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University of Genoa
Faculty of Engineering

Master Thesis in Mechanical Engineering

DEVELOPMENT OF A TOOL FOR THE PREDICTION OF TRANSITION TO TURBULENCE OVER SMALL AIRCRAFT WINGS

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OUTLINE

Two phases:

- 4 months preparation with Professor Jan O. Pralits, Genoa
- 6 months internship at Daher-Socata, Aéroport de Tarbes-Lourdes

OUTLINE

- Introduction and Motivation
- Theory
- Methodology developed
- Test cases validation in 2D
- Test case validation in 3D
- Conclusions and Future Work

INTRODUCTION & MOTIVATION

- Increase of aircraft efficiency to improve the performances.

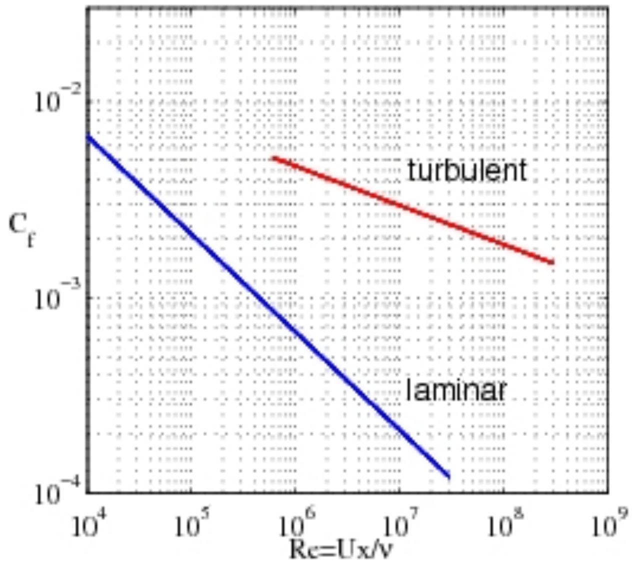
- In aerodynamics friction drag prediction is important.
- Drag is directly linked to transition and turbulence. Laminar flow corresponds to low drag and turbulent flow to larger drag.
- Increasing the laminar flow on the wings, winglets, tail, fin and nacelles can reduce fuel consumption of 15% (potential to save money and environment)
- How and when a flow becomes turbulent is a classic unsolved problem in fluid mechanics. Simplified methods for transition prediction exist.
- Objective: Validate a transition prediction process on 2D profiles and apply it on a 3D geometry, as applied to small aircraft wings.

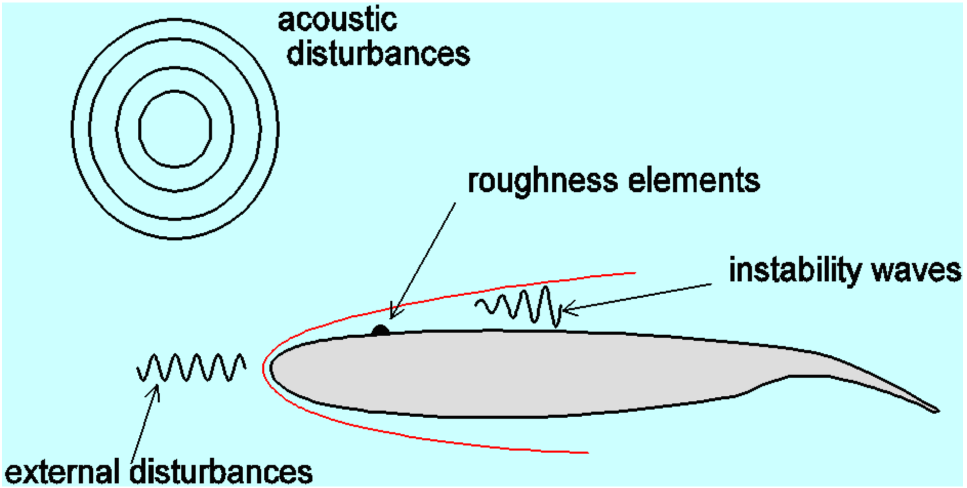
THEORY

THEORY

Transition is assumed to occur when the amplitude of small perturbations, which grow as they propagate downstream, reaches a certain value.

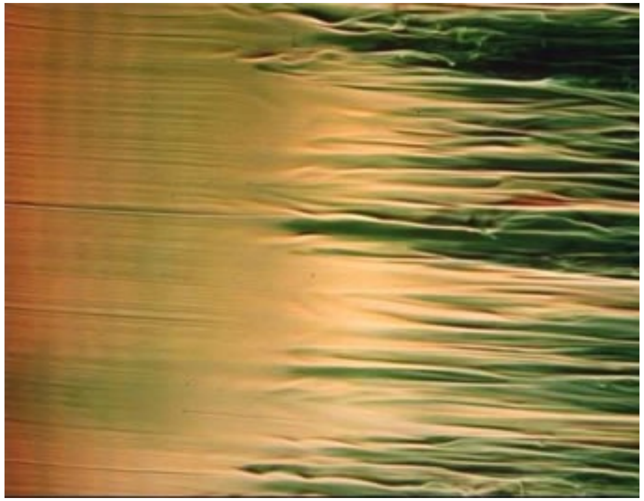
- **LAMINAR FLOW** on wings means lower drag and reduced fuel consumption
- **RECEPTIVITY:** disturbances in the free stream enter the boundary layer as unsteady fluctuations



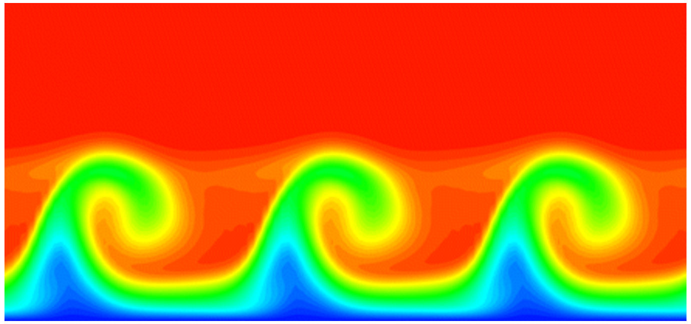


THEORY

Due to receptivity mechanisms disturbances enter the laminar boundary layer, and might trigger unstable disturbances in the boundary layer, such as:



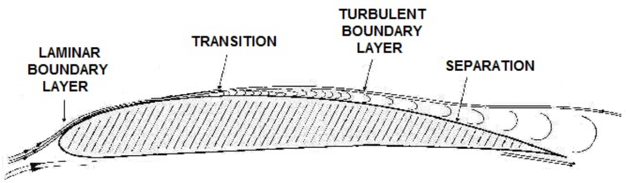
- Tollmien-Schlichting waves: (2D flows)
  - Instabilities develop as wave-like disturbances.
  - Their periodic form grows exponentially.
  - The first stage can be studied by linear theory.
  - After they reach a finite amplitude and a random character.



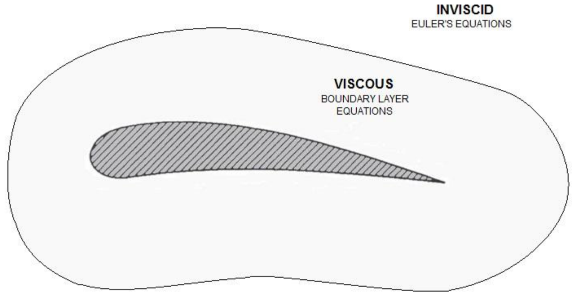
- CrossFlow instabilities: (3D flows)
  - Typical of 3D flow so, for instance for a swept wing.
  - Qualitatively the same phenomena but propagated in a wide range of directions
  - CF instabilities appear as co-rotating vortices

THEORY

Viscosity influences a very thin layer in the immediate neighborhood of the solid wall.



Prandtl's idea of *boundary layer* is to divide the flow into **two regions**, the outer one is approximated with no viscosity and one internal where the friction must be taken into account.



- Considering variables composed by a **base flow** part and a **fluctuating** one, for
  - parallel
  - two-dimensional
  - incompressible flow

$$\vec{V} = \vec{V_b} + \vec{V'} \qquad P = P_b + P'$$

- **Continuity** and **Navier Stokes equations** are simplified considering**:**
  - **Non linear terms** of disturbances can be neglected.
  - **Mean flow quantities** scale is significantly bigger than the disturbances' one.

$$\frac{\partial u'}{\partial x} + \frac{\partial v'}{\partial y} + \frac{\partial w'}{\partial z} = 0$$

$$\begin{cases} \dfrac{\partial u'}{\partial t} + U\dfrac{\partial u'}{\partial x} + v'\dfrac{\partial U}{\partial y} = -\dfrac{\partial p'}{\partial x} + \dfrac{1}{Re}\left(\dfrac{\partial^2 u'}{\partial x^2} + \dfrac{\partial^2 u'}{\partial y^2} + \dfrac{\partial^2 u'}{\partial z^2}\right) \\ \dfrac{\partial v'}{\partial t} + U\dfrac{\partial v'}{\partial x} = -\dfrac{\partial p'}{\partial y} + \dfrac{1}{Re}\left(\dfrac{\partial^2 v'}{\partial x^2} + \dfrac{\partial^2 v'}{\partial y^2} + \dfrac{\partial^2 v'}{\partial z^2}\right) \\ \dfrac{\partial w'}{\partial t} + U\dfrac{\partial w'}{\partial x} = -\dfrac{\partial p'}{\partial z} + \dfrac{1}{Re}\left(\dfrac{\partial^2 w'}{\partial x^2} + \dfrac{\partial^2 w'}{\partial y^2} + \dfrac{\partial^2 w'}{\partial z^2}\right) \end{cases}$$

THEORY

These equations are expressed through only two variables:

$v' = \tilde{v}(y)e^{i(\alpha x+\beta z-\omega t)}$ Normal Velocity

$\eta' = \tilde{\eta}(y)e^{i(\alpha x+\beta z-\omega t)}$ Vorticity

Knowing that $\alpha^2+\beta^2=k^2$, and expressing the derivative in *y* as D, the equations for *v'* and for *η'* are:

$$\left[(-i\omega+i\alpha U)(D^2-k^2)-i\alpha\frac{\partial^2 U}{\partial y^2}-\frac{1}{Re}(D^2-k^2)^2\right]\tilde{v}=0$$

Orr - Sommerfeld Equation

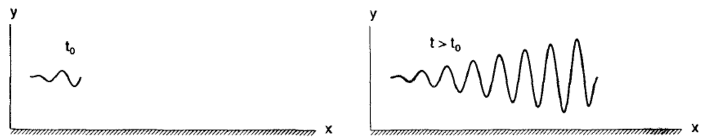
$$\left[\left(-i\omega+i\alpha U-\frac{1}{Re}\right)(D^2-k^2)\right]\tilde{\eta}=-i\beta\frac{\partial U}{\partial y}\tilde{v}$$

Squire Equation

Spatial Analysis

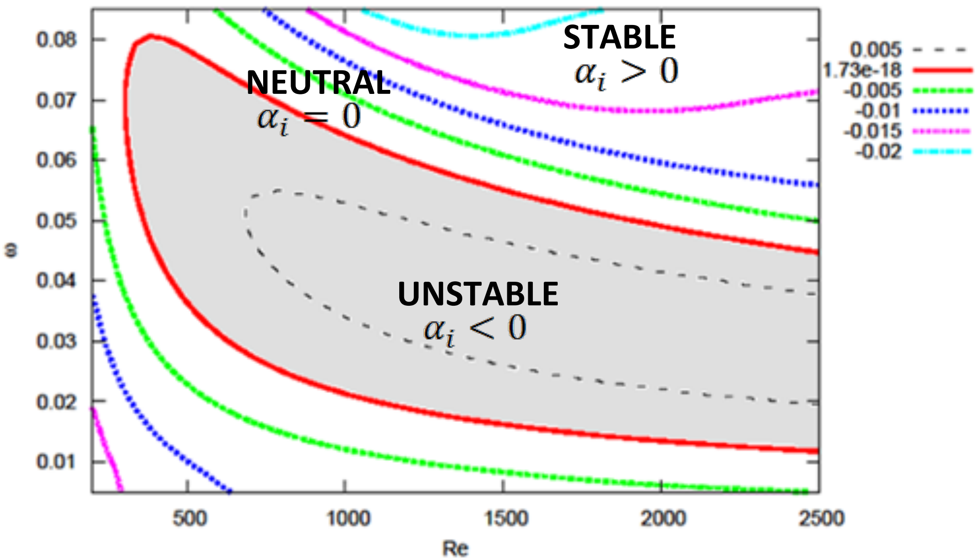
$\omega,\beta \in \mathbb{R}$

$\alpha \in \mathbb{C}$



Perturbation velocity:

$$V' = V(y)e^{i(\alpha_r x+\beta z-\omega t)}\ e^{-\alpha_i x}$$

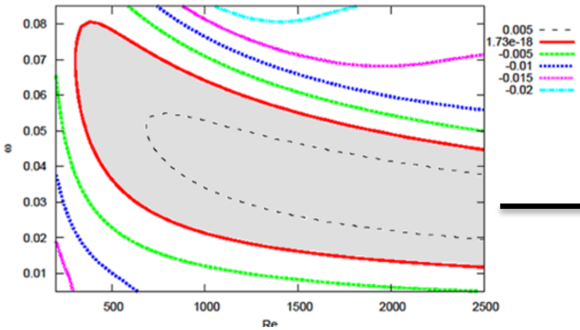


THEORY

At a given station, the total amplification rate of a spatially growing wave can be defined as:

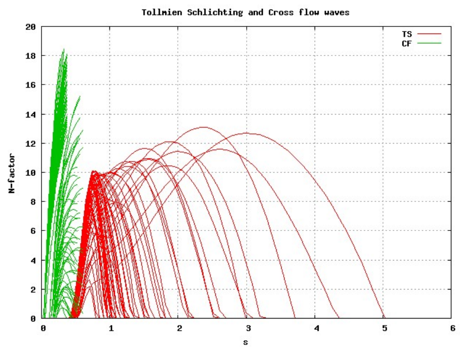
$$\ln(A/A_0) = \int_{x_0}^{x} -\alpha_i(x)dx$$

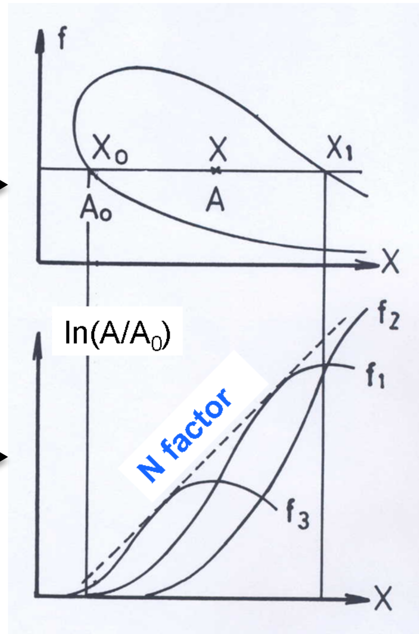
- A = wave amplitude
- A_0 = X_0 position (where the wave begins to be unstable)



The envelope of the total amplification curves is:

$$N = \max_f[\ln(A/A_0)]$$

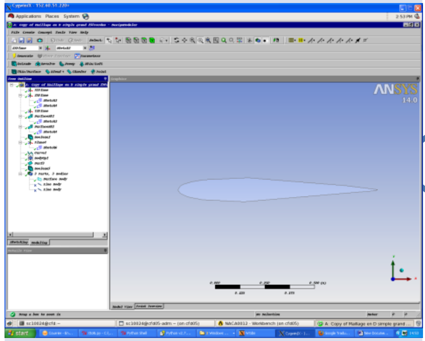




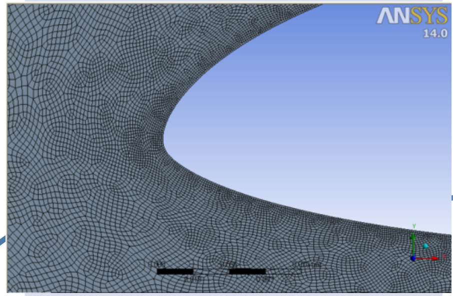
METHODOLOGY DEVELOPED

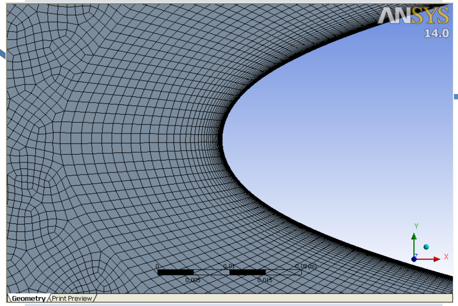
METHODOLOGY DEVELOPED

WING PROFILE

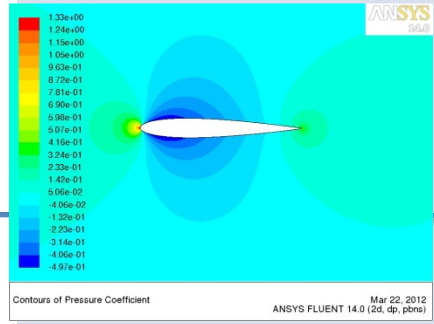


MESH





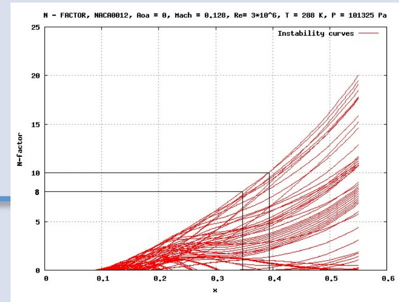
RESULTS

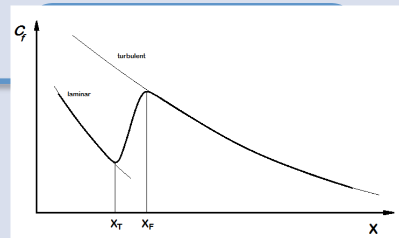


Fluent

SST-TRANSITION MODEL

POST-PROCESS



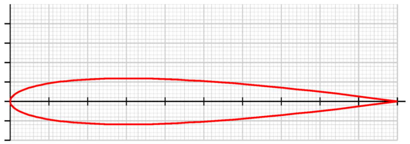


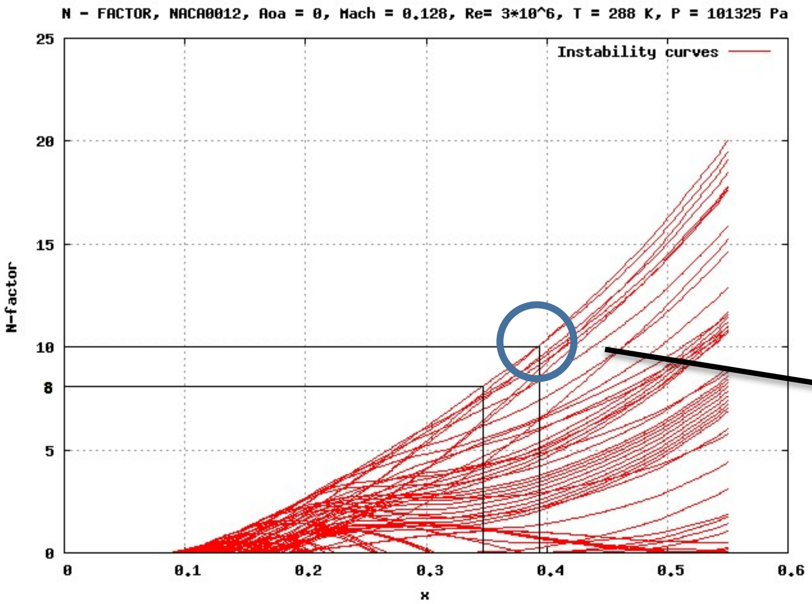
TEST CASES 2D

TEST CASES (2D)

NACA0012

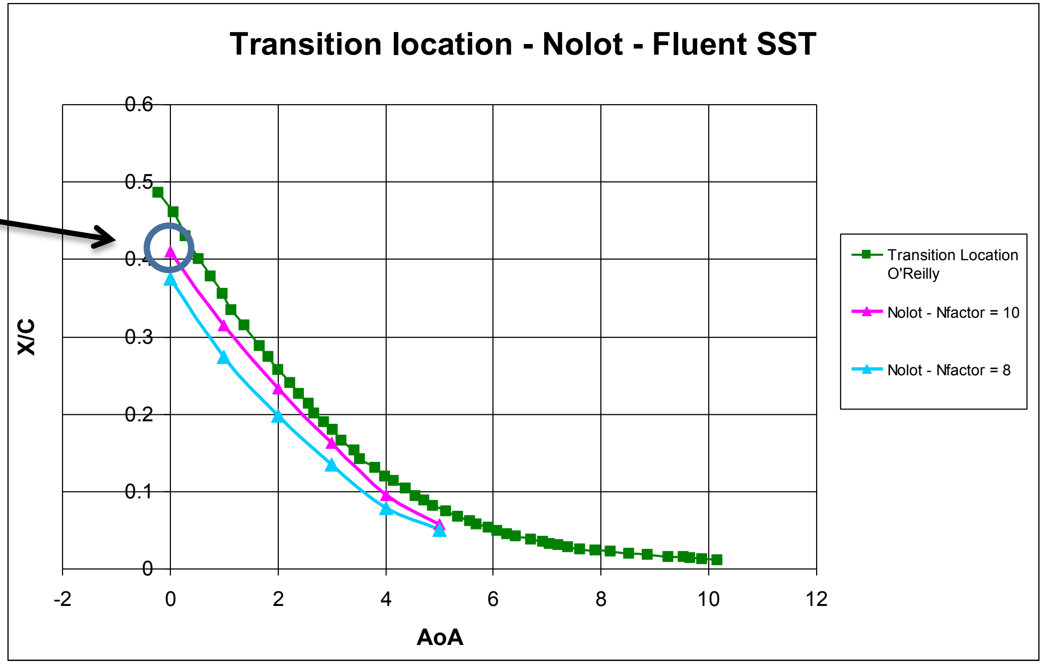
Mach = 0.128, T = 288.15 K, P= 101325 Pa, Re =3x10^6





← **N-factor plot, amplification rate for AoA = 0°**

EXPERTIMENTS vs Nolot →



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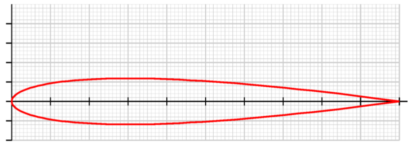
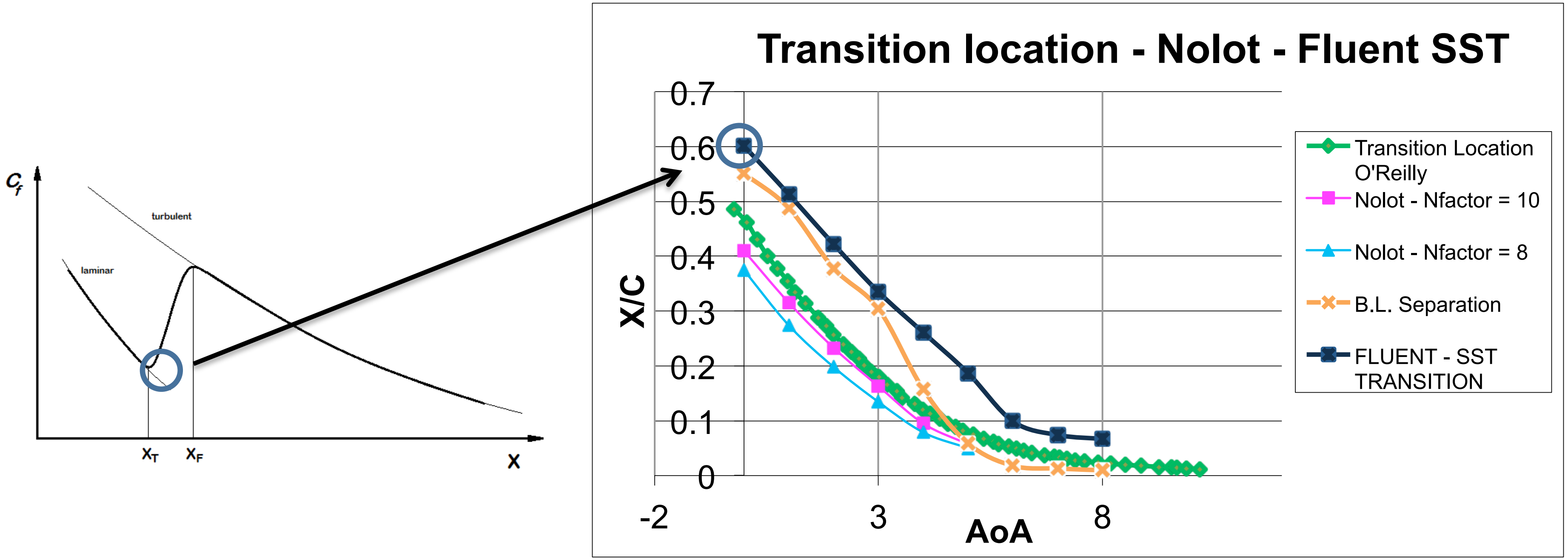


Viscous Calculation

Transition location in **viscous case -> Cf**

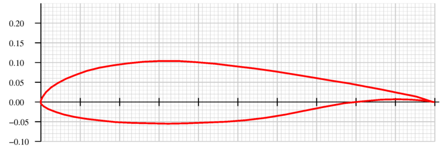
Rapid growth -> switch from laminar to turbulent



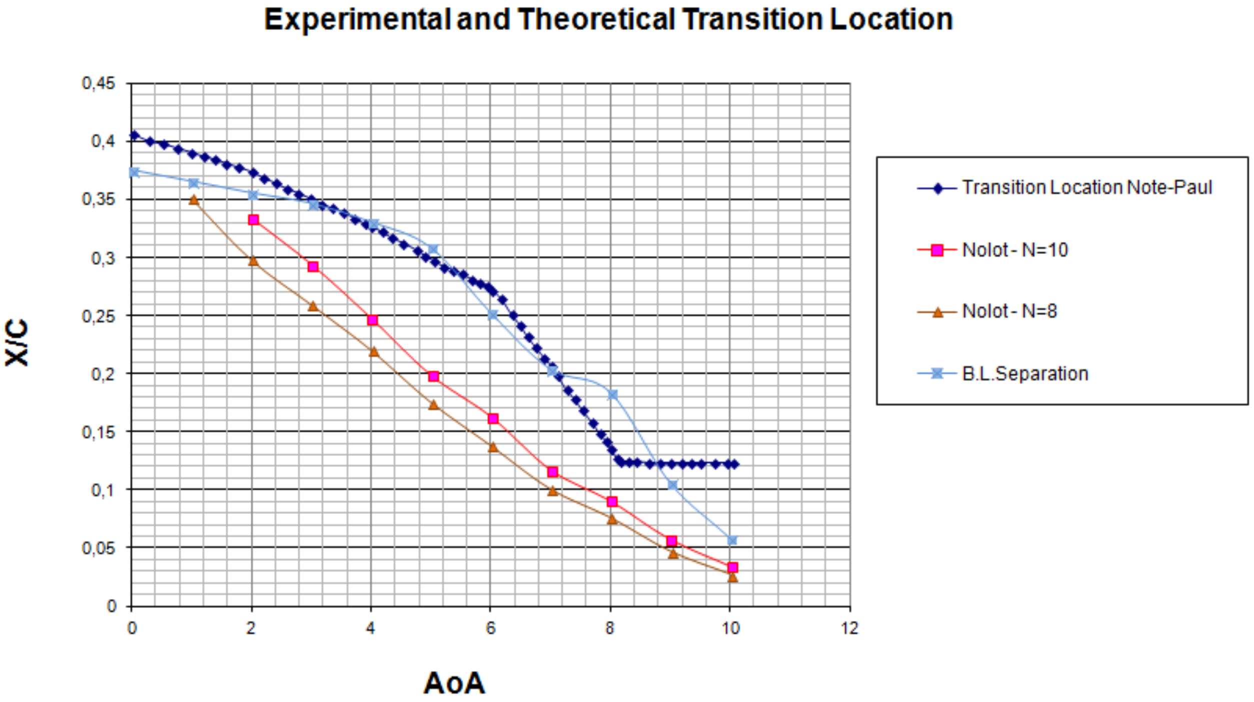
TEST CASES (2D)

NLF0416

Mach = 0.1, T = 288.15 K, P= 101325 Pa, Re =4x10^6



Transition location in the article ("Transition-Flow-Occurrence-Estimation "A New Method" by Paul-Dan Silisteanu and Ruxandra M. Botez) is actually the the separation location.



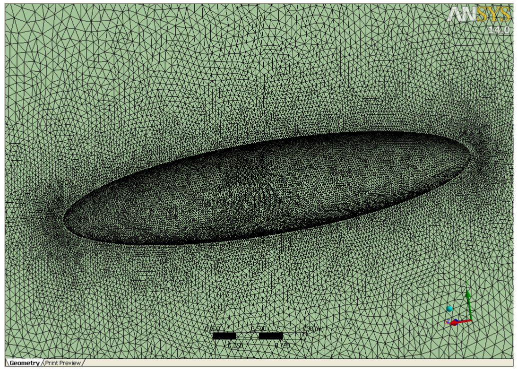
TEST CASE 3D

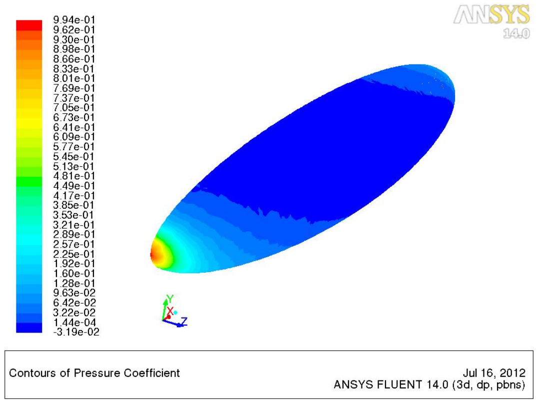
TEST CASE (3D)

Mach = 0.3, T = 281.53 K, P= 101325 Pa, Re =7.2x10^6

SPHEROID

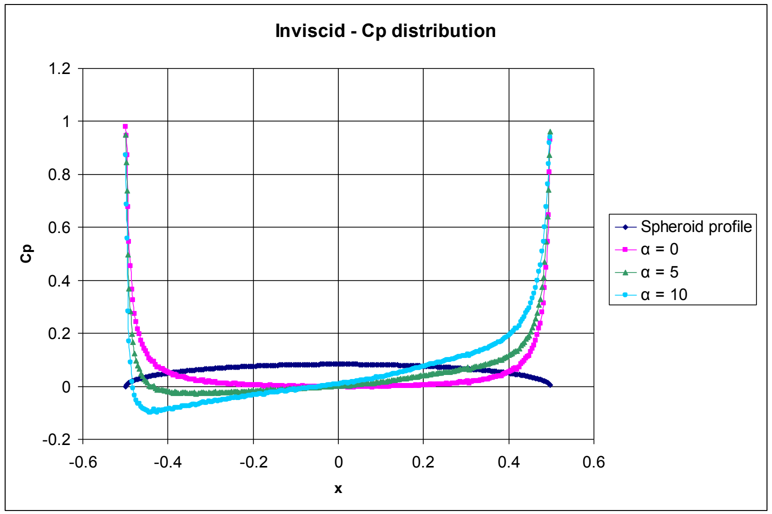
MESH and **PRESSURE DISTRIBUTION** on the spheroid (for inviscid calculation):





Cp distribution **on the symmetry plane** for:

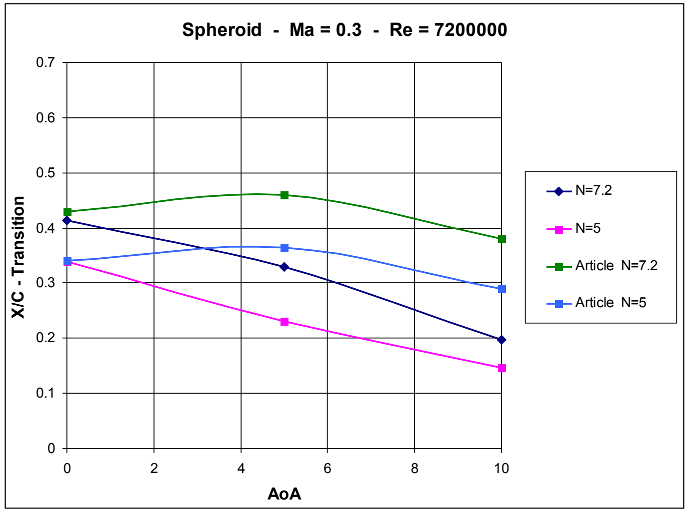
AoA=0°
AoA=5°
AoA=10°



Nolot Transition location VS Experiments

↓

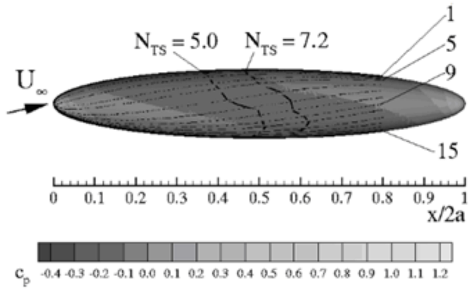
Only AoA=0° case → ok

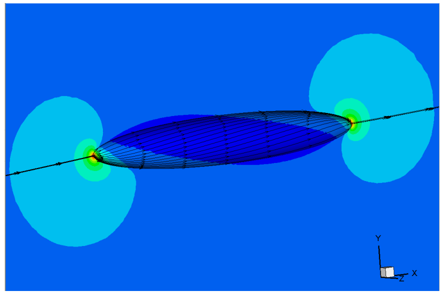


TEST CASE (3D)

SPHEROID

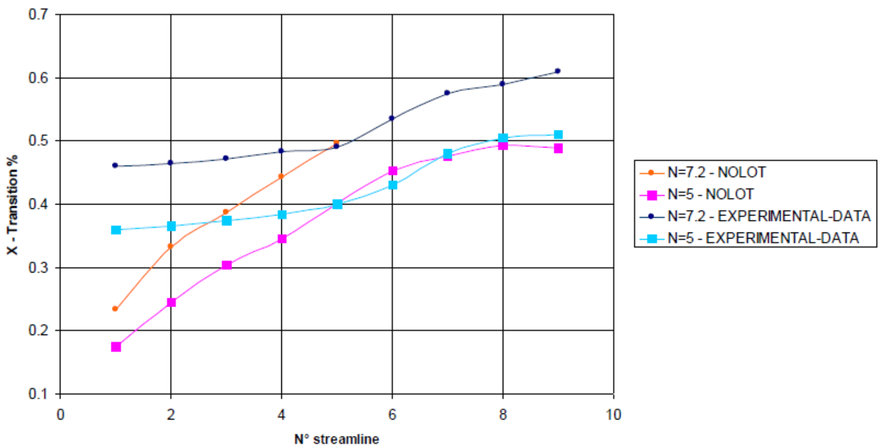
- **NEW IDEA** → study along the streamlines
- **No crossflow** → two-dimensional analysis





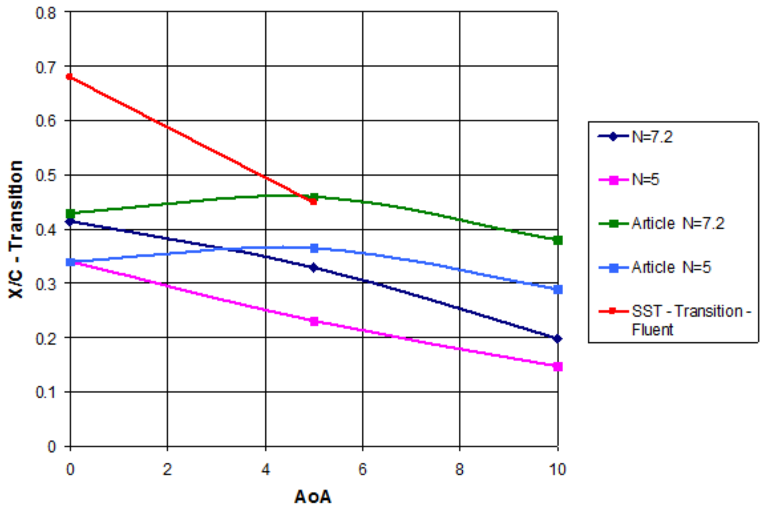
Results of the analysis ALONG THE STREAMLINES:

Far from the symmetry plane → Nolot ok
For N=7.2 → Nolot not ok



VISCOUS CALCULATION:

AoA = 10° → no convergence
AoA = 5° → Fluent ok
AoA = 0° → Fluent **not** ok



CONCLUSIONS

- A **methodology** to predict transition based on physical mechanisms has been implemented and verified in an industrial fluid solver (software)
- **Validation** is **successful** for **2D** profiles, as **NACA0012**.
- For the **NLF0416 profile** we can**not be sure** of the results since the literature provide us only the boundary layer separation.
- **Validation** for the **3D geometries** is more complicated for 3D effects.
- **Same methodology along the streamlines** is ok but far from the symmetry plain.
- For the moment **Nolot code** works only on **simple geometries** like a spheroid (**axisymmetric**), infinite swept wings.

FUTURE WORK

- **Manage** the entire **methodology** to make it **faster, efficient** and **reliable**.

- Make a study of the **entire spheroid** to see **how much the symmetry plane influences the flow** close to it.

- **Improving the Nolot** code **to use it along the streamlines** allows to extend the methodology from 2D to 3D geometries.

THANKS FOR THE ATTENTION