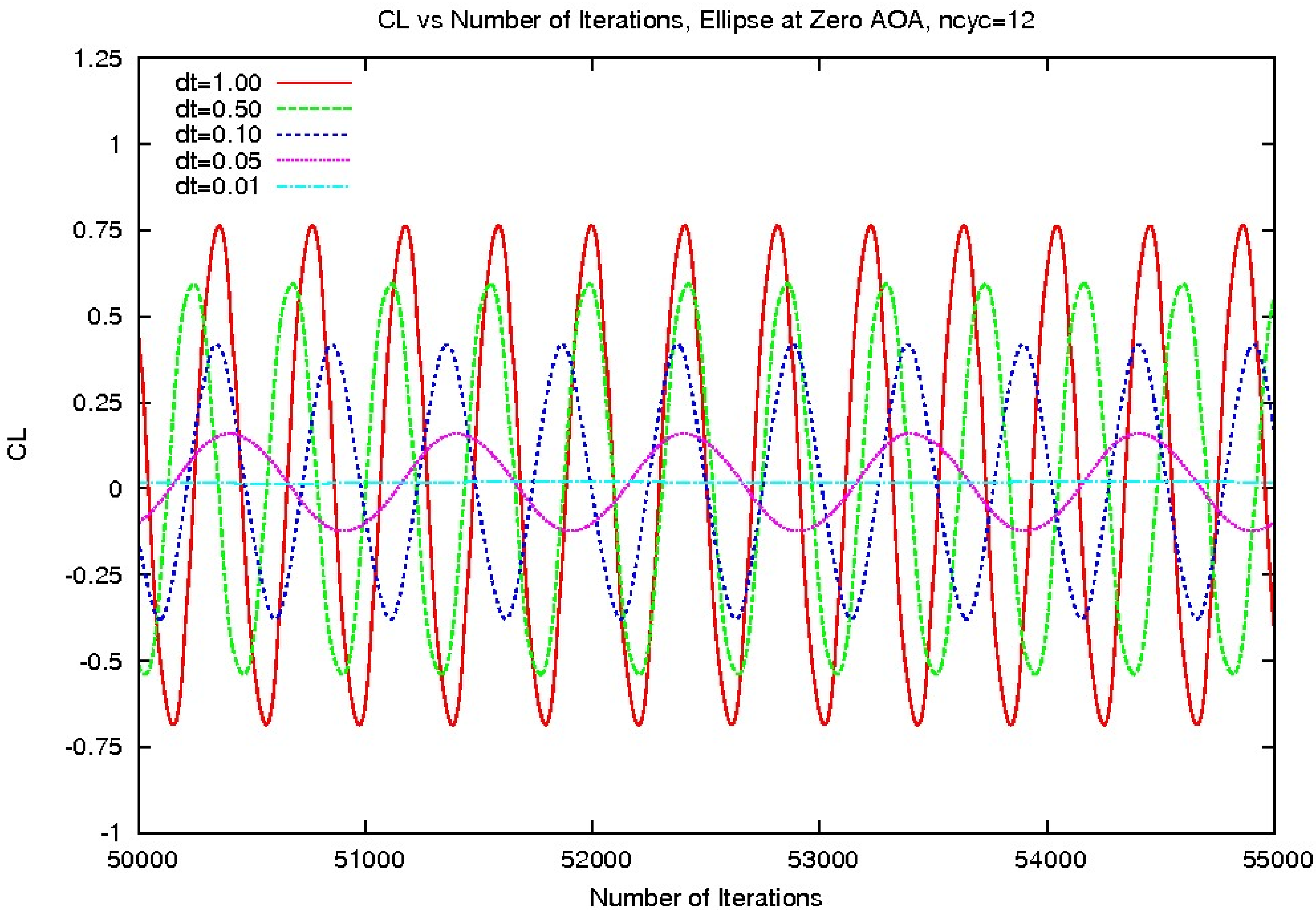
Zero Angle of Attack

- How does the solution change with dt?
- Lift coefficient was plotted vs. iterations
- Observe the plots
  - Two values of dt
  - No other changes

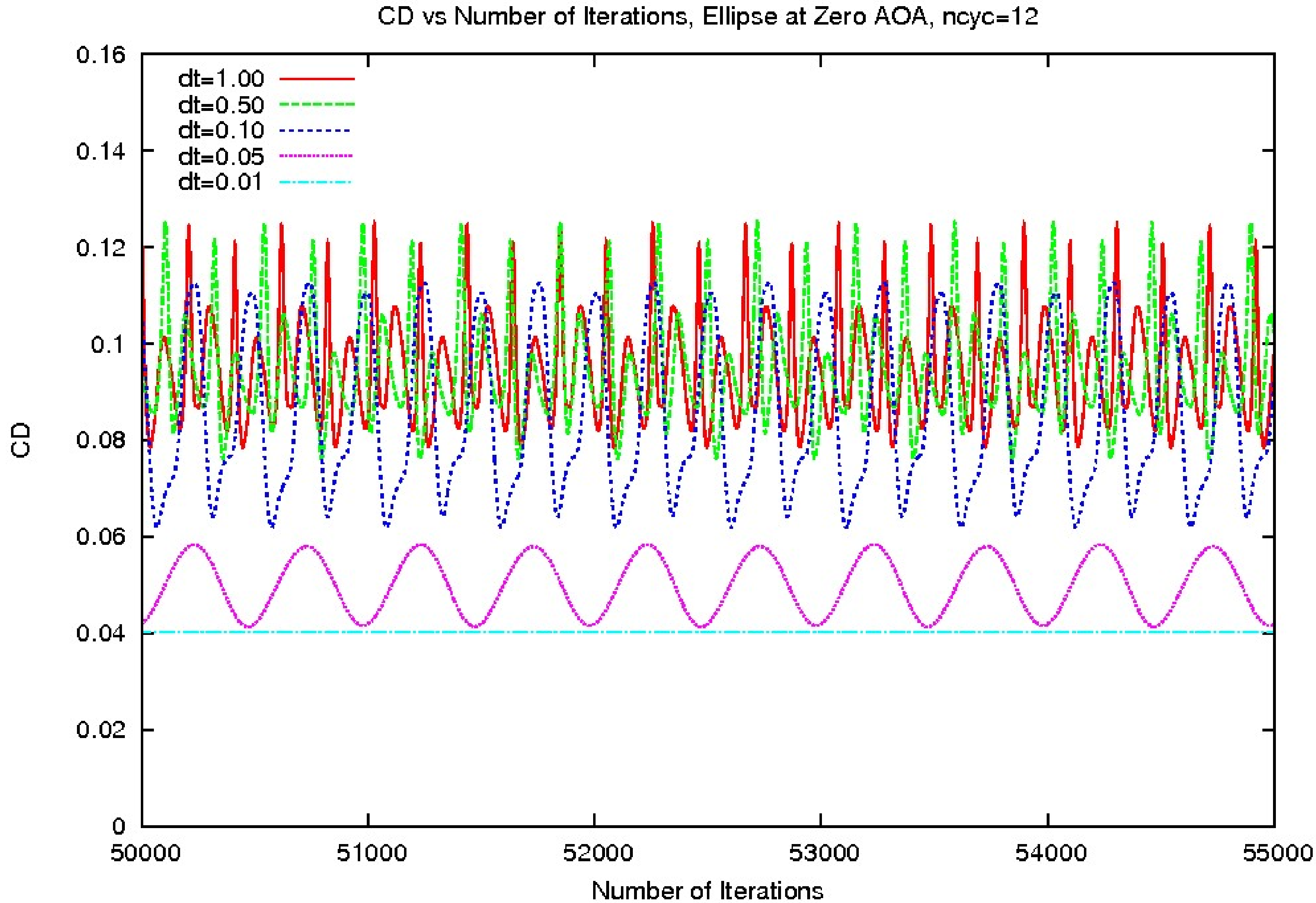




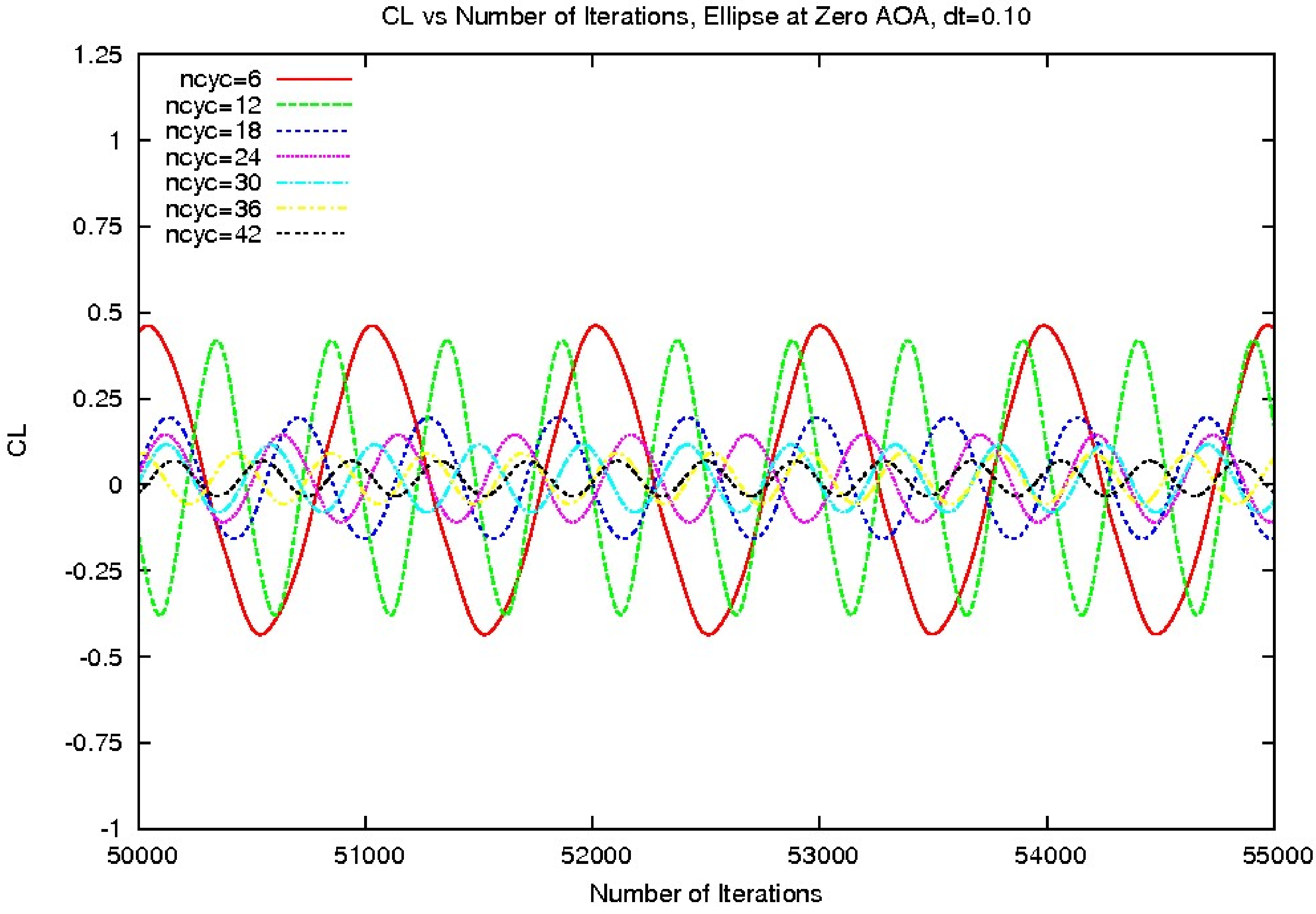
Dependence of C_L on Time Step, ncyc = 12



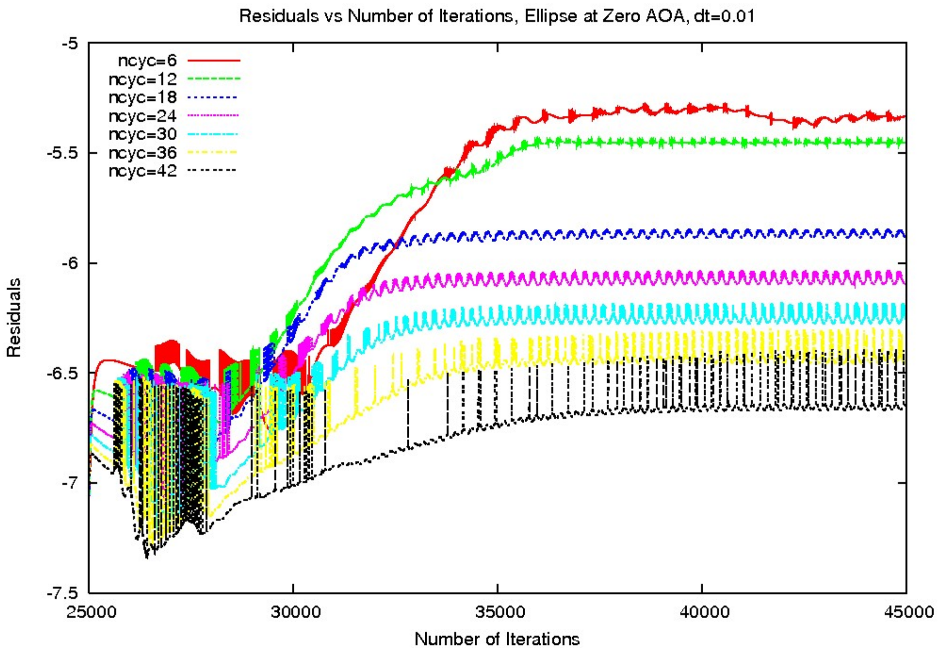
Dependence of C_D on Time Step, ncyc = 12

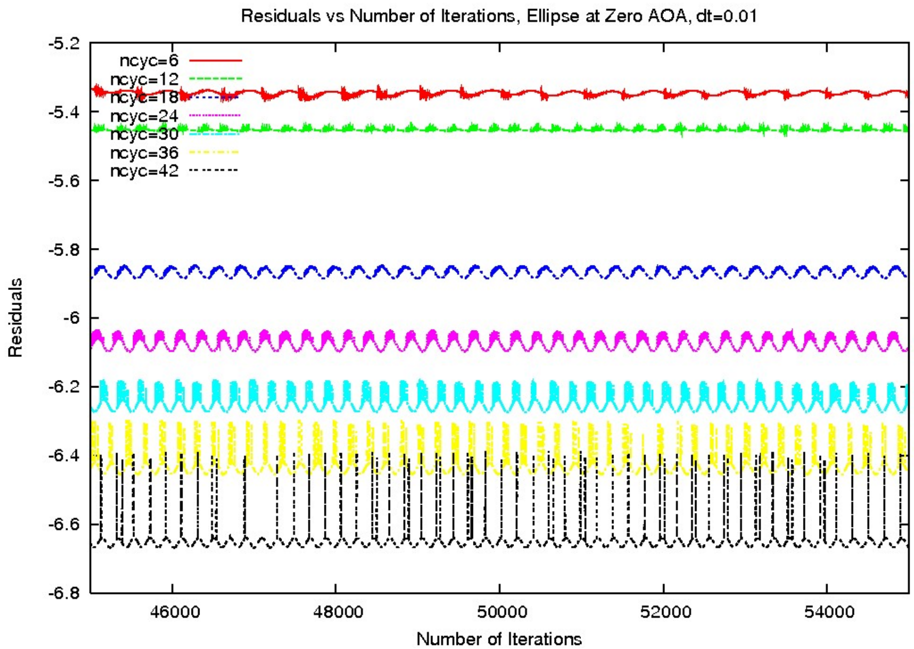


Dependence of Solution on # of Cycles, ncyc, dt = 0.1



Residuals





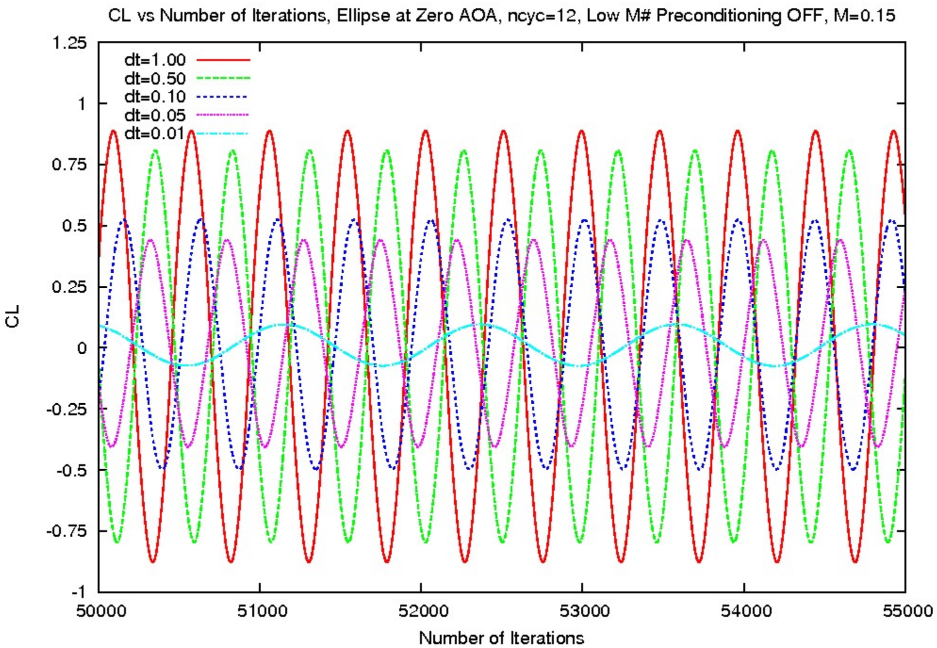
- As the solution becomes steady, the residuals decrease
- As the residuals decrease, frequent jumps appear in residual values
- Steady solution is not a good solution

How can this be fixed?

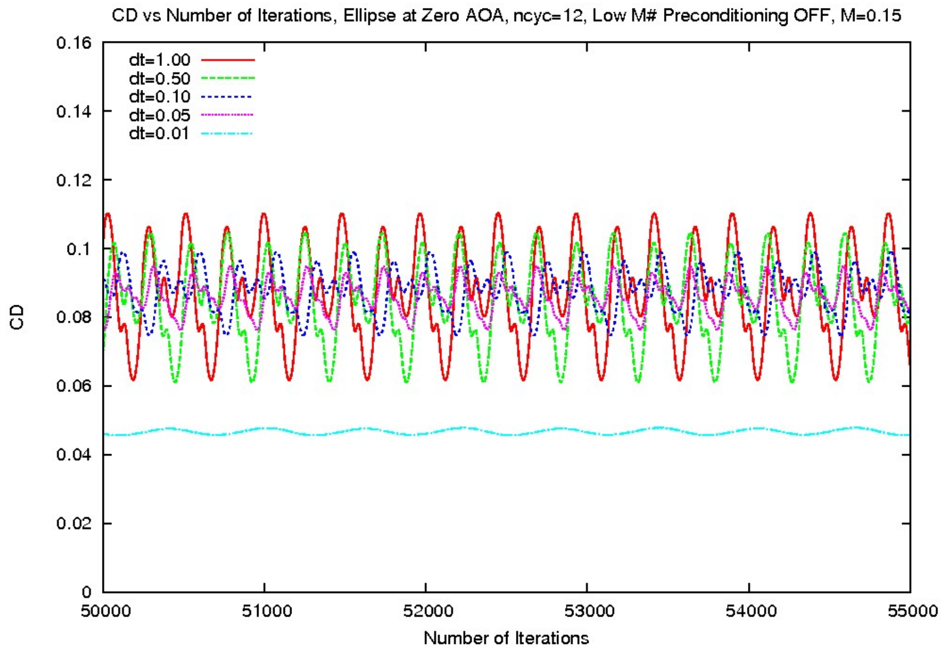
1. Try increasing Mach number
   – Low Mach number preconditioning has known issues
2. Try running full Navier Stokes equations
   – Includes cross derivative terms not usually included in thin-layer approximation
3. Try running in series mode
   – Problem may be with splitting large grid into pieces
   – May be why solution was not resolved at boundaries

Higher Mach Number

C_L

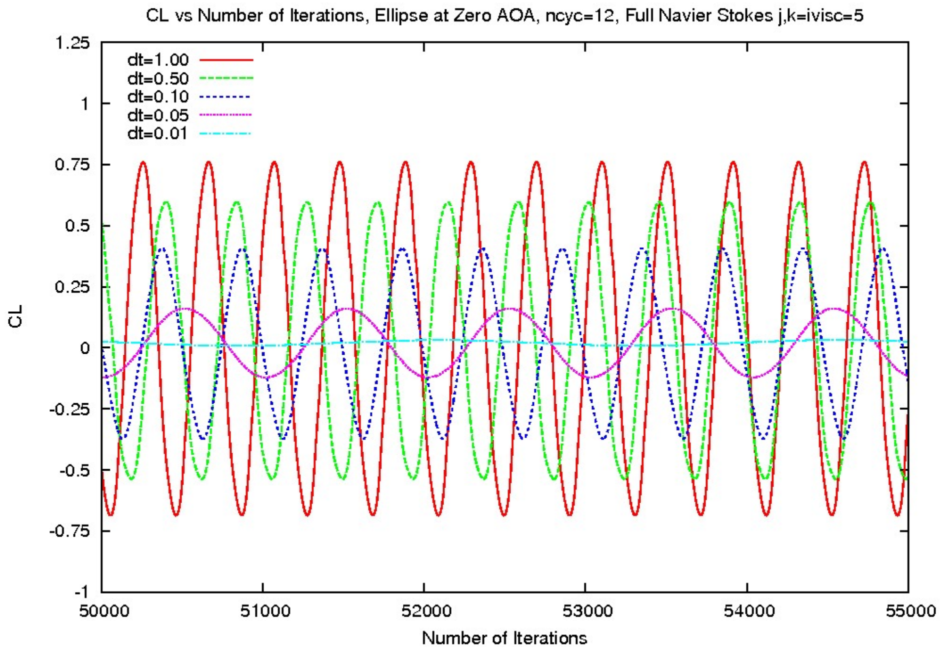


C_D

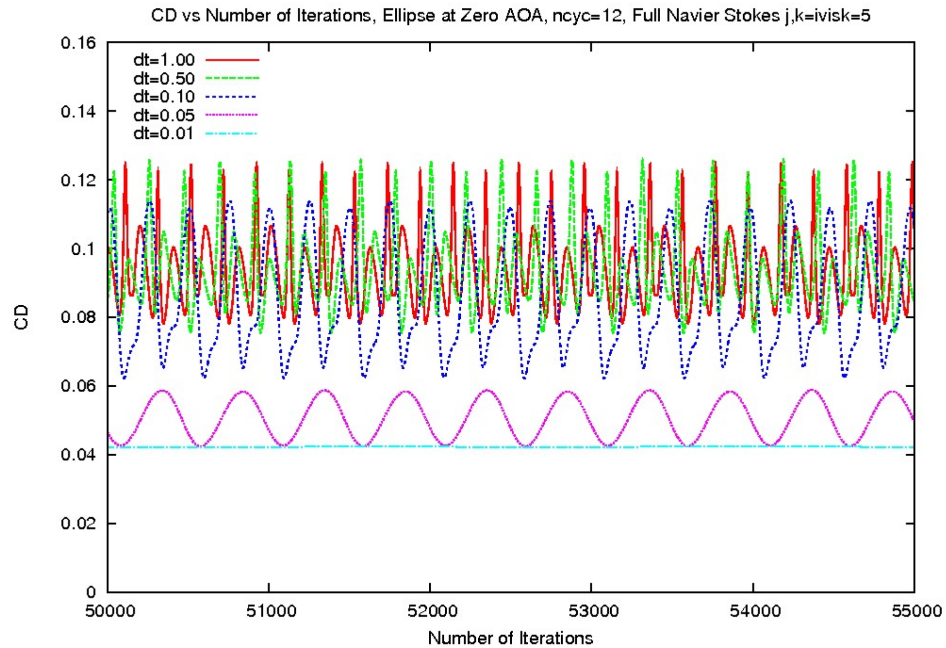


Full Navier Stokes

C_L

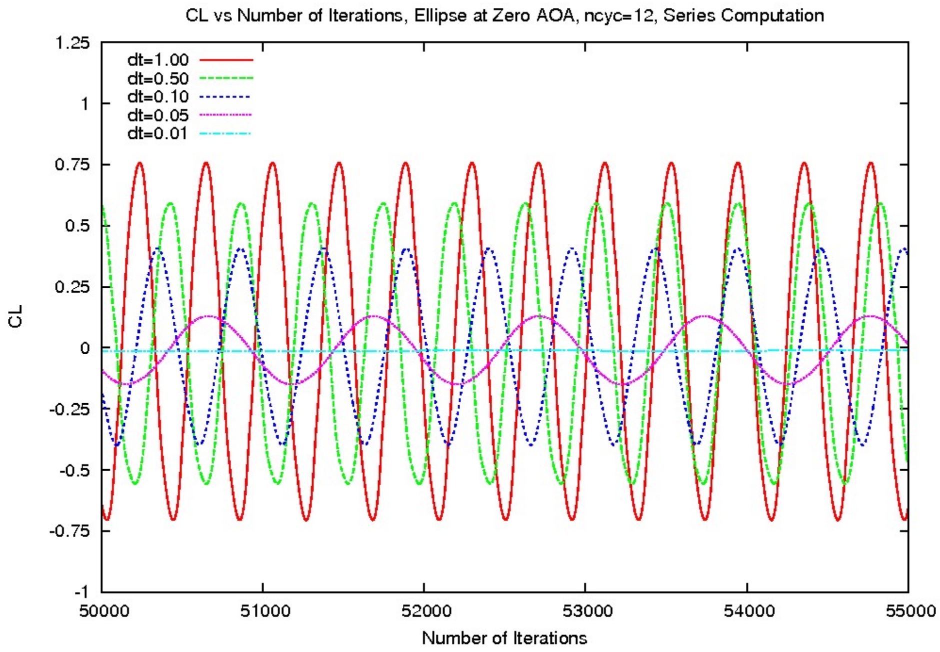


C_D

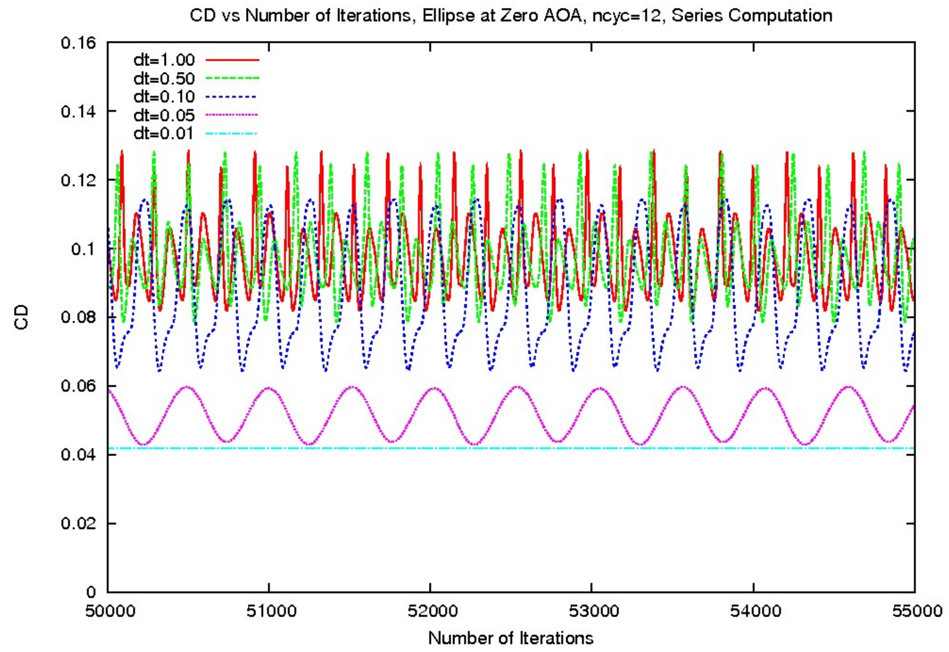


Series Computation

C_L



C_D

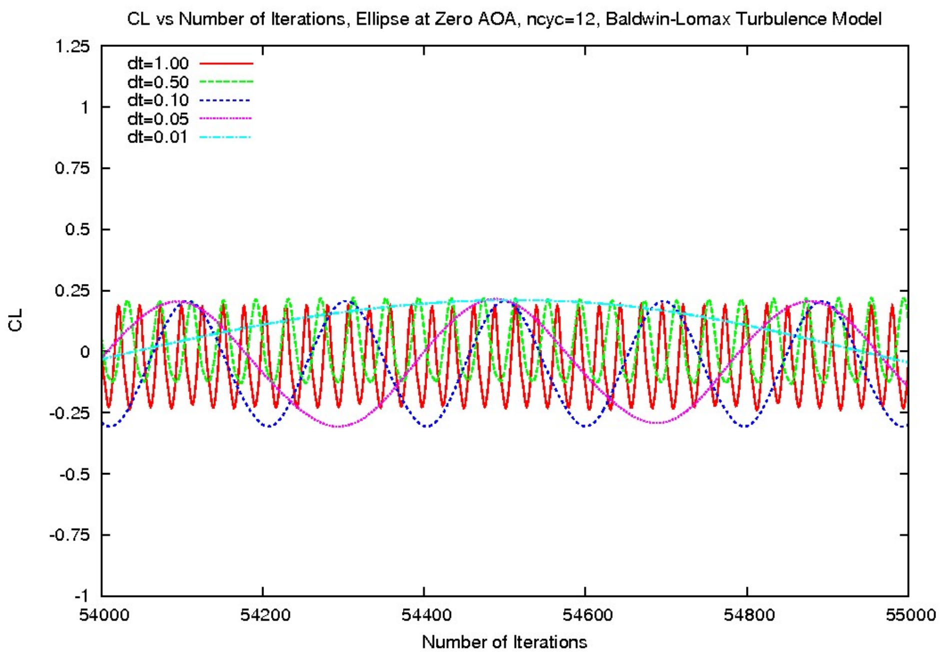


How else can this be fixed?

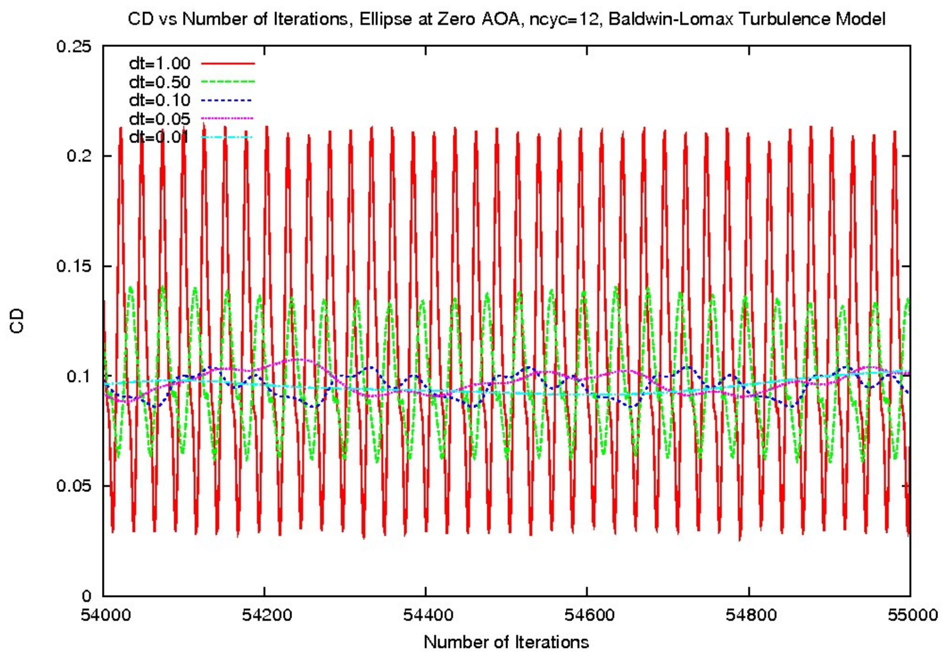
- Try employing another turbulence model
- Spalart-Allmaras model is robust model
  - Most commonly used model
  - But it is not working
- Baldwin-Lomax with Degani-Schiff modification is also known to be robust
  - Older model
  - Original model used by CFL3D

Baldwin-Lomax Model

C_L



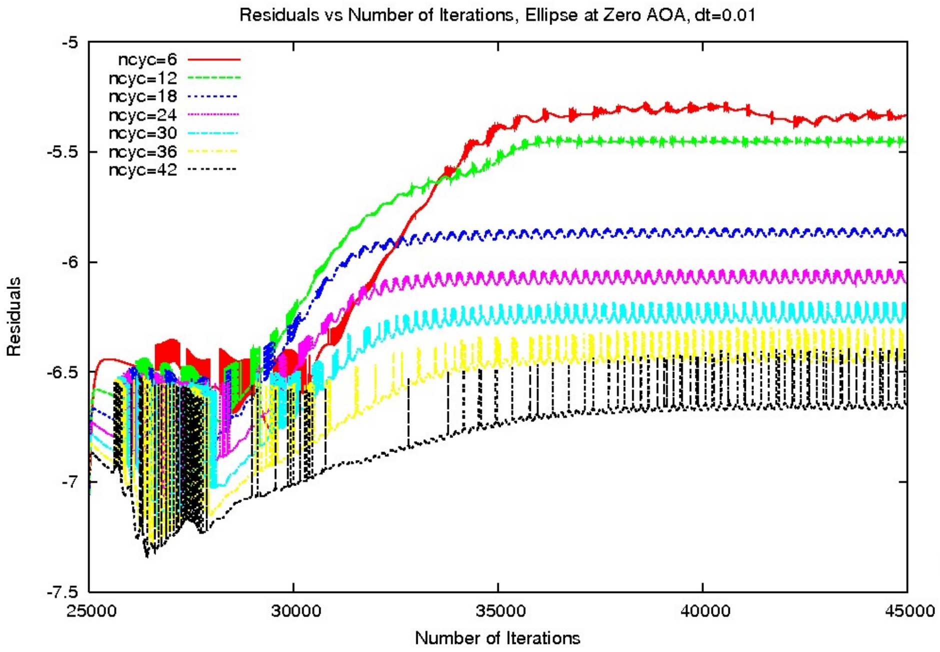
C_D



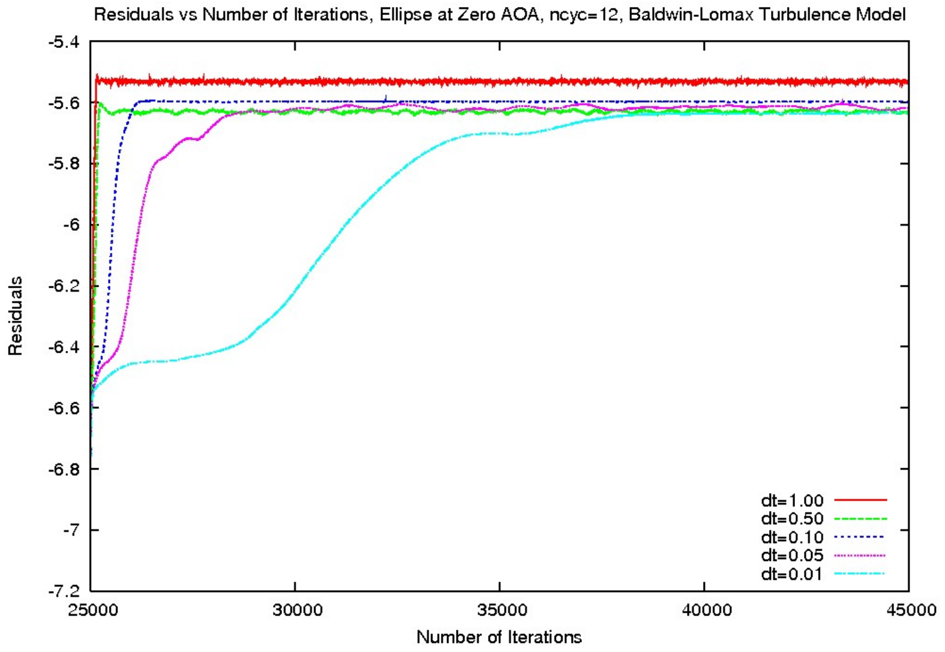
- surprisingly good results
- frequency and amplitude of oscillations independent of dt, ncyc
- for high values of dt, C_D oscillated too much
- but for high values of dt solution is not expected to be accurate

Residuals

Spalart-Allmaras Model

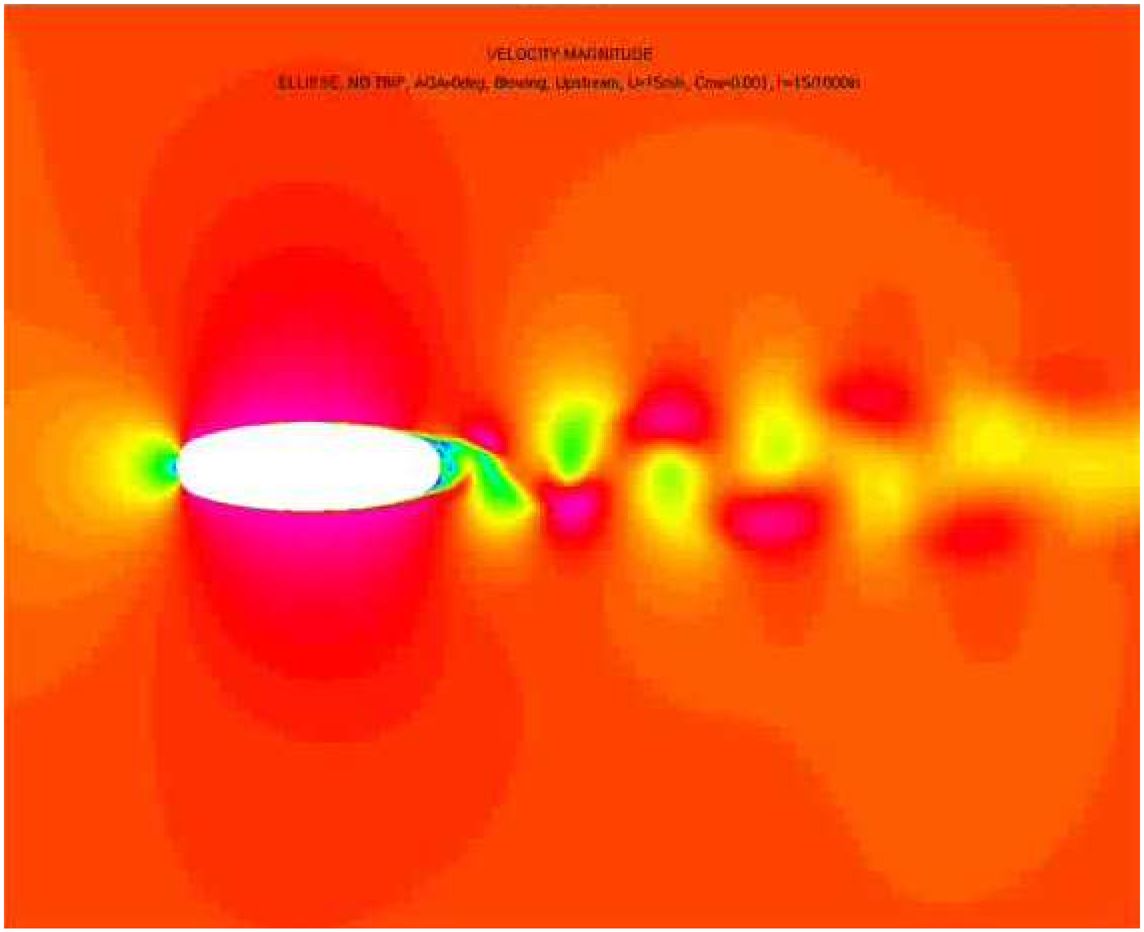


Baldwin-Lomax Model



- residuals are now in a reasonable range
- no observable jumps
- as dt decreases, the solution gets better, residuals decrease

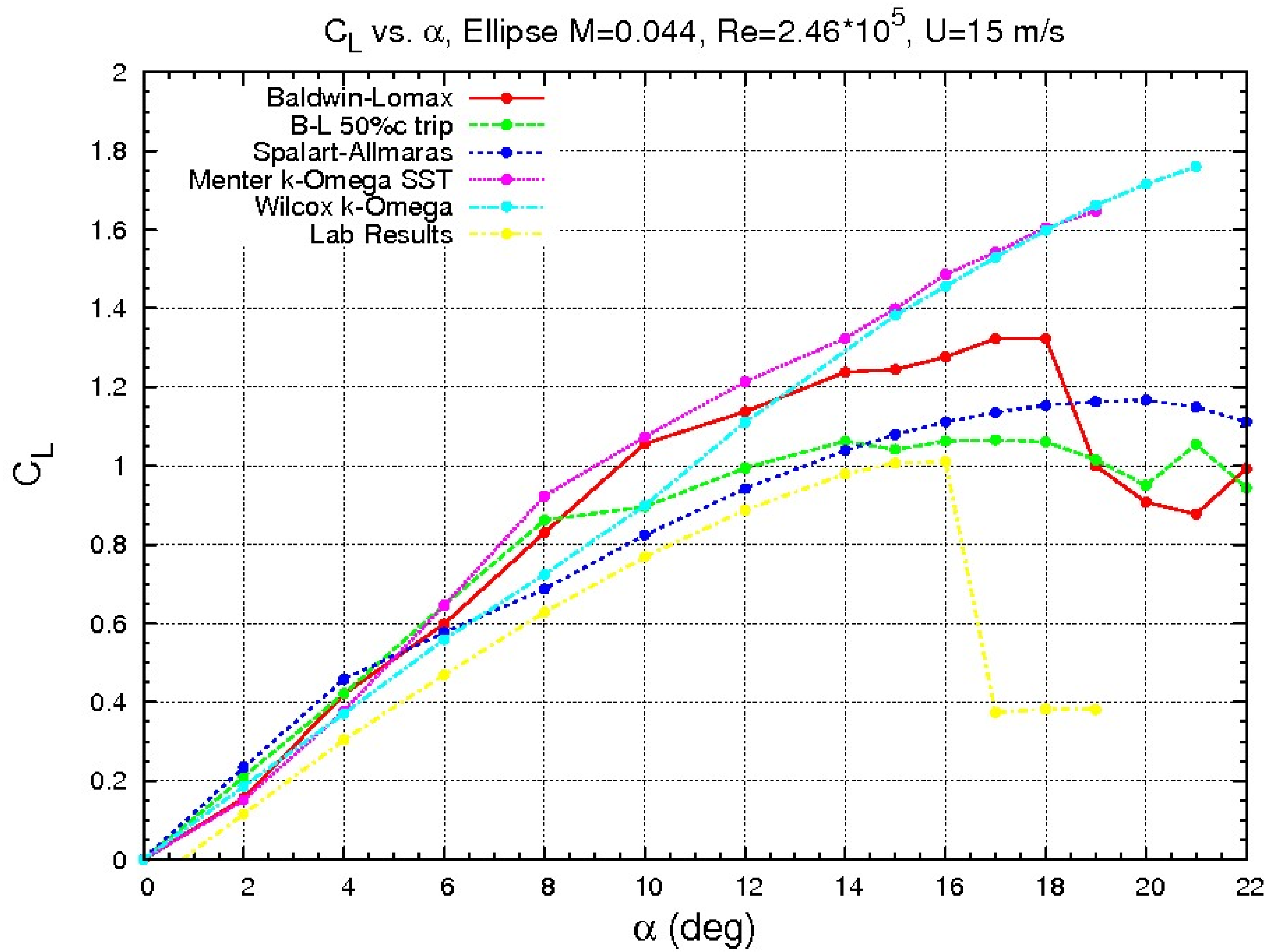
Baldwin-Lomax Model



Study of Turbulence Models

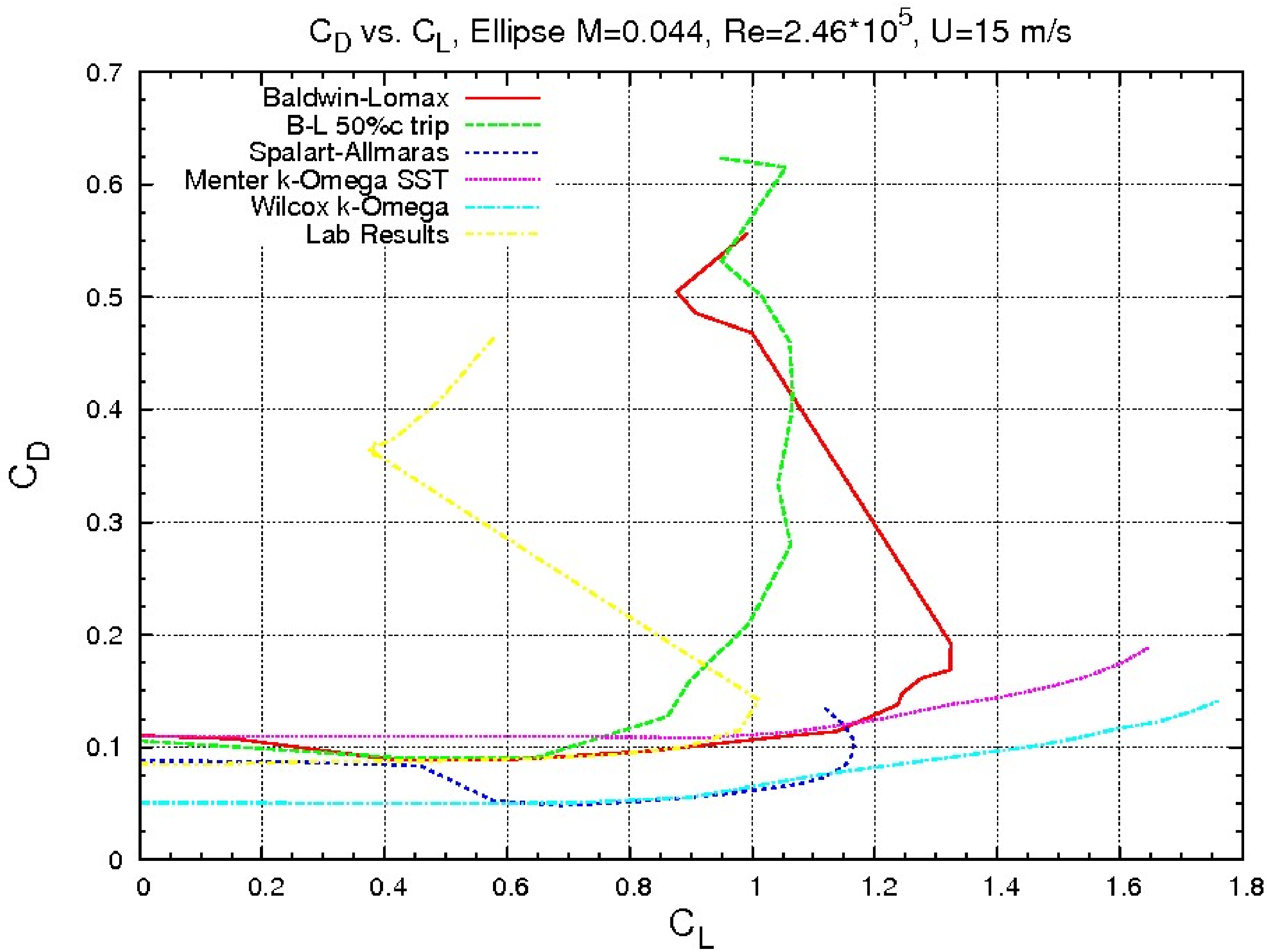
1. Baldwin-Lomax
2. Spalart-Allmaras
3. Menter’s k-Omega SST model
4. Wilcox k-Omega model

C_L vs. α



C_L vs. α, Ellipse M=0.044, Re=2.46*10^5, U=15 m/s
Baldwin-Lomax
B-L 50%c trip
Spalart-Allmaras
Menter k-Omega SST
Wilcox k-Omega
Lab Results
C_L
α (deg)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
0
2
4
6
8
10
12
14
16
18
20
22

C_D vs. C_L

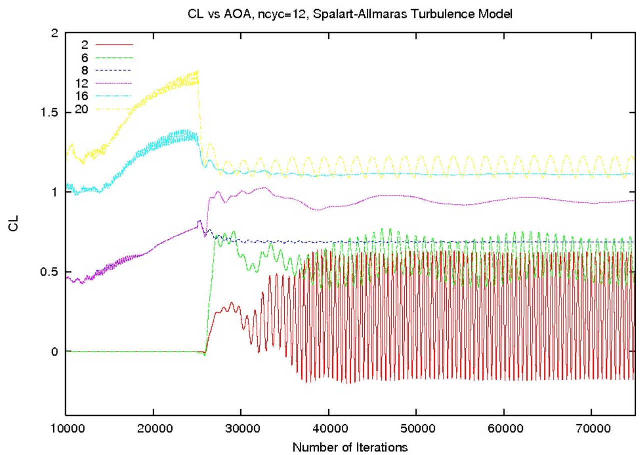


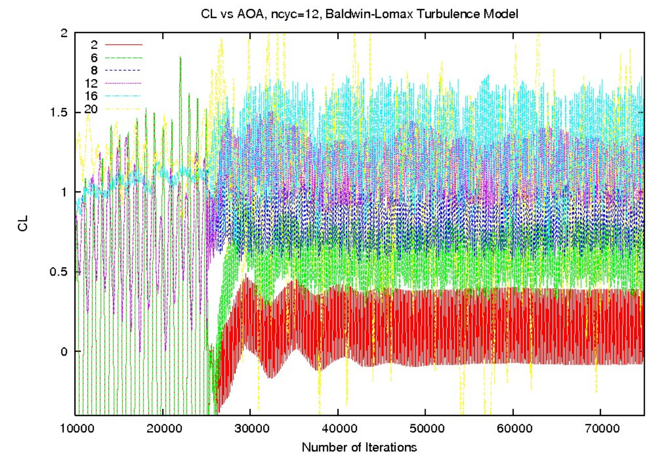
CD vs. CL, Ellipse M=0.044, Re=2.46*10^5, U=15 m/s
Baldwin-Lomax
B-L 50%c trip
Spalart-Allmaras
Menter k-Omega SST
Wilcox k-Omega
Lab Results
CD
CL
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8

Time Dependent Behavior

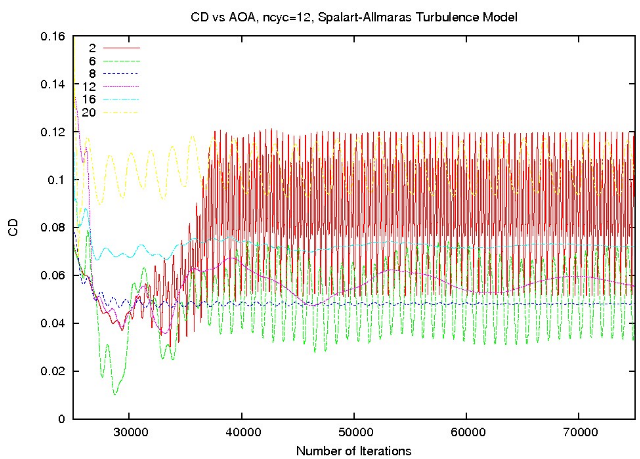
Spalart-Allmaras Model | Baldwin-Lomax Model

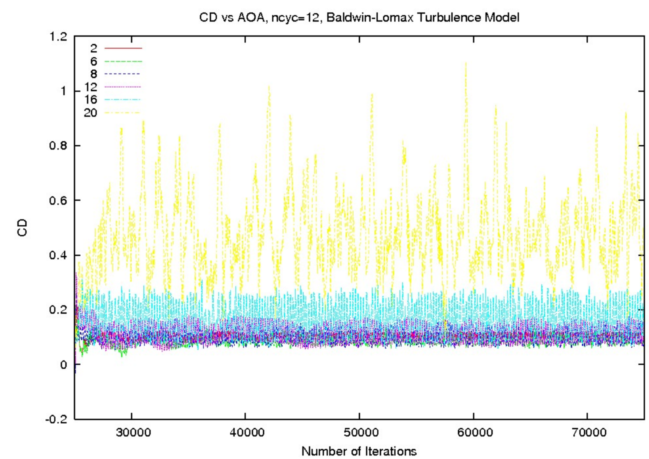
C_L





C_D





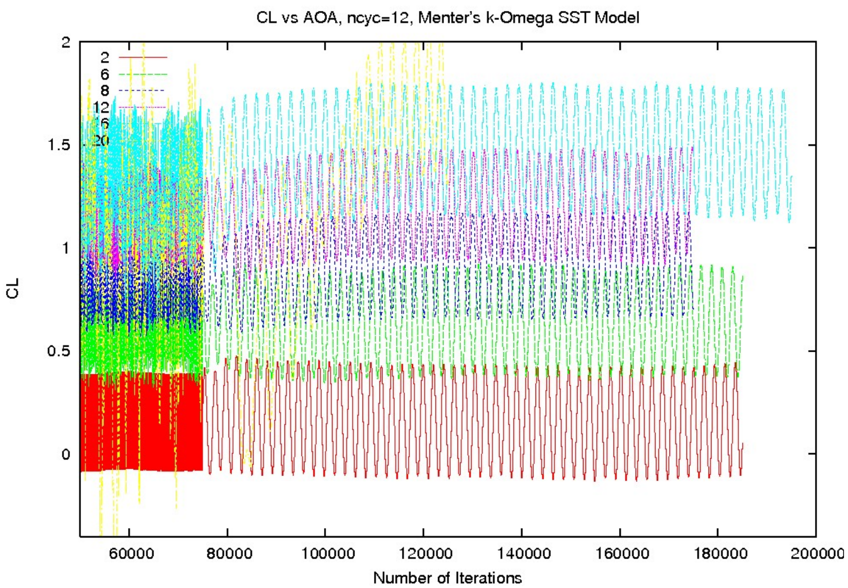
The angle of attacks of 2, 6, 8, 12, 16, and 18 are plotted

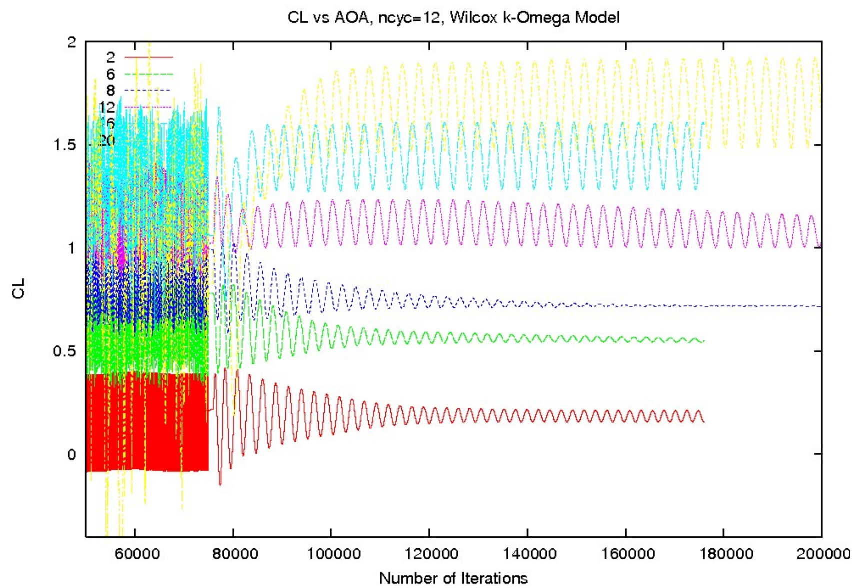
Time Dependent Behavior

Menter's k-Omega SST Model

Wilcox k-Omega Model

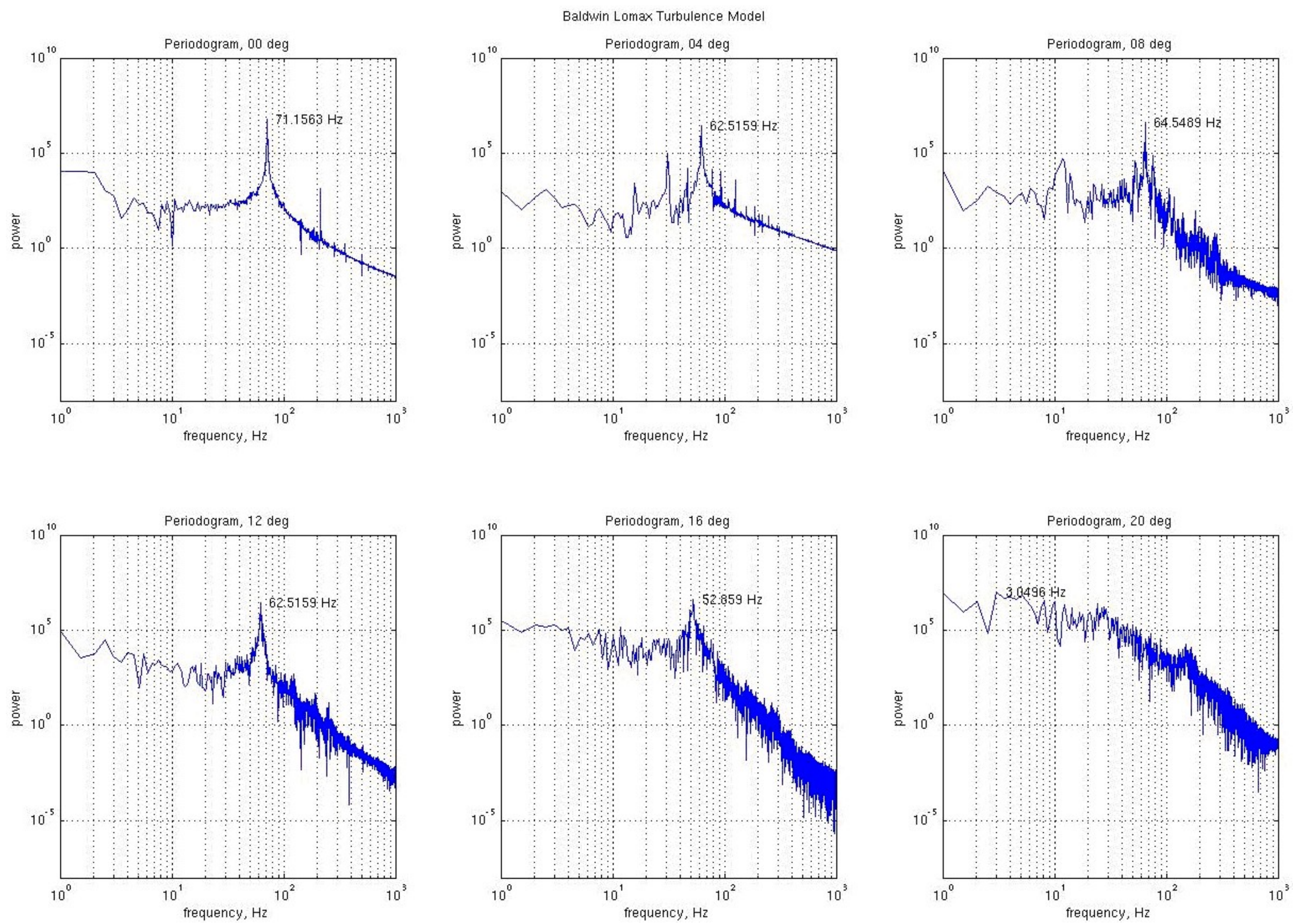
C_L





The angle of attacks of 2, 6, 8, 12, 16, and 18 are plotted

Power Spectrum: Baldwin-Lomax



Power Spectrum Summary

Frequency range from α = 0 to 20 degrees:

• Baldwin-Lomax	71Hz – 52Hz
• Spalart-Allmaras	25Hz – 7Hz
• Menter k-Omega	61Hz – 51Hz
• Wilcox k-Omega	56Hz – 38Hz

- At zero AOA, the frequency should be about 65Hz in order to have a Strouhal number of 0.2 where St = f*L/V
- The Spalart-Allmaras model does not oscillate at a reasonable frequency
- All other models predict frequencies that are somewhat close

Conclusions - 1

What was well predicted by the Spalart-Allmaras model?

(Time averaged results)

- Baseline Ellipse, C_L vs. α, C_p vs. x/c
- Baseline Ellipse with Cusp, C_L vs. α, C_p vs. x/c
  - Negative lift slope curve for small α
- Trailing Edge Blowing/Suction C_L vs. C_μ
  - C_L was underestimated for the ellipse
  - C_L was overestimated for the ellipse with a cusp
  - But the shape of the curve was well predicted for both
- Leading Edge Suction C_L vs. C_μ and C_D vs. C_μ
  - Hysteresis
  - Values of C_L and C_D
  - The value of C_μ necessary for recovery from stall

Conclusions - 2

Issues with Spalart-Allmaras model:
(Time dependent results)

- Converged to a steady solution
- Solution depended highly on dt and ncyc
- Residuals would make sudden jumps
- As AOA increased, solution went from unsteady to steady
- Predicted frequencies were unreasonable

Overall Spalart-Allmaras conclusions:

- Predicts various flow phenomenon with reasonable accuracy
- These predictions are limited to averaged values over time
- Time dependent behavior is poorly predicted

Conclusions about other models:

- Baldwin-Lomax was most robust with reasonable predictions
- Menter k-Omega SST predicted time-dependent behavior well
- Wilcox k-Omega model became steady at 8 degrees AOA