DETAILED EVALUATION OF CFD PREDICTIONS AGAINST LDA MEASUREMENTS FOR FLOW ON AN AEROFOIL

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Presentation Outline

- Introduction and objectives
- Experimental methodology: LDV measurements
- Numerical methodology: PMB approach
- Results and discussion
- Conclusions and prospects

Introduction and objectives

- The detailed knowledge of the boundary-layer response to unsteadiness induced by oscillating models is of major interest in a wide range of aeronautical applications.

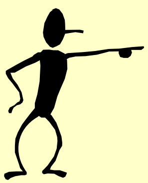
- This work concerns an experimental and numerical investigation of the unsteady boundary-layer on a NACA0012 aerofoil oscillating in pitching motion.

- The experimental part of the present study is based on the Embedded Laser Doppler Velocimetry, developed at LABM for unsteady boundary-layer investigation.

- From the numerical point of view, simulations were performed using the PMB solver developed at GU based on a RANS approach of turbulence.

Presentation Outline

- Introduction and objectives



- Experimental methodology: ELDV measurements
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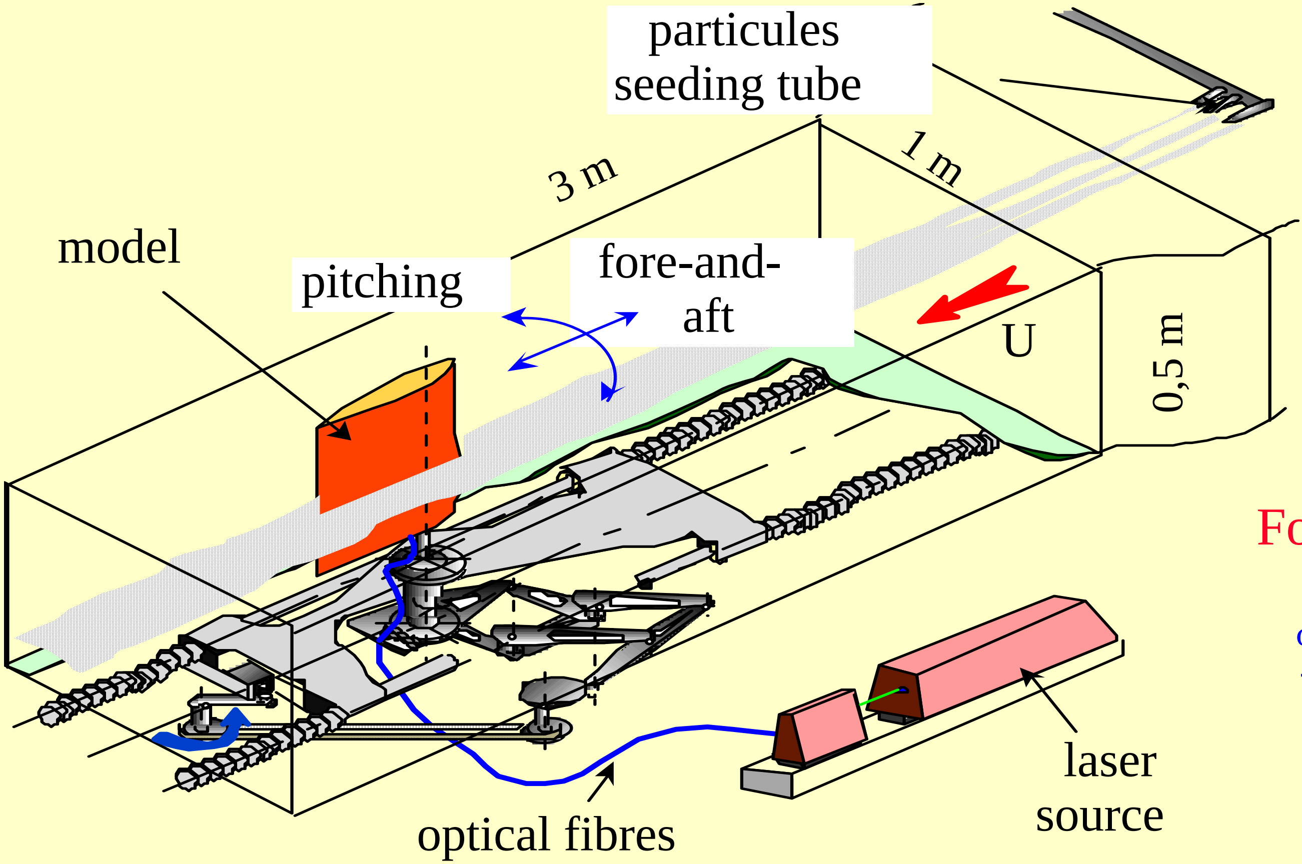
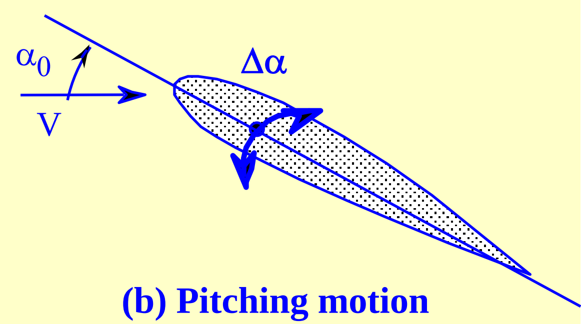
S2 Luminy wind-tunnel-Experimental Set-up



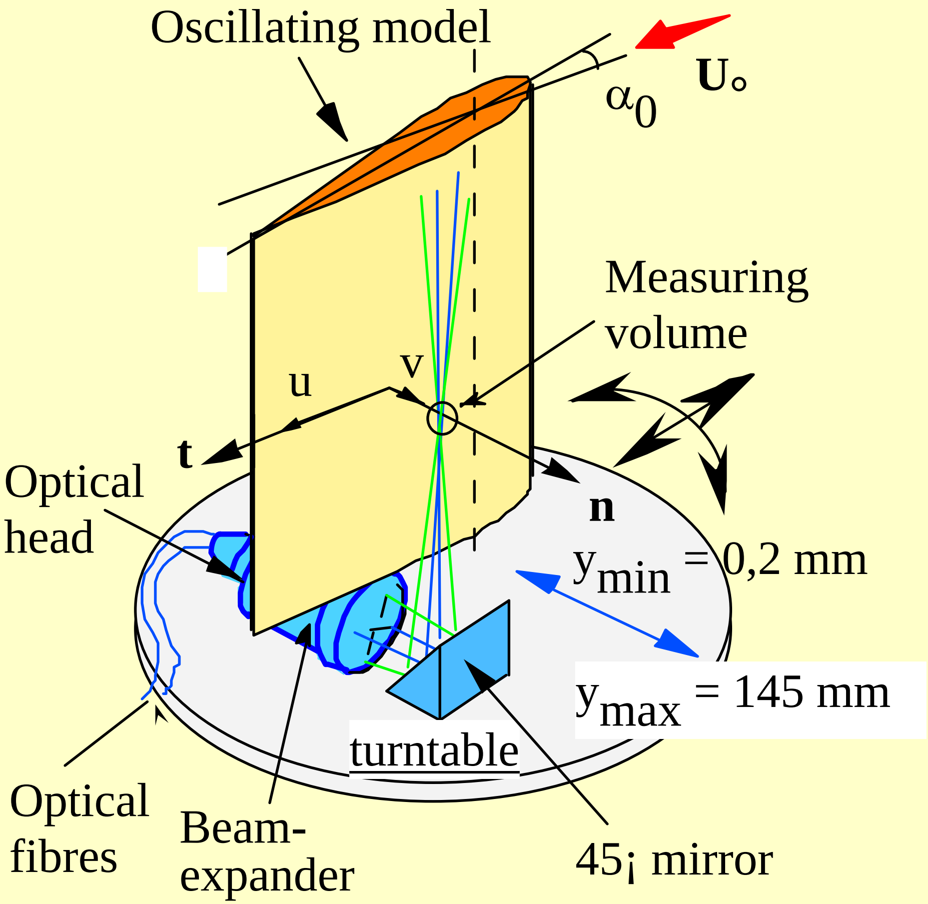
Forced unsteadiness law



(b) Pitching motion

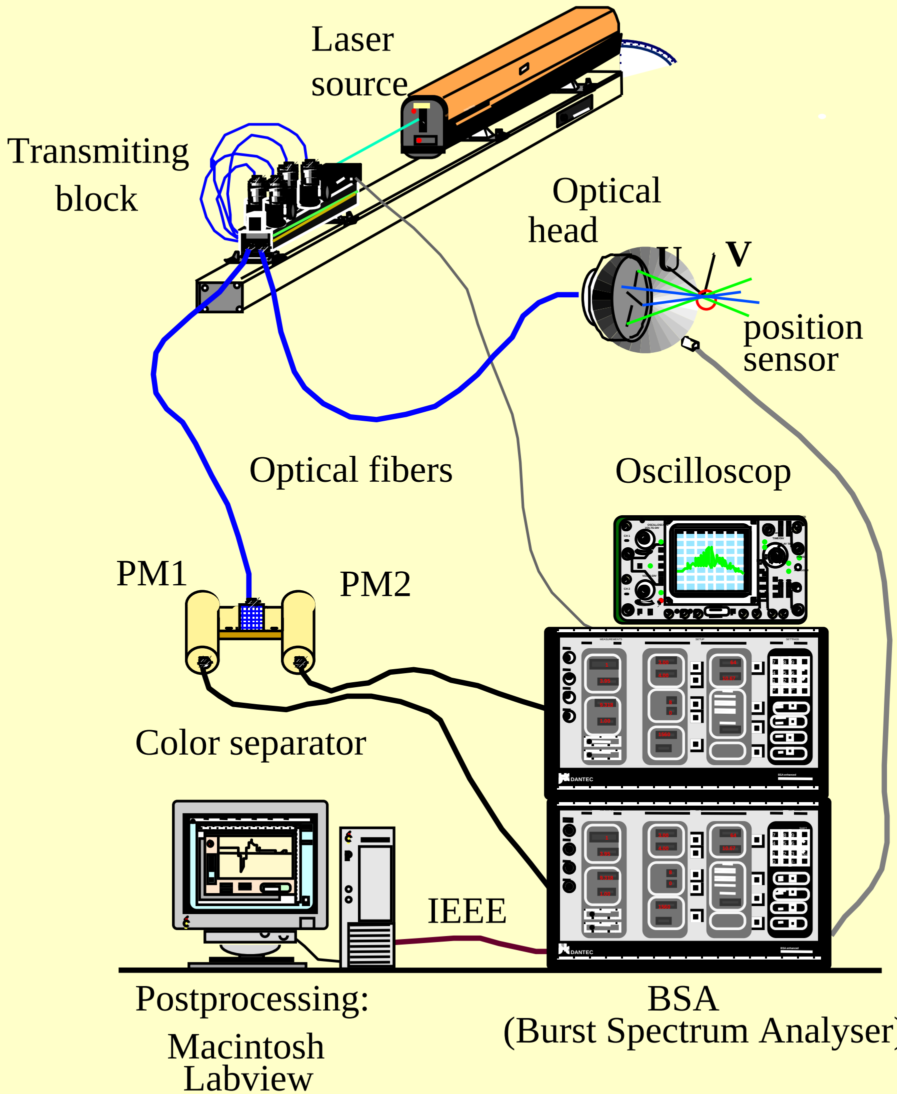
$\alpha(t) = \alpha_0 + \Delta\alpha \cos(\omega t)$

Embedded Laser Doppler Velocimetry Method (ELDV)

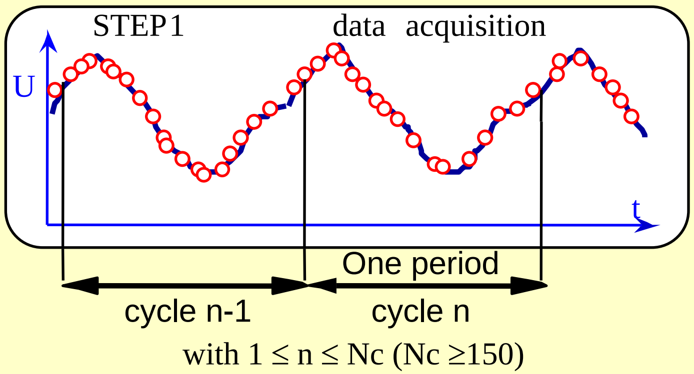


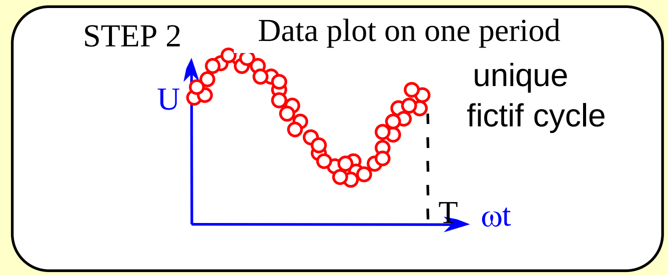
- Embedded optical head linked with the model
- Reference frame linked with the moving surface
- Focal length f = 400 mm
- Survey along the chord (x direction)
- Survey along the normal (y direction)

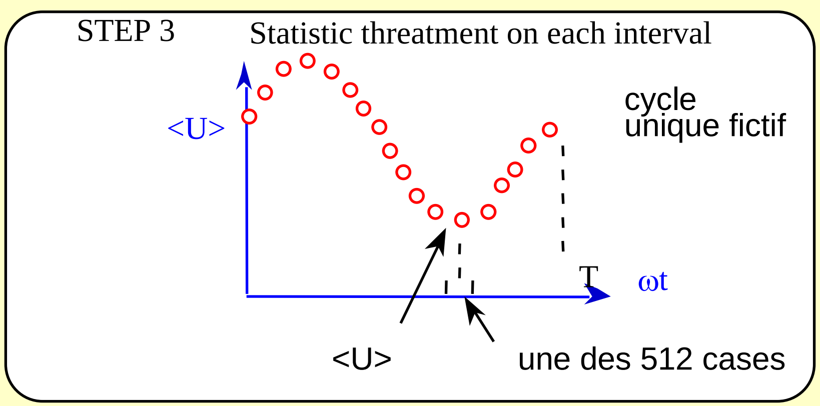
ELDV Acquisition

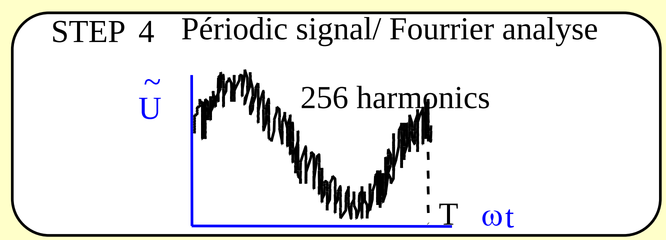


Unsteady measurements processing









$u'(t) = U(t) - \tilde{U}(\omega t)$

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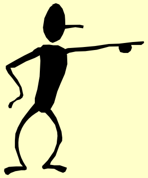

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Parallel Multi-Block (PMB) : RANS approach for the turlence

PMB RANS approach principle

- Transport equations

$$\frac{\partial W}{\partial t}+\frac{\partial\left(F^{i}-F^{\upsilon}\right)}{\partial x}+\frac{\partial\left(G^{i}-G^{\upsilon}\right)}{\partial y}=0$$

$$W=\left(\rho,\rho u,\rho v,\rho e_T\right)$$

$$F^{i}=\left(\rho u,\rho u^{2}+p,\rho uv,\rho uh\right)$$

$$G^{i}=\left(\rho u,\rho uv,\rho v^{2}+p,\rho vh\right)$$

$$F^{\upsilon}={}^{1}\!/\!_{\mathrm{Re}}\left(0,\tau_{xx},\tau_{xy},u\tau_{xx}+v\tau_{yy}+q_x\right)$$

$$G^{\upsilon}={}^{1}\!/\!_{\mathrm{Re}}\left(0,\tau_{xy},\tau_{yy},u\tau_{xy}+v\tau_{yy}+q_y\right)$$

$$\tau_{xx}=-(\mu+\mu_T)\left(2\frac{\partial u}{\partial x}-\frac{2}{3}\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}\right)\right)+\frac{2}{3}\rho k$$

$$\tau_{yy}=-(\mu+\mu_T)\left(2\frac{\partial v}{\partial y}-\frac{2}{3}\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}\right)\right)+\frac{2}{3}\rho k$$

$$\tau_{xy}=-(\mu+\mu_T)\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}\right)$$

PMB RANS approach principle

- The resolution method

Implicite scheme :

$$\frac{W_{i,j,k}^{n+1} - W_{i,j,k}^{n}}{\Delta t} = -\frac{1}{V_{i,j,k}} R_{i,j,k}\left(W_{i,j,k}^{n+1}\right)$$

Turbulence models: 1 or 2 equations models. Spalart-Allmaras (SA), k-ω et SST.

$$\rho = \overline{\rho} + \rho' \qquad p = \overline{p} + p' \qquad u = \overline{u} + u' \qquad v = \overline{v} + v'$$

PMB RANS approach principle

- Le modèle SA

$$\nu_T = \tilde{\nu} f_{\upsilon 1}$$

$$f_{\upsilon 1} = \frac{\chi^3}{\chi^3 + c_{\upsilon 1}^3} \qquad \chi \equiv \frac{\tilde{\nu}}{\nu}$$

$$\frac{D\tilde{\nu}}{Dt} = c_{b1}\tilde{S}\tilde{\nu} + \frac{1}{\sigma}\left[\nabla.\left(\left(\nu + \tilde{\nu}\right)\nabla\tilde{\nu}\right) + c_{b2}\left(\nabla\tilde{\nu}\right)^2\right] - c_{\omega 1} f_{\omega}\left[\frac{\tilde{\nu}}{d}\right]^2$$

$$\tilde{S} \equiv S + \frac{\tilde{\nu}}{\kappa^2 d^2} f_{\upsilon 2} \quad f_{\upsilon 2} = 1 - \frac{\chi}{1 + \chi f_{\upsilon 1}} \quad f_{\omega} = g\left[\frac{1 + c_{\omega 3}^6}{g^6 + c_{\omega 3}^6}\right]^{1/6} \quad g = r + c_{\omega 2}\left(r^6 - r\right) \quad r \equiv \frac{\tilde{\nu}}{\tilde{S}\kappa^2 d^2}$$

$$c_{b1} = 0.135 \quad \sigma = 2/3 \quad c_{b2} = 0.622 \quad \kappa = 0.41 \quad c_{\omega 1} = 2.762 \quad c_{\omega 2} = 0.3 \quad c_{\omega 3} = 2 \quad c_{\upsilon 1} = 7.1$$

PMB RANS approach principle

- Le modèle k-ω

$$\mu_T = \rho k / \omega$$

$$\rho \frac{\partial k}{\partial t} + \rho V.\nabla k - \frac{1}{\mathrm{Re}} \nabla.\left[\left(\mu + \sigma^* \mu_T\right)\nabla k\right] = P_k - \beta^* \rho k \omega$$

$$\rho \frac{\partial \omega}{\partial t} + \rho V.\nabla \omega - \frac{1}{\mathrm{Re}} \nabla.\left[\left(\mu + \sigma \mu_T\right)\nabla \omega\right] = P_\omega - \beta \rho k \omega^2$$

$\alpha = 5/9$ $\quad\beta = 3/40$ $\quad\beta^* = 9/100$ $\quad\sigma = 1/2$ $\quad\sigma^* = 1/2$

PMB RANS approach principle

- Le modèle de transport du tenseur visqueux (SST)

$$\mu_T = \frac{\rho k/\omega}{\max[1;\Omega F_2/(a_1\omega)]}$$

$$F_2 = \tanh\left[\left(\max\left[2\frac{\sqrt{k}}{0.09\omega y};\frac{500\mu}{\rho y^2\omega}\right]\right)^2\right]$$

$$\rho\frac{\partial k}{\partial t} + \rho V.\nabla k - \frac{1}{\mathrm{Re}}\nabla.[(\mu+\sigma^*\mu_T)\nabla k] = P_k - \beta^*\rho k\omega$$

$$\rho\frac{\partial \omega}{\partial t} + \rho V.\nabla \omega - \frac{1}{\mathrm{Re}}\nabla.[(\mu+\sigma_{\omega 1}\mu_T)\nabla \omega] = P_\omega - \beta\rho k\omega^2 + 2(1-F_1)\frac{\rho\sigma_{\omega 2}}{\omega}\nabla k\nabla\omega$$

$$F_1 = \tanh\left[\left[\min\left(\max\left[\frac{\sqrt{k}}{0.09\omega y};\frac{500\mu}{\rho y^2\omega}\right];\frac{4\rho\sigma_{\omega 2}k}{CD_{k\omega}y^2}\right)\right]^4\right]$$

$$CD_{k\omega} = \max\left[\frac{2\rho\sigma_{\omega 2}}{\omega}\nabla k\nabla\omega;10^{-20}\right]$$

$a_1 = 0.31$ $\beta^* = 0.09$ $\kappa = 0.41$

Results

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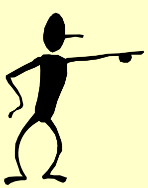

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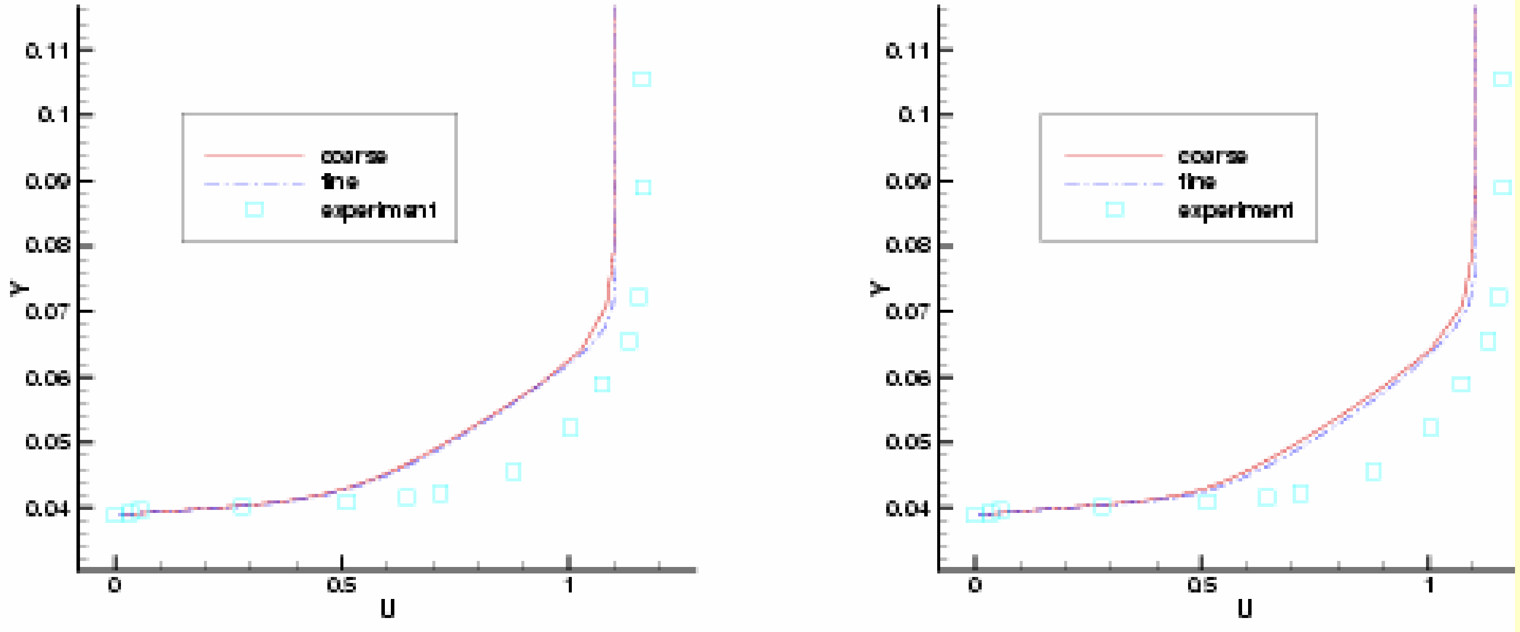
2 meshes results

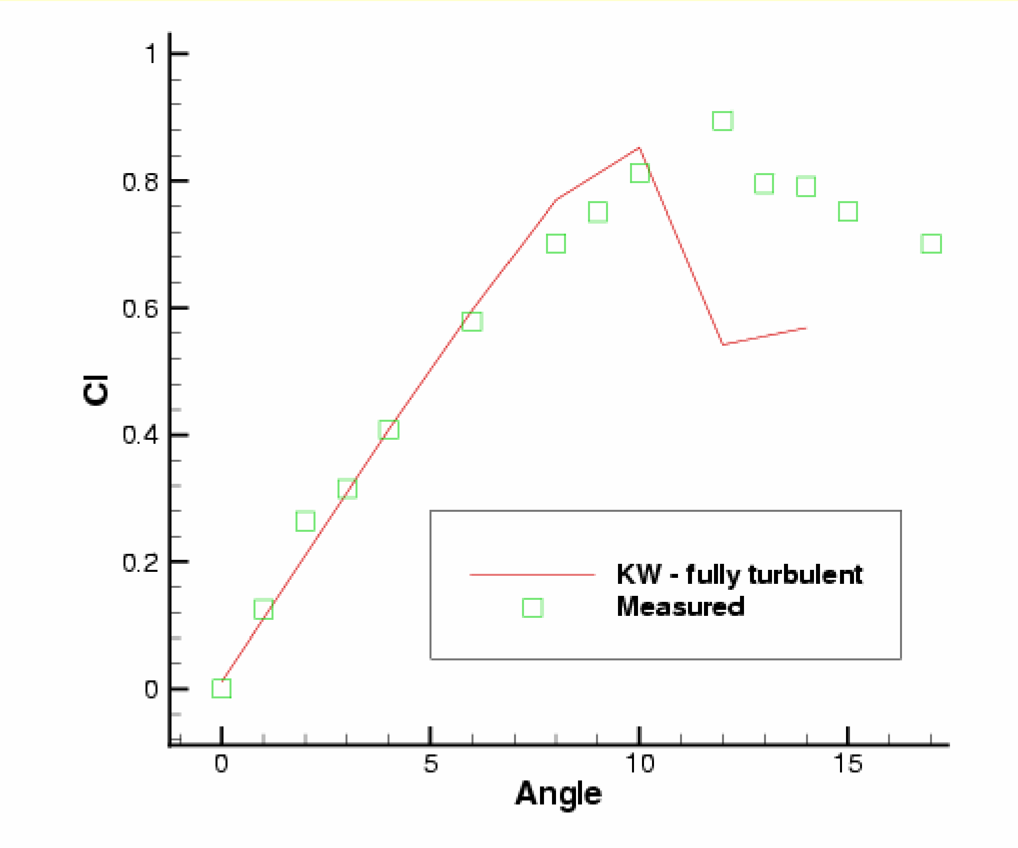


KW model

SA model

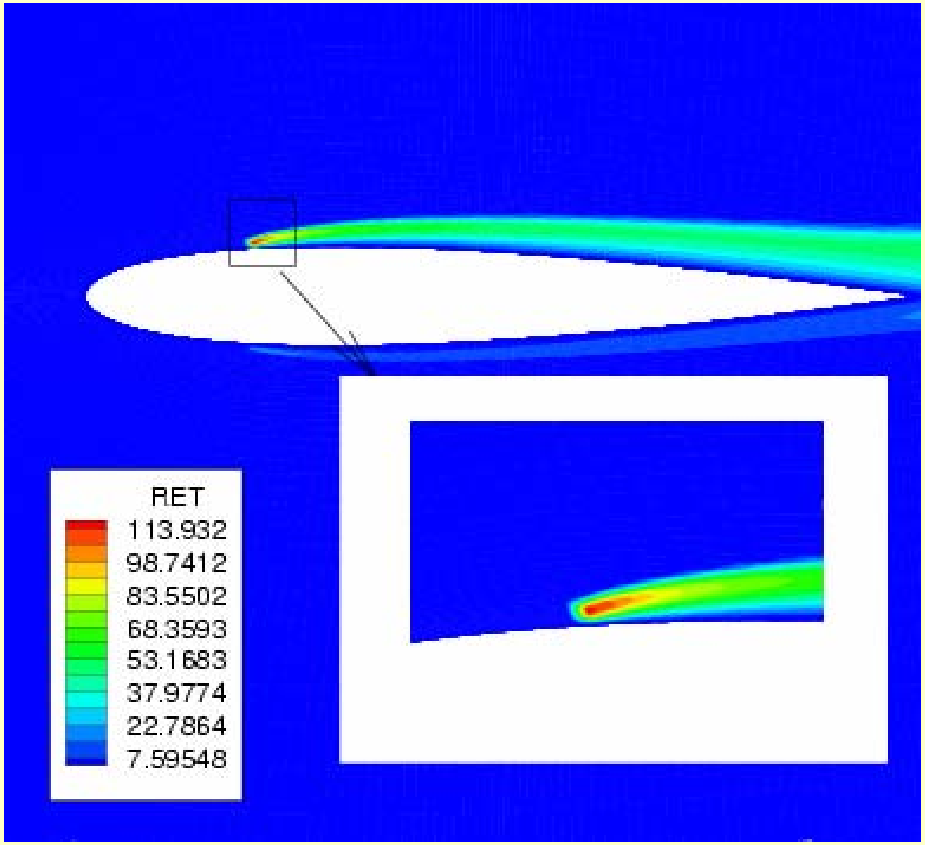
Fine mesh, 27501 points
Coarse mesh, 6975 points

Lift coefficient



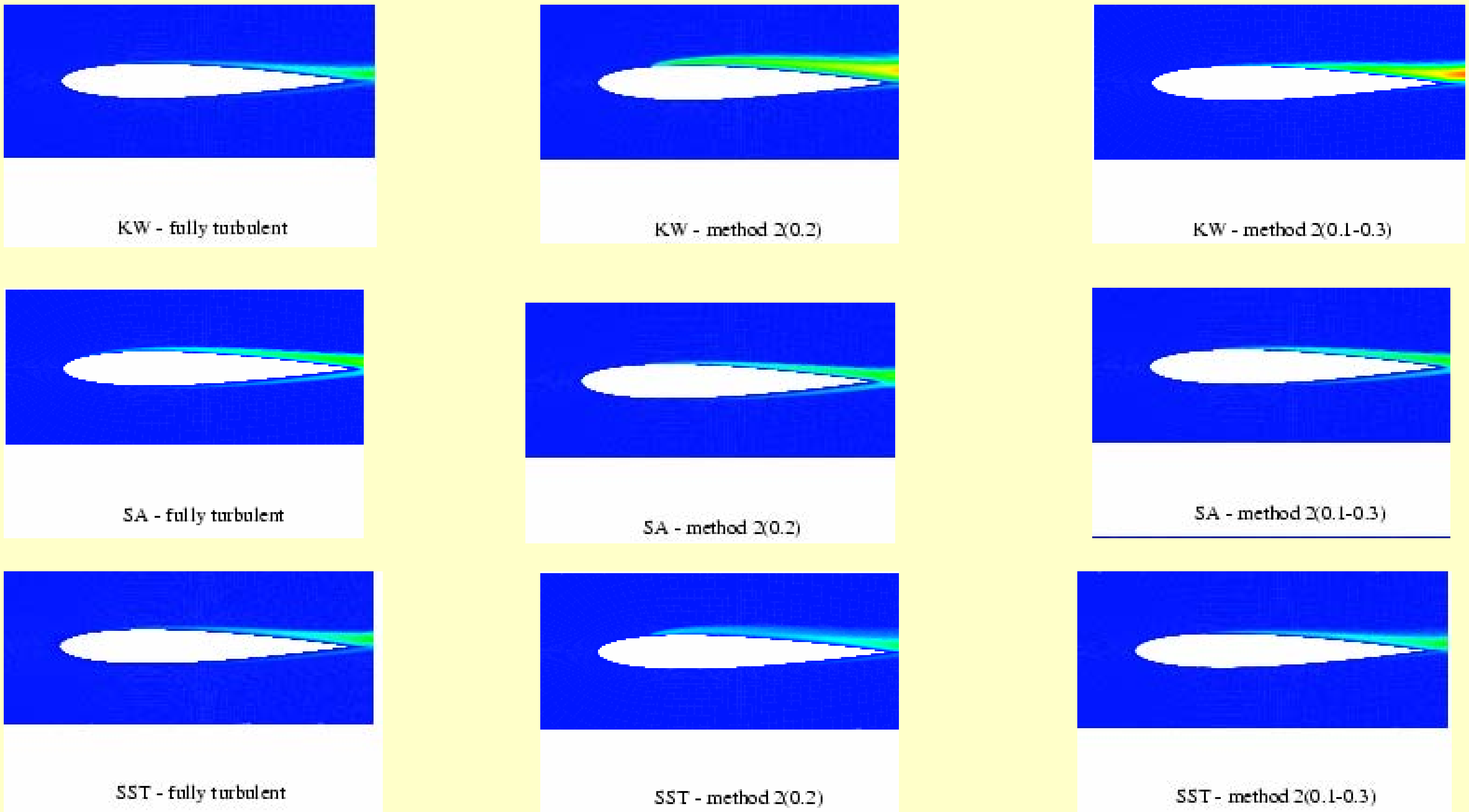
Fixed incidence case

Turbulence Reynolds Number



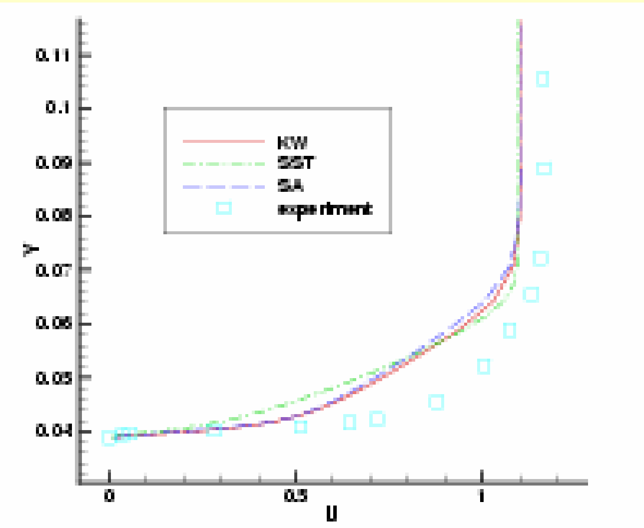
k-ω model with imposed transition at s/c=0.2

Turbulence Reynolds Number

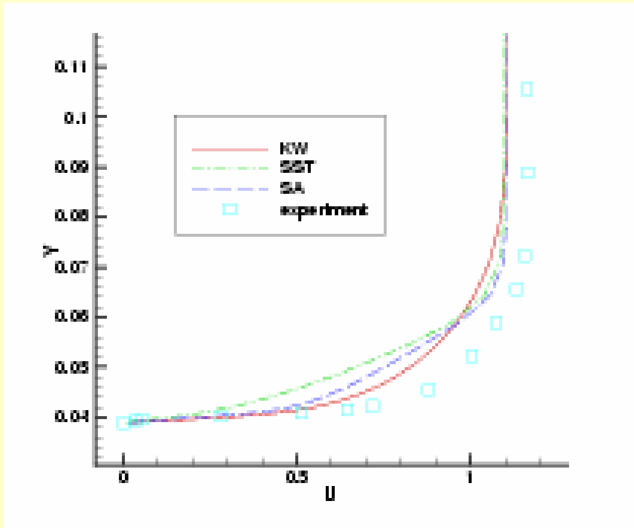


Différents model with or without transition

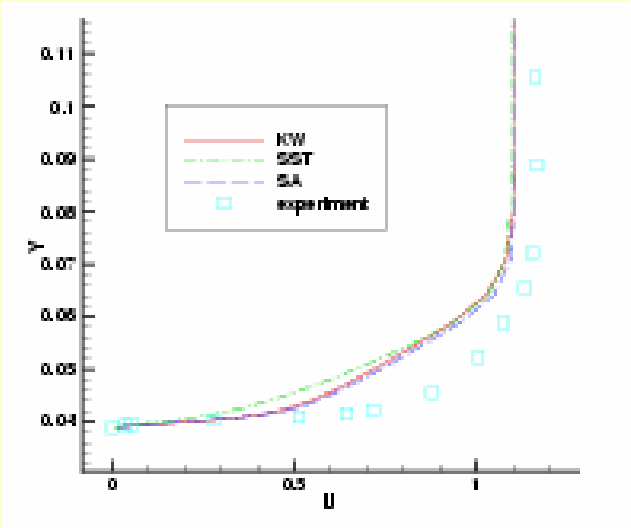
Velocity Profiles



Fully turbulent

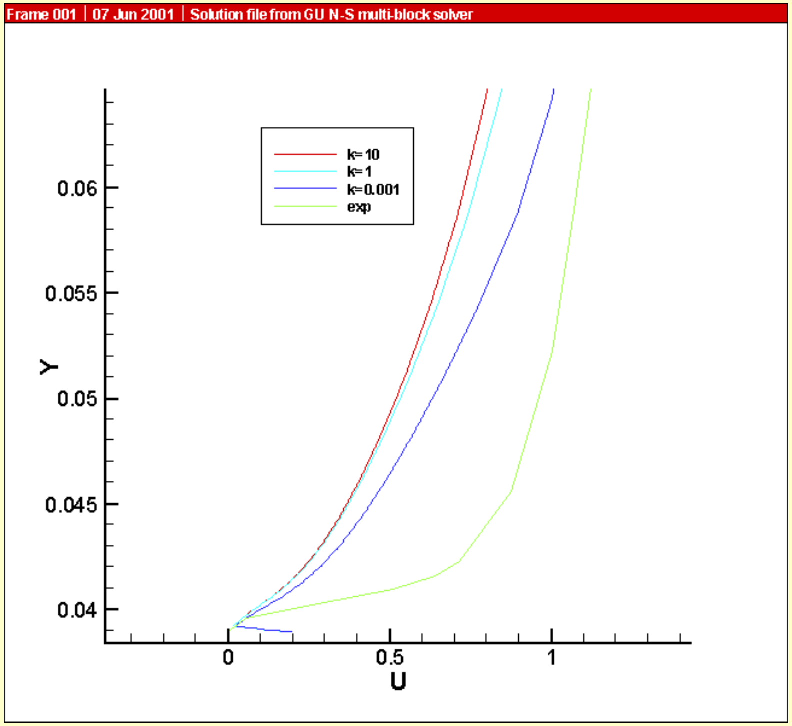


Transition fixed at s/c=0.2

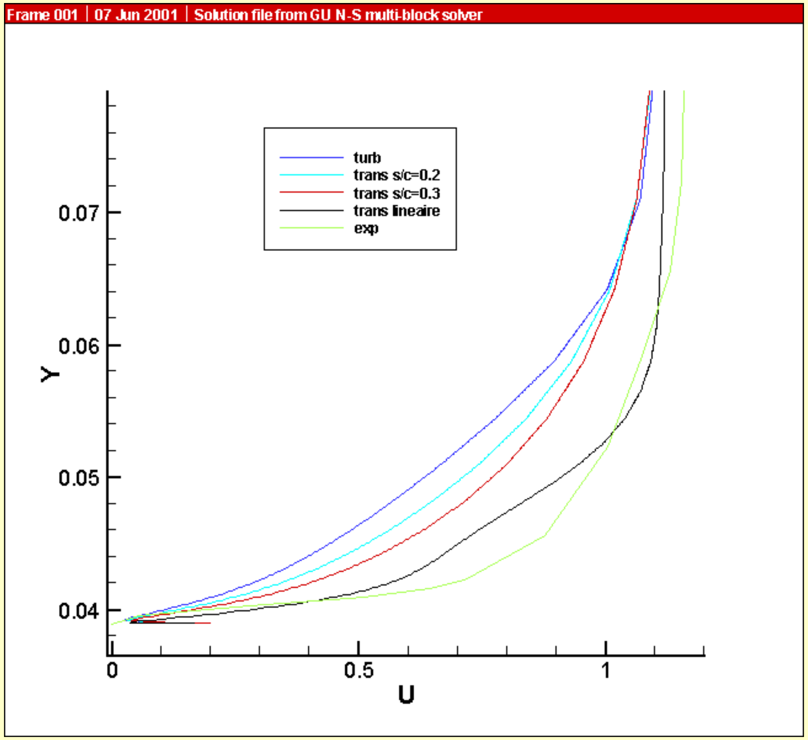


Transition increasing linéairly between s/c=0.1 and s/c=0.3

Velocity Profiles

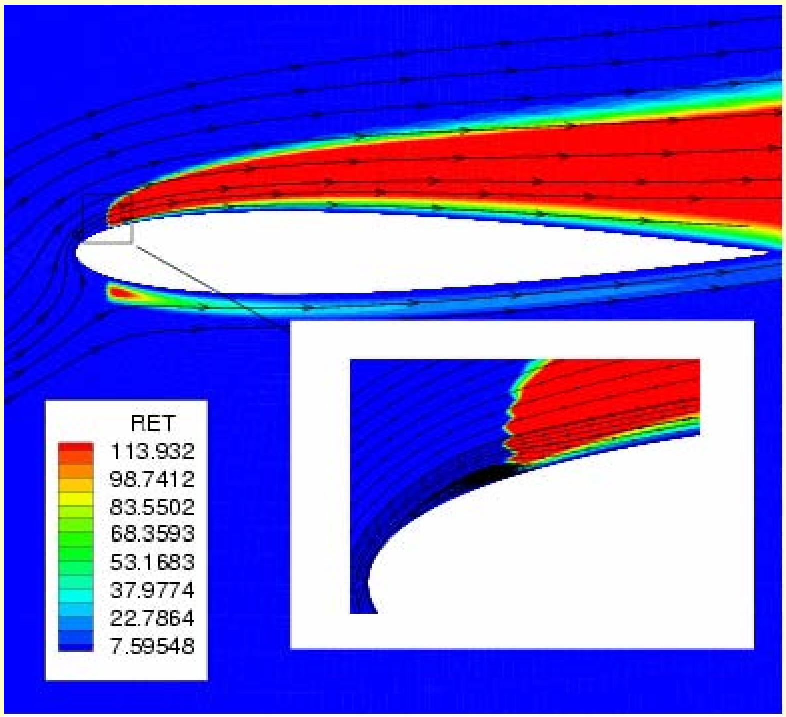


SST model for differents values of k

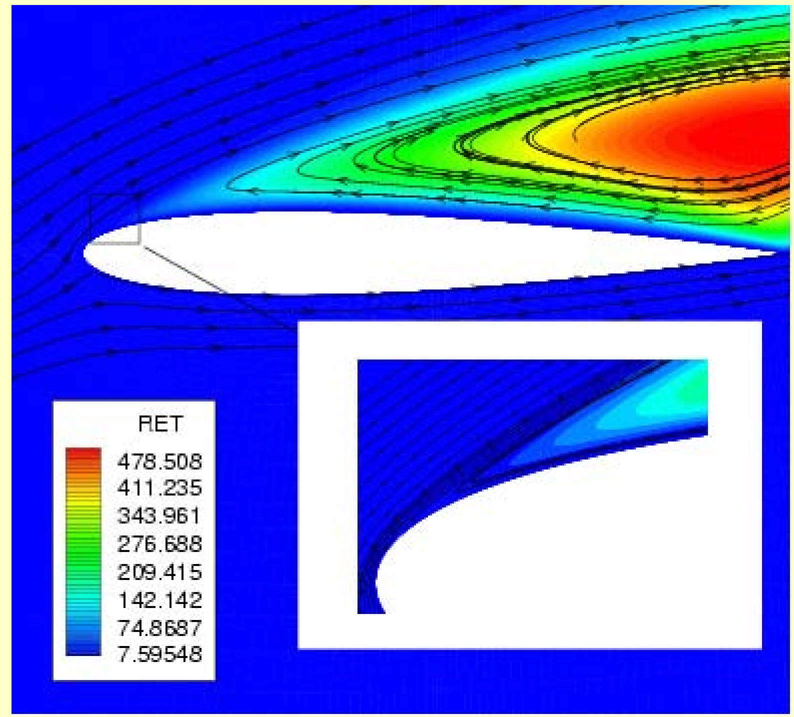


SST models for differents transition localisations and k=0.001

Turbulence Reynolds Number

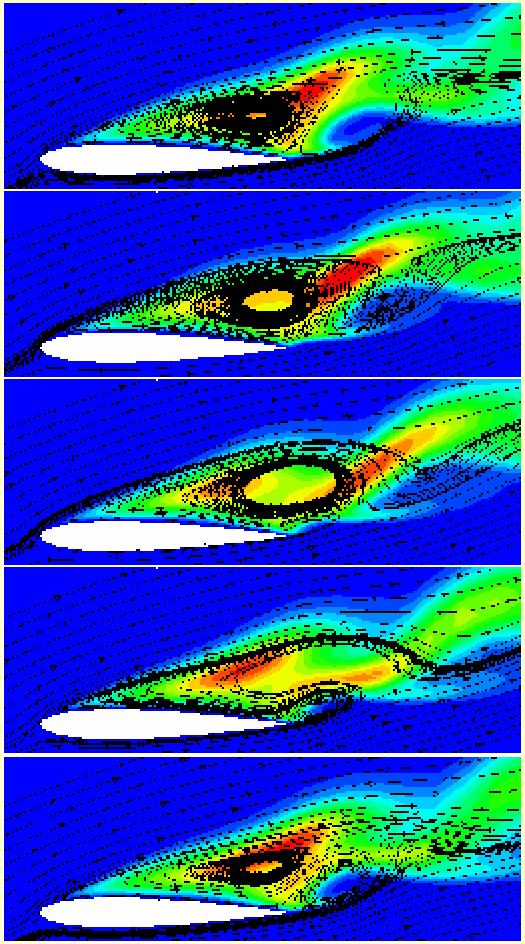


α=15 deg: SST model with transition fixed at s/c=0.05



α=15 deg: SST model fully turbulent

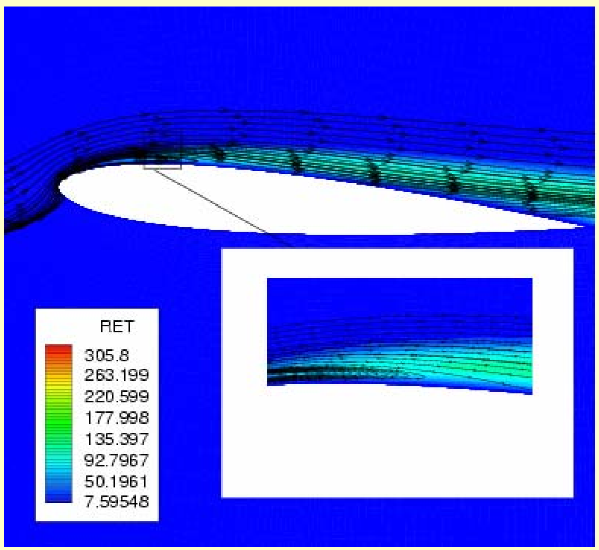
Turbulence Reynolds Number



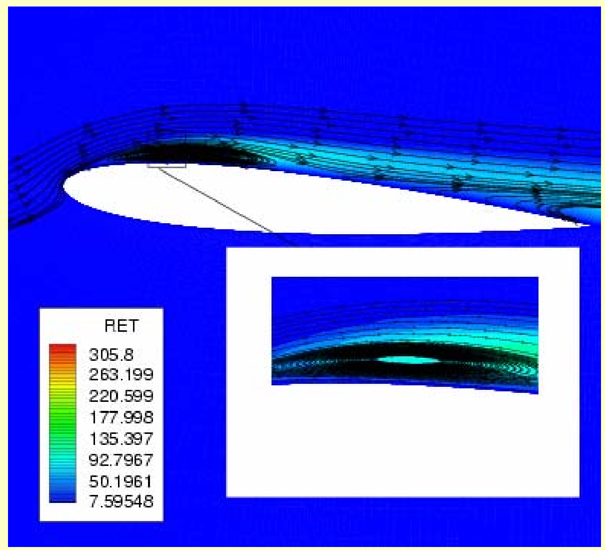
Vortex shedding with a characteristic dimensionless frequency of k= 0.51

Turbulence Reynolds Number

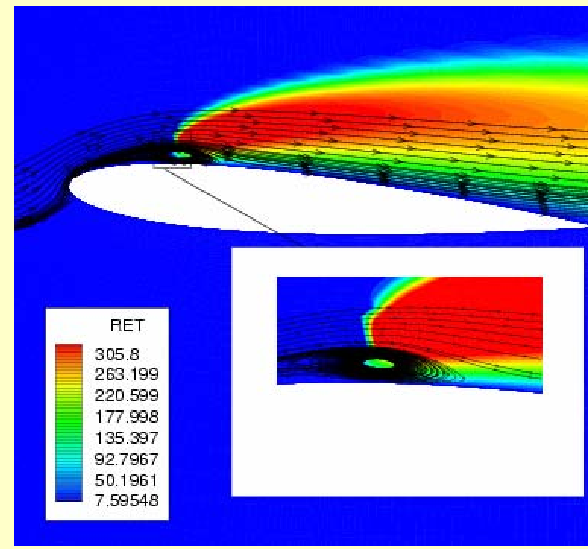
Pitching motion, $\alpha(t)=\alpha_0+\Delta\alpha\cos(\omega t)$
α_0=6deg, $\Delta\alpha$ 6 deg, $k=\omega c/2U_\infty=0.188$



12°: k-ω model fully turbulent



12°: SST model fully turbulent

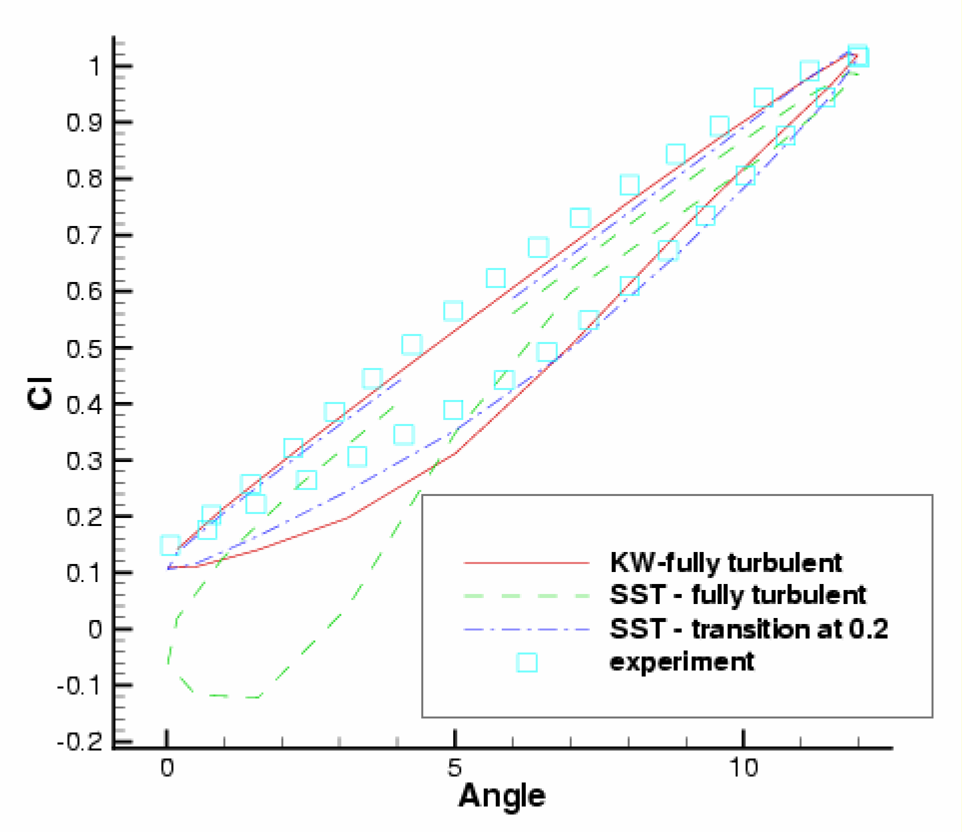


12°: SST model with transition location at s/c=0.2

Lift coefficient

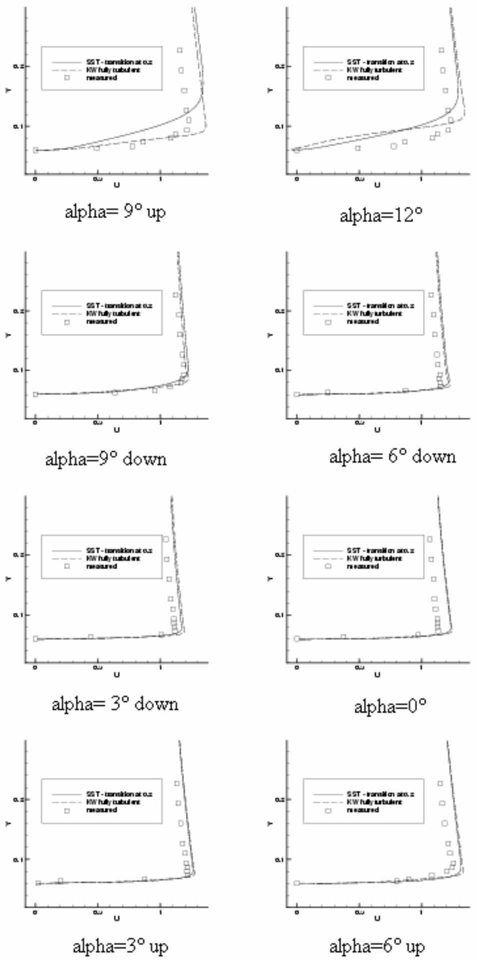
Pitching motion, $\alpha(t)=\alpha_0+\Delta\alpha\cos(\omega t)$

α_0=6deg, $\Delta\alpha$ 6 deg, $k=\omega c/2U_\infty=0.188$



Hysteresis loops

Velocity Profiles



SST model with transition located at s/c=0.2 an k-ω model fully turbulent

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Conclusions

- Using such ELDV measurement methods, the boundary-layer behaviour can be fully investigated and characterized in a moving frame of reference.
- Analysis of the effects of forced unsteadiness (due to the pitching motion) on B.L.
- Dependence on turbulence model and transition
- Better agreement with experiment for transitionnal models for static incidence, before stall. Fully turbulent dodels are more adapted for oscillation case