Data Assimilation Method for EFD/CFD Integration

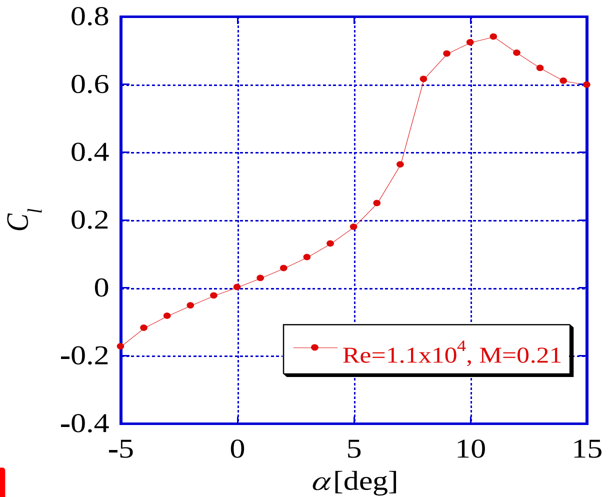
Takumi Ambo, Chen Fang
Department of Aerospace Engineering / Institute of Fluid Science
Tohoku University

Background -Aerodynamics of low *Re* number condition-

- **Appearance of Small airplanes**
  - Unmanned air vehicle (UAV)
  - Micro air vehicle (MAV)
- **Flight in Low *Re* conditions (*Re* = 10^4~10^5)**
  - Aerodynamic characteristics
    - Different from High Re number condition
    - Nonlinearity
  - Flow field around wing
    - Separation or transition of boundary layer
    - Formation of separation bubble
- **Three-dimensionality**
  - Generation of wingtip vortex

    ⇒ Three-dimensional flow field

Unmanned Air Vehicles
(http://en.wikipedia.org/wiki/Unmanned_aerial_vehicle)



Lift coefficient of NACA0012-34 airfoil
(Anyoji *et al*, 2010)

It is necessary to investigate aerodynamic characteristics on the three-dimensional wing in low *Re* condition.

Background -EFD & CFD-

Experimental Fluid Dynamics (EFD)

Advantage
- Credible data
- (Real flow)

Disadvantage
- High cost
- Long experimental time
- Limited information
- Difference from the real flight (Wall & Support interference)

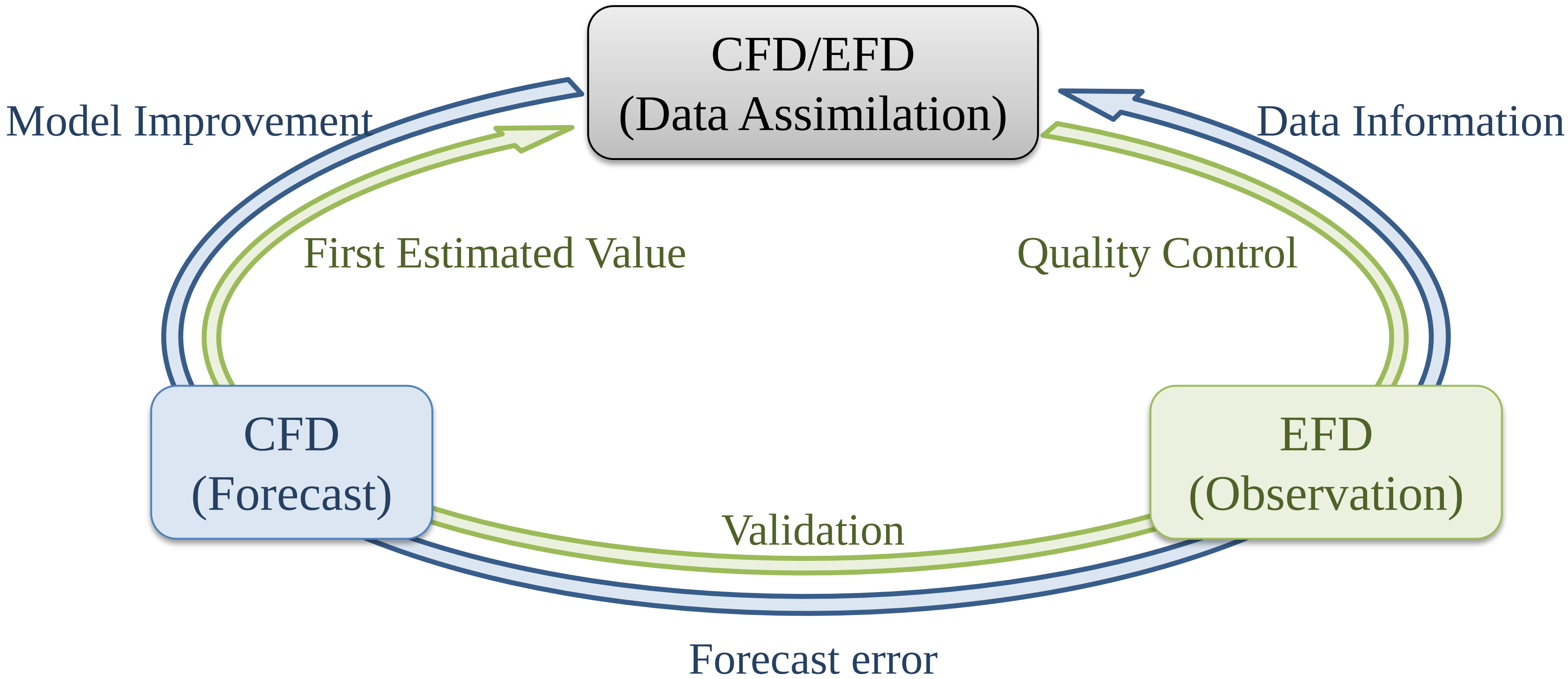
Complement

Computational Fluid Dynamics (CFD)

Advantage
- Low cost
- Big information content

Disadvantage
- Computational accuracy relies on the scheme and mesh

Background -Data Assimilation-

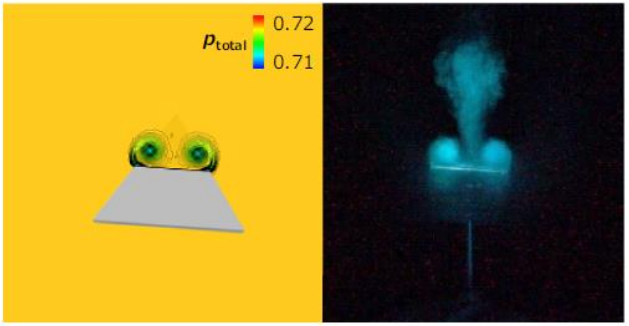


- Data assimilation is an analysis technique in which the observed information is accumulated into the model state by taking advantage of consistency constraints with laws of time evolution and physical properties.

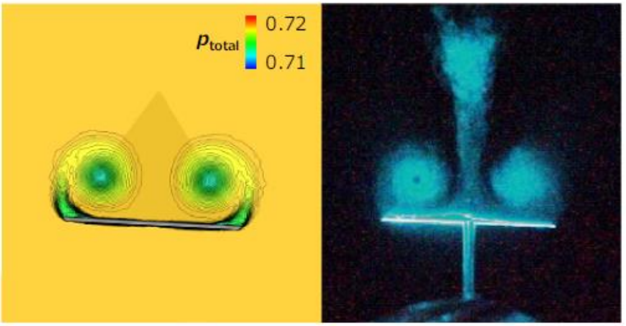
Past Studies

■ Data assimilation

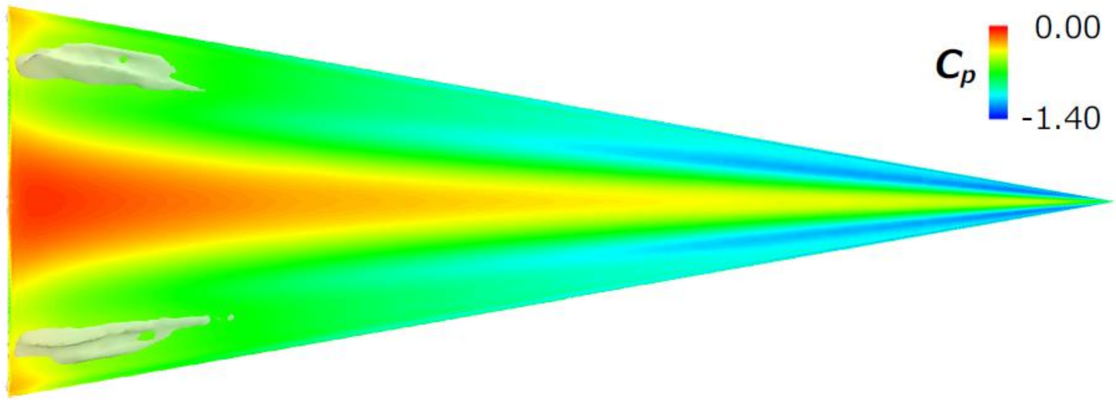
- Computational Study of Flow around a Delta Wing for Measurement-Integrated Simulation with Dynamic Wind Tunnel Testing (Shuta Ito, 2013)



(a) $x/c = 0.5$



(b) $x/c = 1.0$



(c) C_p 分布および $u = 0$ の等値面

図 4.19　$t/T = 0.0$ における渦の比較（上），C_p 分布と $u = 0$ の等値面（下）

Objective

Make the numerical simulation become high-precision using Data assimilation method to understand the aerodynamic phenomenon

Contents

- EFD
  - Force measurement
  - Flow visualization
- CFD
  - Calculating Lift coefficient and surface streamline

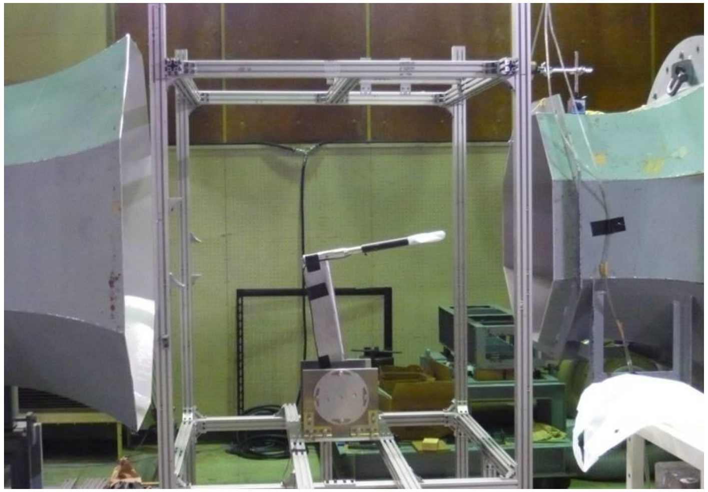
EXPERIMENTAL FLUID DYNAMICS (EFD)

Experimental Equipment

■ Wind-tunnel

➢ Low Turbulence Wind Tunnel (Tohoku Univ.)

- Type : closed circuit
- Test section : open type and octagon
- Test section size : cross distance of 0.8 m
- Turbulence intensity : 0.02 %



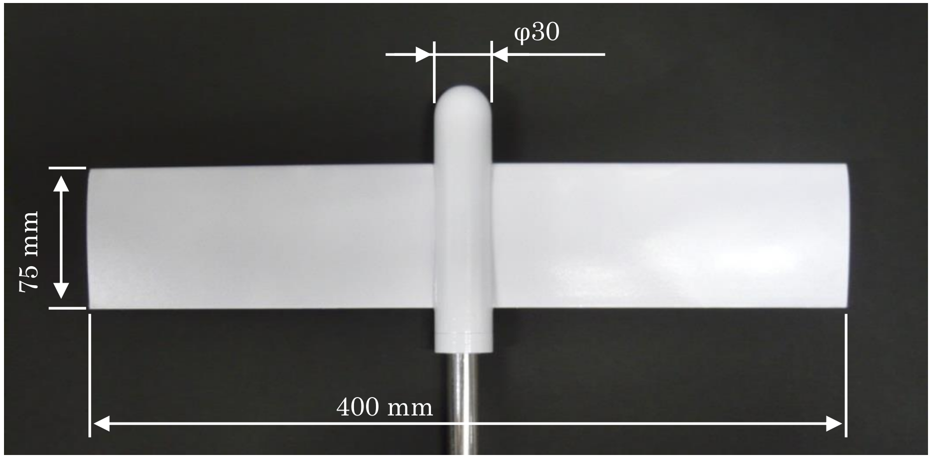
■ Test model

➢ Wing

- Airfoil : NACA0012
- Chord length : 75 mm
- Span length : 400 mm
- Material :Wood(MDF)

➢ Body

- Diameter : 30 mm
- Material : Aluminum



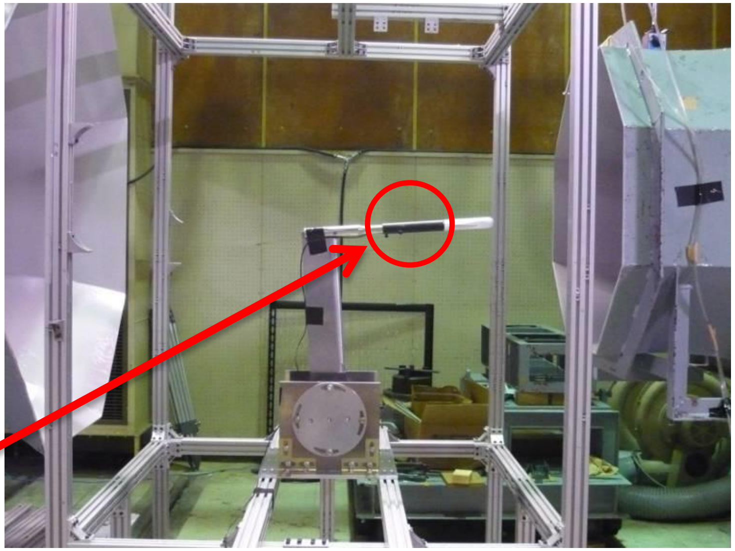
NACA0012 Airfoil

Measurement method -Force measurement-

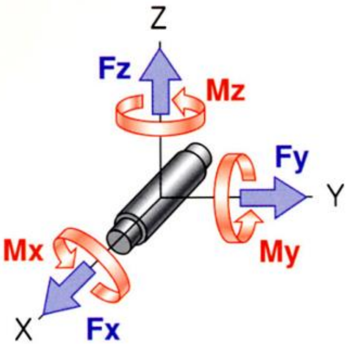
- <u>Sting six-component balance</u>
  (NISSHO-ELECTRIC-WORKS, LMC-61112)

Rated load

・Fx－120 N	・Mx－4 N・m
・Fy－250 N	・My－10 N・m
・Fz－250 N	・Mz－10 N・m

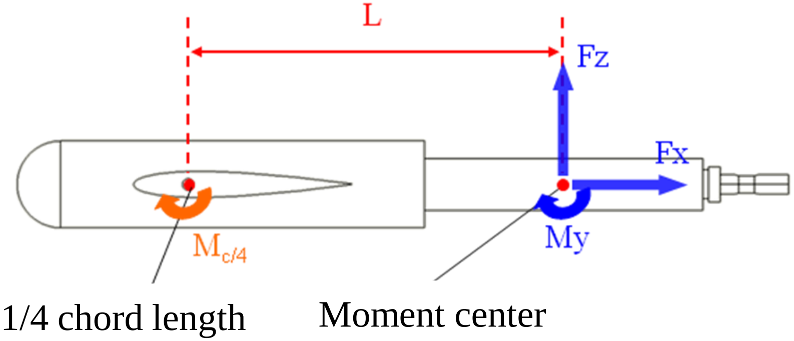


Sting six-component balance



<u>Calculating Pitching-moment</u>

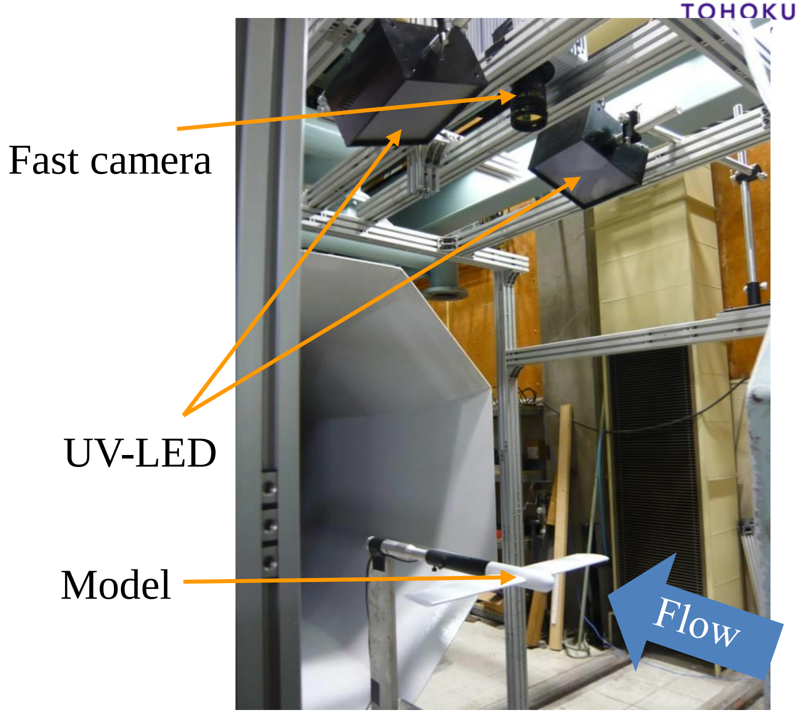
$$M_{c/4} = M_y - F_z \times L$$



Measurement method -Visualization-

■ Global Luminescent Oil-Film Skin-Friction Meter (GLOF method)

- Oil doped with luminescent molecules is put on the test model.
- Skin friction can be measured to capture time-changing of emission intensity.

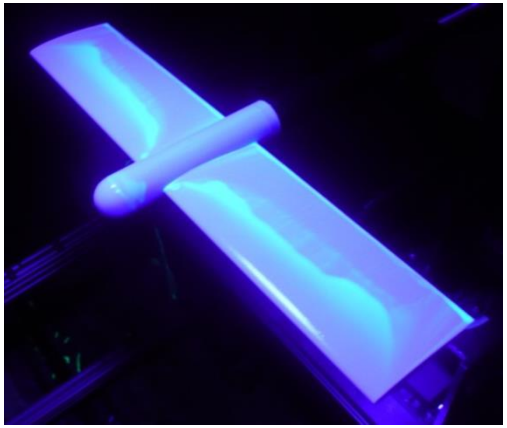


■ Systems

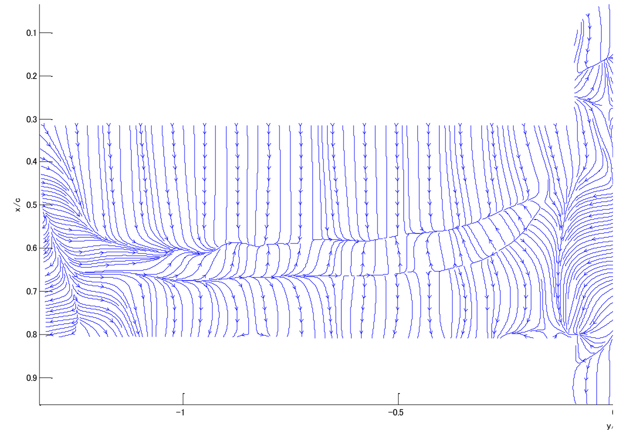
- Fast camera：Lends and optical filter are set forward of camera
- Light source：UV-LED units

■ Luminescent oil film

- Oil：Silicone oil
- Fluorescent dye：Perylene



Luminescent oil film on the model

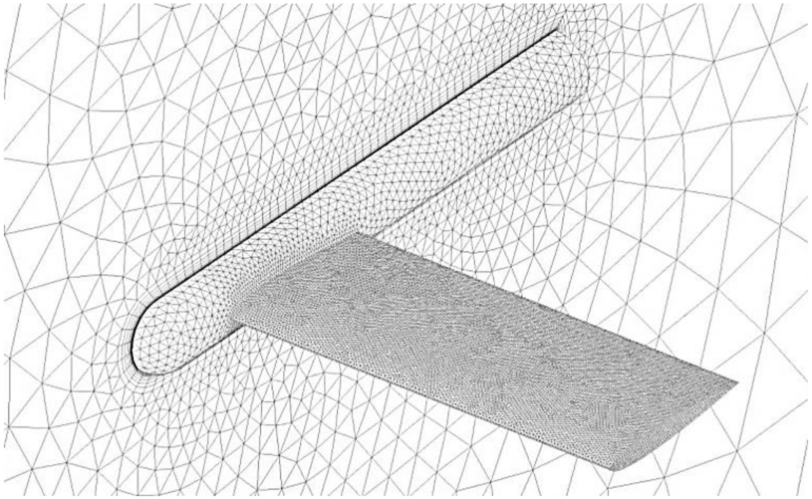


Line of frictional stress

COMPUTATIONAL FLUID DYNAMICS (CFD)

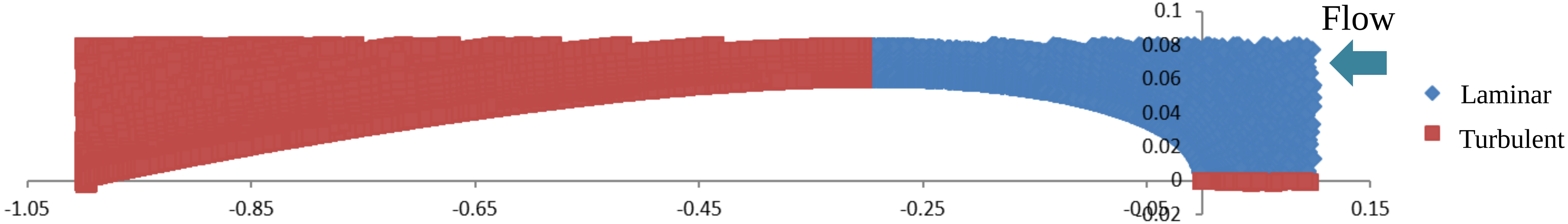
Computation

- FaSTAR : Developed by JAXA
  - Aerodynamic coefficients
  - Surface streamline



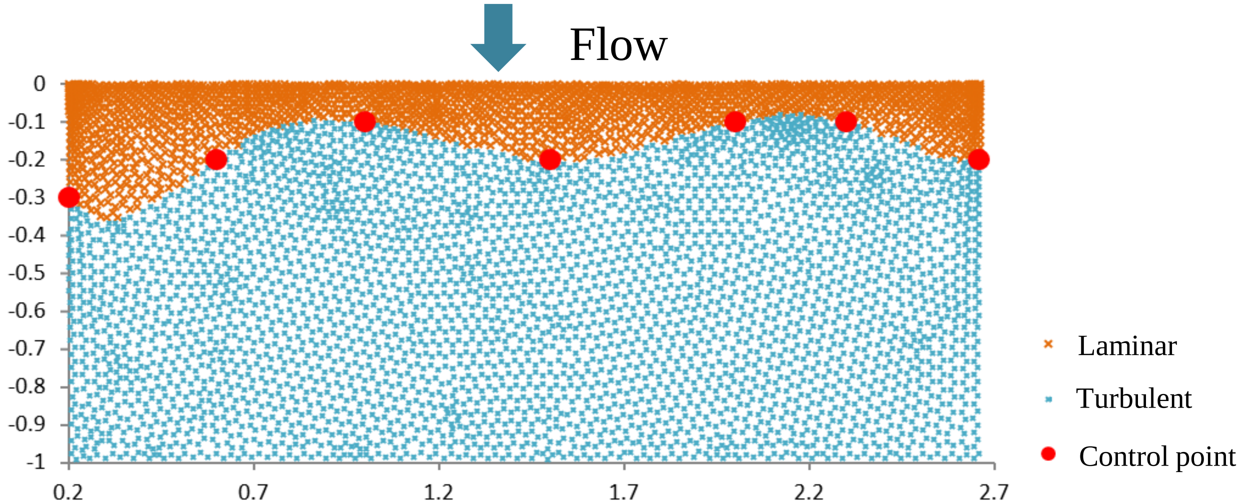
- Realization of the laminar flow - turbulence transition calculation
  : Turbulence energy equation of Menter SST model

$$\frac{D\rho k}{Dt} = \gamma * \underline{\min\left(P, \frac{Re_\infty}{M_\infty} 20\beta^* \rho\omega k\right)} - \frac{Re_\infty}{M_\infty}\beta^* \rho\omega k + \frac{M_\infty}{Re_\infty}\frac{\partial}{\partial x_j}\left[(\mu + \sigma_k \mu_t)\frac{\partial k}{\partial x_j}\right]$$



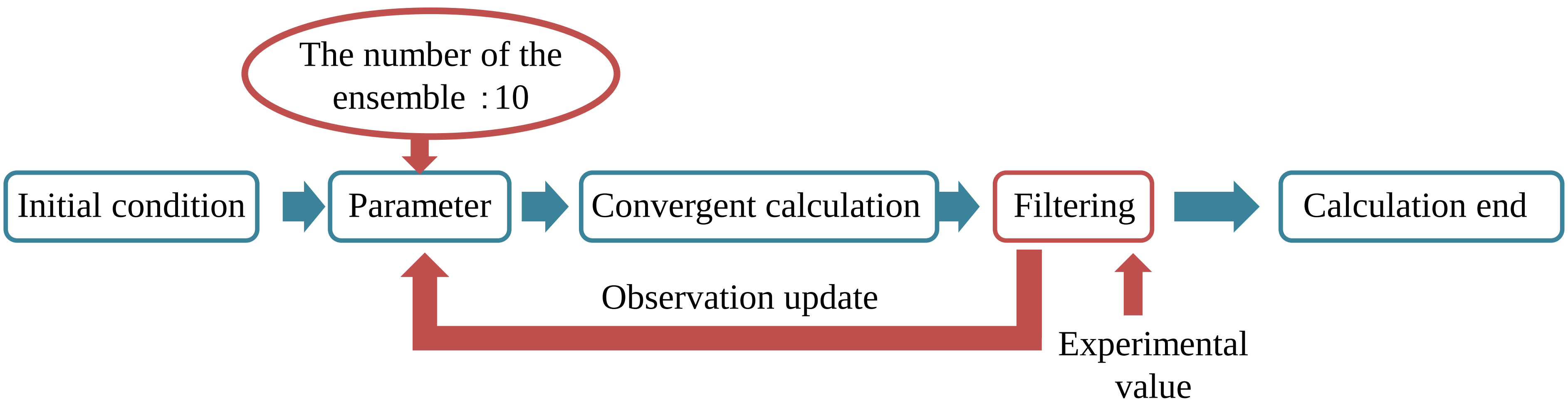
Intermittency factor distribution
(Laminar flow cell $\gamma = 0$, Turbulent flow cell $\gamma = 1$)

Computation

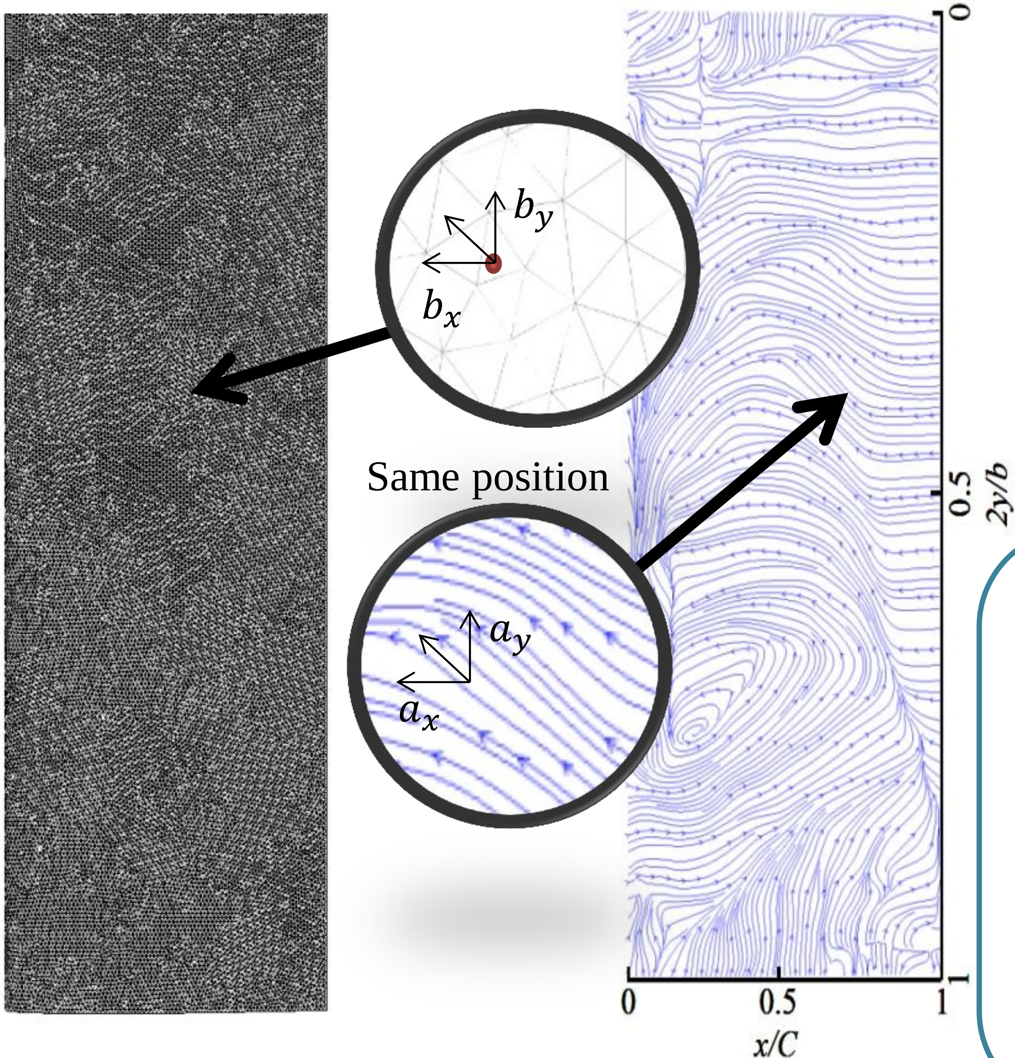


＊Initial condition : It is decided based on separation position of experimental results.

■ Assimilation method：Ensemble Kalman Filter (EnKF)



Computation



Computational grid

Line of frictional stress
(Experiment)

Difference of observation and model :

$$H(x) - y = \frac{a_y}{a_x} - \frac{b_y}{b_x}$$

Objective function of Kalman filter
(minimization of J):

$$J = \sum_{\substack{Surface \\ mesh\ point}} \left[\frac{1}{2} \left(\frac{a_y}{a_x} - \frac{b_y}{b_x} \right)^2 \right]$$

Test conditions

Experimental conditions

Wind-tunnel	Low turbulence wind-tunnel
Free-stream velocity [m/s]	30
Angle of Attack, α [deg]	-10 ~ 30 [deg]
Measurement	Aerodynamic forces, Frictional stress line

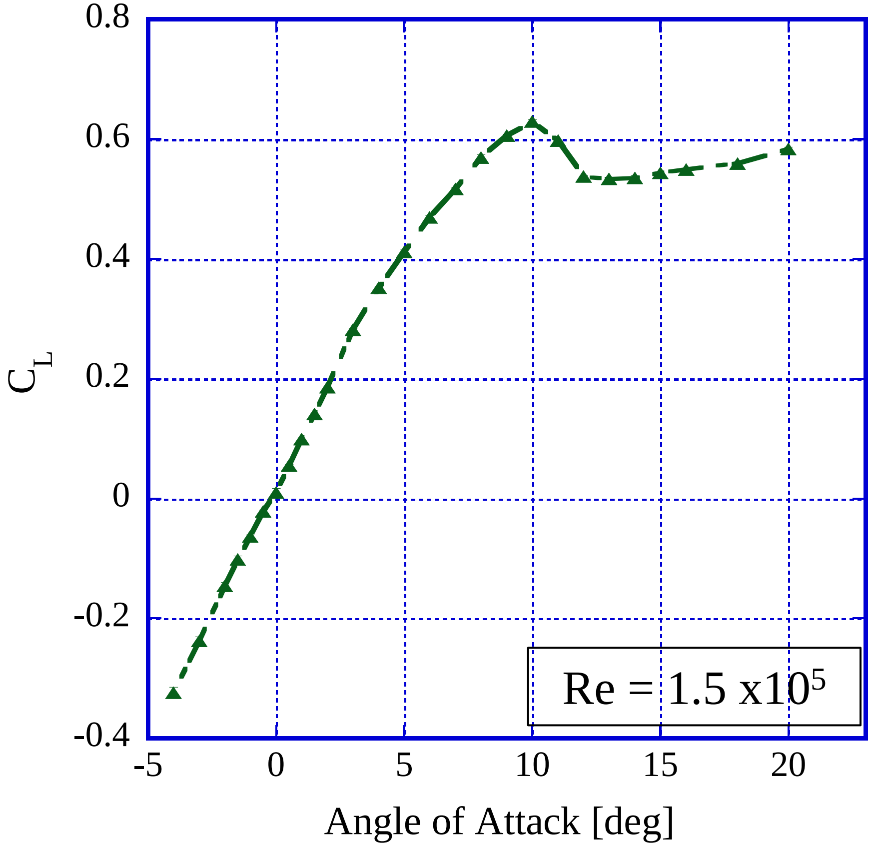
Calculation conditions

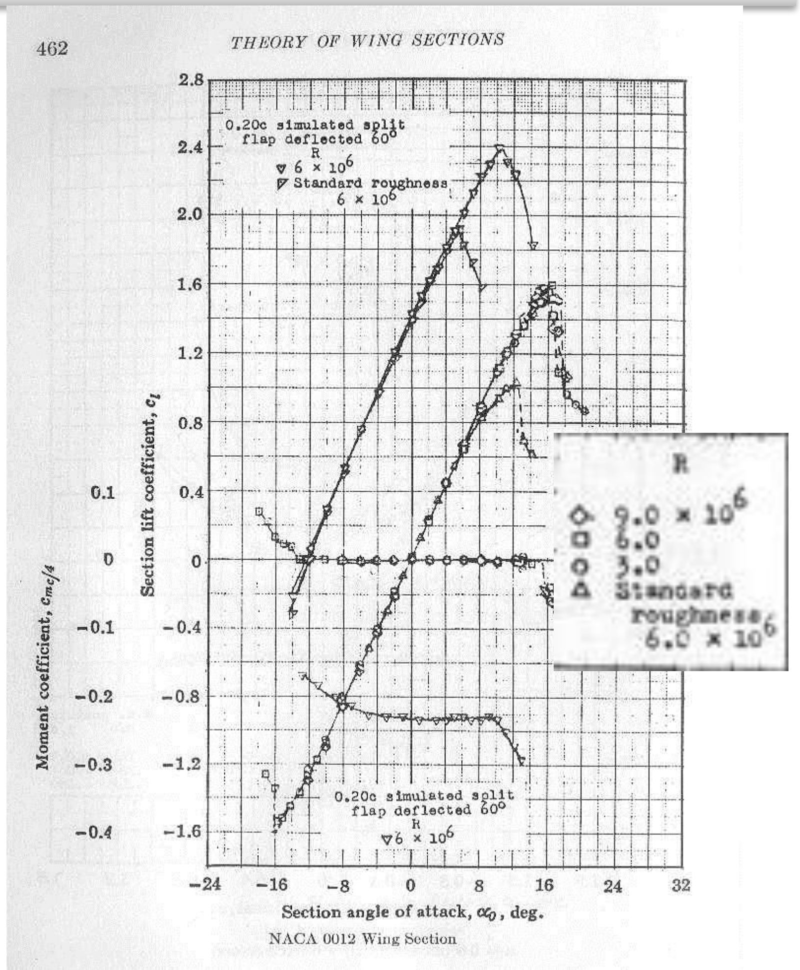
Free-stream velocity [m/s]	30
Angle of Attack, α [deg]	0 ~ 15
Re	1.5×10^5
Turbulence model	Menter SST
Analysis method	Steady
Number of grid	2×10^6

RESULTS

Results -Lift coefficient-

- Lift force

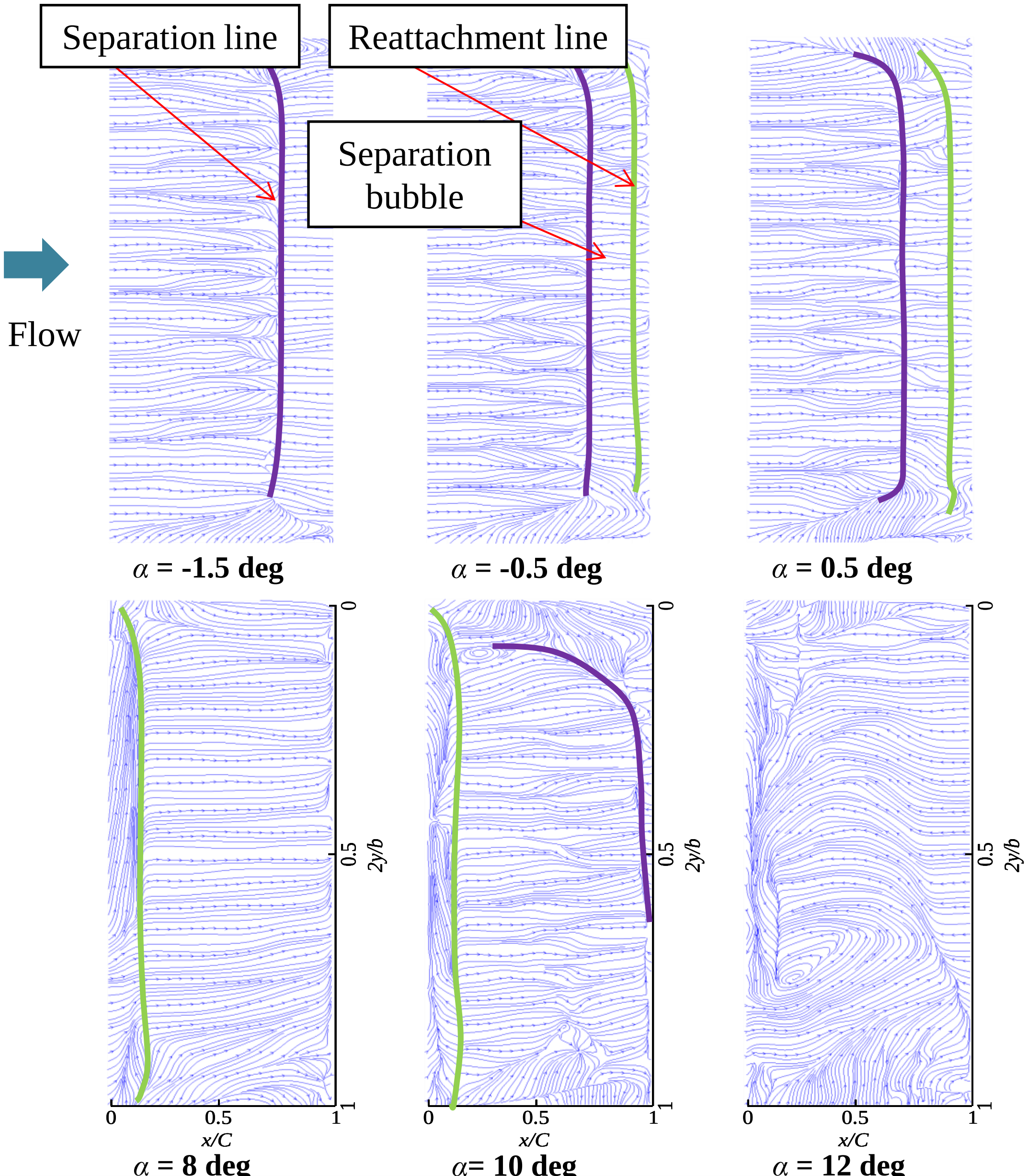




Theory of wing sections (1959)

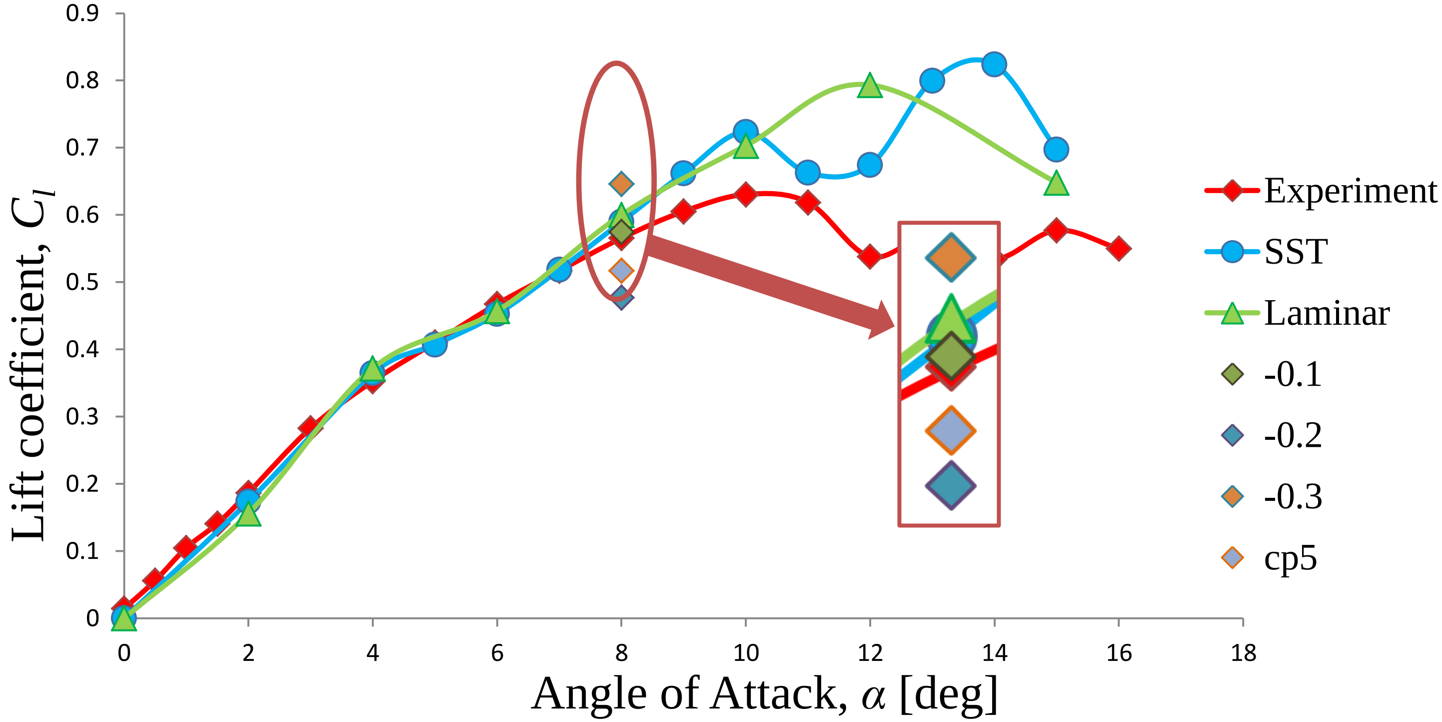
- The characteristics of lift force is different from high Re number condition.
- Stall angle and maximum lift coefficient are lower.

Results - Frictional stress line -



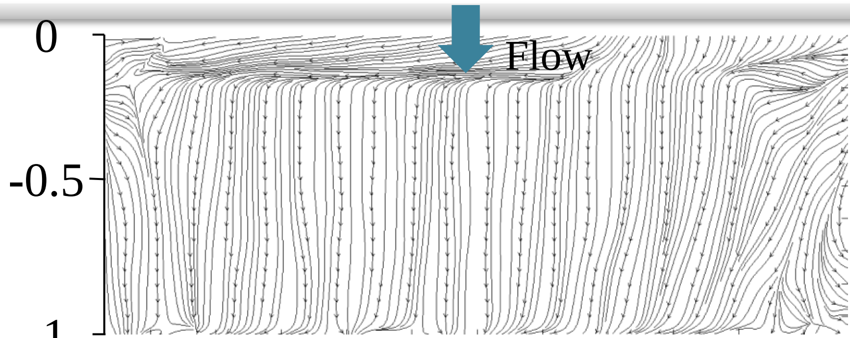
- Laminar separation is occurred near trailing edge.
- Separation bubble appears after α=-0.5 deg.
- Separation bubble shift forward along with increase of AoA.
- Leading edge separation bubble is formed in α=8 deg.
- Flow separate from trailing edge in α=10 deg.
- Most of flow field is dominated by reverse flow is α=12 deg.

Results -Calculated Lift coefficient-

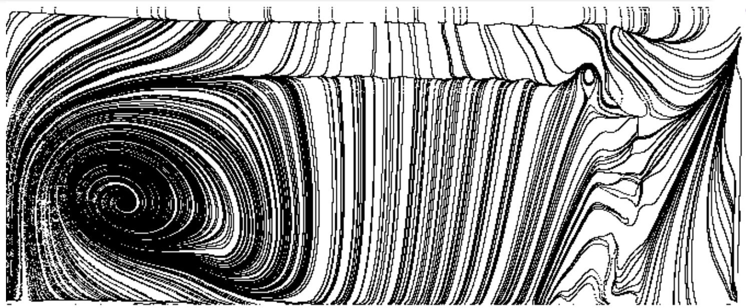


- Under α= 8 deg : Experimental value ≈ Calculated value.
- After α = 8 deg ➡ There're difference between EFD and CFD results.
- High AoA ➡ Separation bubble in leading edge ➡ Convergence is difficult.
- Shifting boundary of laminar and turbulent ➡ C_l changes.

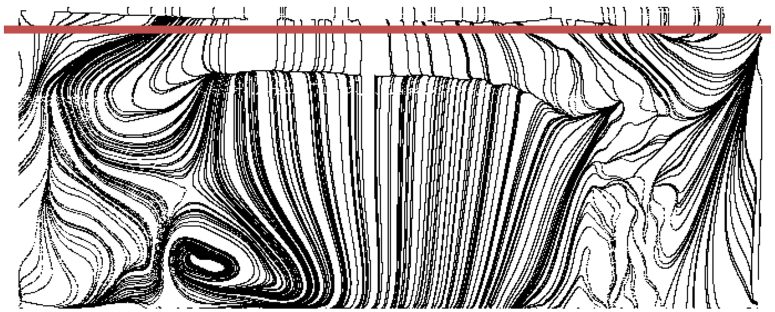
Results - Calculated Surface streamline, $\alpha = 8$ deg -



Experimental frictional stress line

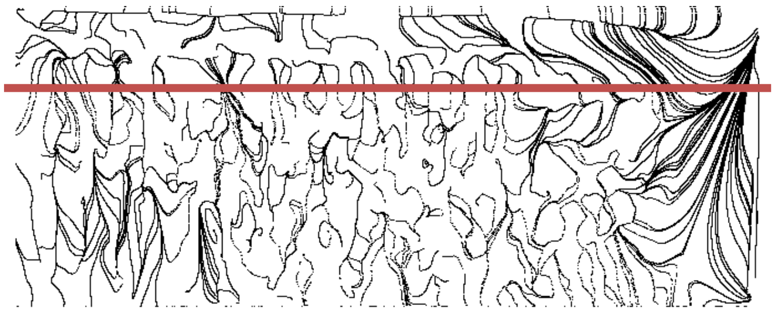


Without transition

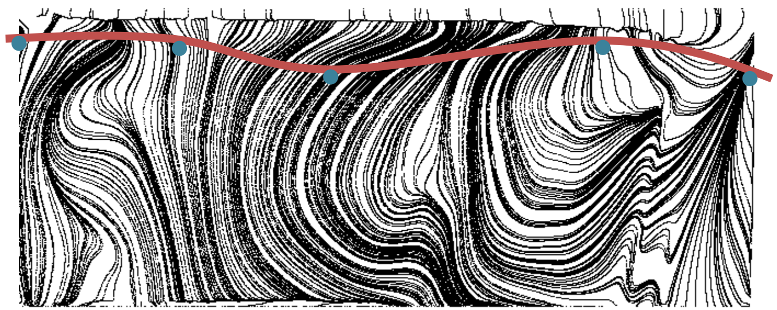


Transition line locates $x/c = 0.1$

Transition line locates $x/c = 0.2$



Transition line locates $x/c = 0.3$



Transition line defined with 5 control points

To control boundary layer transition points using data assimilation method is useful as a means for approximating CFD results with EFD results

Summary

Experiment and Calculation using same model were conducted and each results were compared.

- In EFD, force measurement and flow visualization were conducted.
- In CFD, location of transition line influences lift coefficient and surface streamline.

Future Works

- Conducting calculation of controlling boundary layer transition points using data assimilation method.
- Apply this method to other unsteady flow conditions like dynamic wind-tunnel testing.

Thank you for your attention