Częstochowa University of Technology

Institute of Thermal Machinery

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TRANSITION MODELING IN TURBOMACHINERY FLOWS

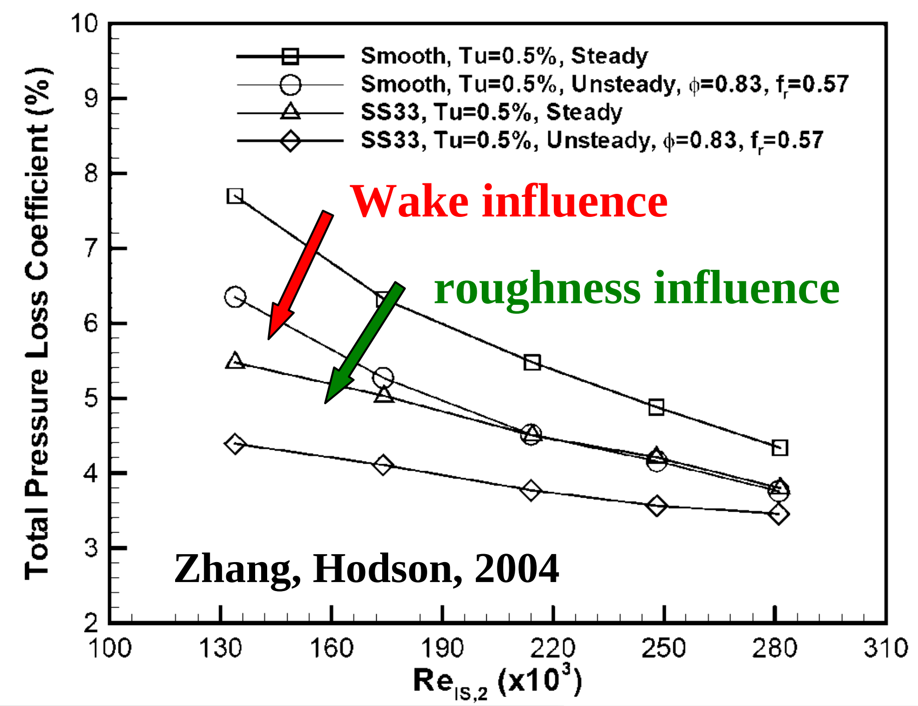
Papers:

1. PIOTROWSKI W., ELSNER W., DROBNIAK S., Transition Prediction on Turbine Blade Profile with Intermittency Transport Equation, 2010, Trans.ASME J.Turbomach. Vol.132 nr 1
2. ELSNER W., WARZECHA P., Modeling of rough wall boundary layers with an intermittency transport model, 2010, TASK QUARTERLY 14 No 3
3. PIOTROWSKI W., KUBACKI S., LODEFIER K., ELSNER W., DICK E., Comparison of Two Unsteady Intermittency Models for Bypass Transition Prediction on a Turbine Blade Profile, Flow Turbulence Combust, 2008

Scope of the presentation

1. Motivation
2. Intermittency Transport model (ITM) – basic assumption
3. Intermittency Transport model (ITM) – modifications to account for a wall roughness >> (ITM_R)
4. Calculations of simple flows with rough walls
5. Verification of ITM_R procedure for turbine blade with wall roughness
6. Some examples of steady and unsteady calculations
7. Concluding remarks

Motivation



Influence of artificial roughness

High-loaded

T106 blade

VKI, 2004

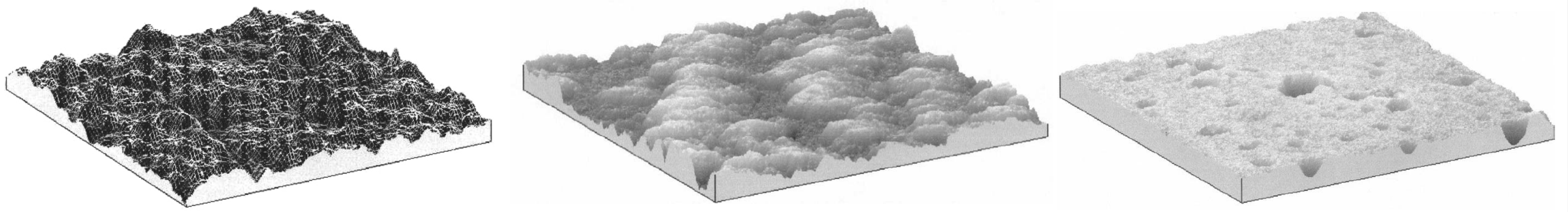
The study suggests that such a blade with as-cast surface roughness has a lower loss than a polished one !

It is useful for the designer to have an estimate of the effects of upstream wakes and surface roughness on both heat transfer and aerodynamic performance

Motivation

The blade surfaces varied significantly with time. The types of surfaces could be categorized as:

- erosion (due to prolonged use or hostile operating environments – the surface is typically characterized as having peaks above and valleys below the mean surface level),
- deposits (deposits were typically raised above the mean surface level of the blade),
- corrosion/pitting (small canyons of measuring depths of 250 µm and widths of 5 cm).



(Ellering, 2001)

Rough surfaces are characterized by statistical parameters such as average centerline roughness Ra, which are correlated to the well-defined equivalent sandgrain roughness, k_s

The other measure is nondimensional sandgrain height $K_s^+ = \frac{u_\tau k_s}{\nu}$

Motivation

As the roughness height progressively increases l-t transition moves forward on !

There are many various approaches to model transitional flows, but generally Transition Models

- require empirical input for transition onset detection
- are based on non local formulations
- not compatible with modern CFD approaches

An alternative

Transition Model based on the local formulations γ-Re$_\theta$ (Menter'04)

Intermittency Transport Model (ITM) - γ-Re$_\theta$ extended by inhouse correlations (Piotrowski at al., 2007)

Intermittency Transport Model - basic assumptions

Solver => Fluent => 4 User's Defined Scalars

$\left.\begin{array}{r}\textbf{k transport equation}\\ \boldsymbol{\omega}\ \textbf{transport equation}\end{array}\right\}$ **Modified SST turbulence model**

+

Intermittency factor (γ) transport equation

+

Local transition onset momentum thickness Reynolds number ($Re_{\theta t}$) transport equation

Intermittency Transport Model - basic assumptions

Transport Equation for Intermittency Factor (γ)

$$\frac{\partial(\rho\gamma)}{\partial t}+\frac{\partial(\rho U_j\gamma)}{\partial x_j}=P_{\gamma 1}-E_{\gamma 1}+P_{\gamma 2}-E_{\gamma 2}+\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_f}\right)\frac{\partial\gamma}{\partial x_j}\right]$$

Transition Sources

$$P_{\gamma 1}=2\cdot \boxed{F_{length}}\cdot\rho\cdot S\cdot[\gamma\cdot F_{onset}]^{0.5} \qquad E_{\gamma 1}=c_{e1}\cdot P_{\gamma 1}\cdot\gamma$$

Destruction/Relaminarization Sources

$$P_{\gamma 2}=0.06\cdot\rho\cdot\Omega\cdot\gamma\cdot F_{turb} \qquad E_{\gamma 2}=50\cdot P_{\gamma 2}\cdot\gamma$$

The main difference to other intermittency models lies in the formulation of F_{onset} used to trigger the intermittency production

$$F_{onset}=f\left(F_{onset\_1}\right)$$

where $$F_{onset\_1}=\frac{\mathrm{Re}_V}{2.193\cdot\boxed{\mathrm{Re}_{\theta c}}}$$

(Piotrowski at al., 2007)

$$Re_{\theta c}=f\left(\tilde{R}e_{\theta t}\right) \Longrightarrow \mathrm{Re}_{\theta c}=F_P\cdot\tilde{\mathrm{Re}}_{\theta t}$$

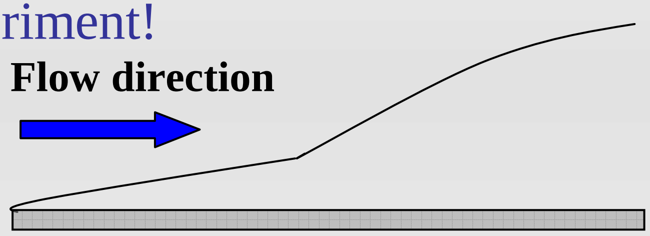
$\mathrm{Re}_{\theta c}$ and **F_{length}** could be correlated to the local transition momentum thickness Reynolds number **$\mathrm{Re}_{\theta t}$** obtained from the additional transport equation

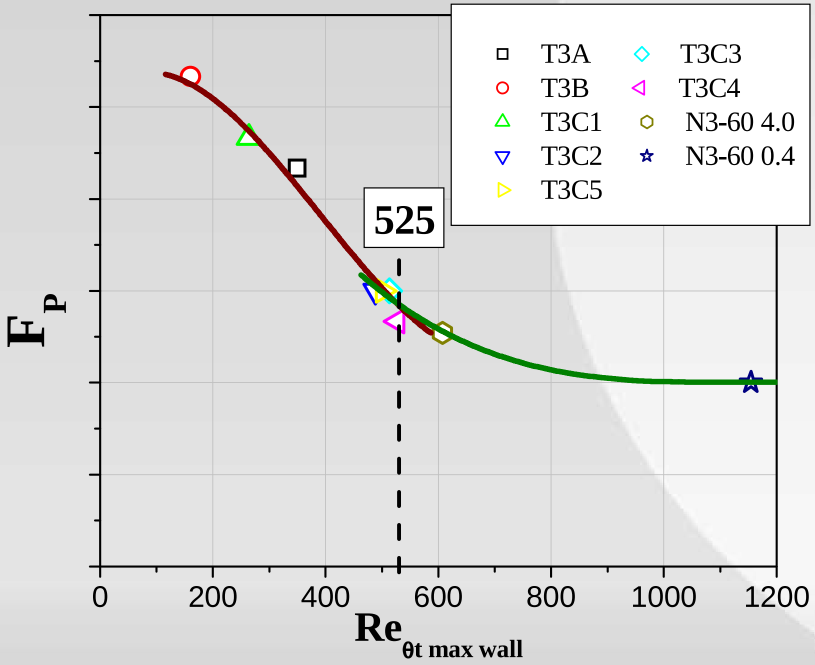
Intermittency Transport Model - missing correlations

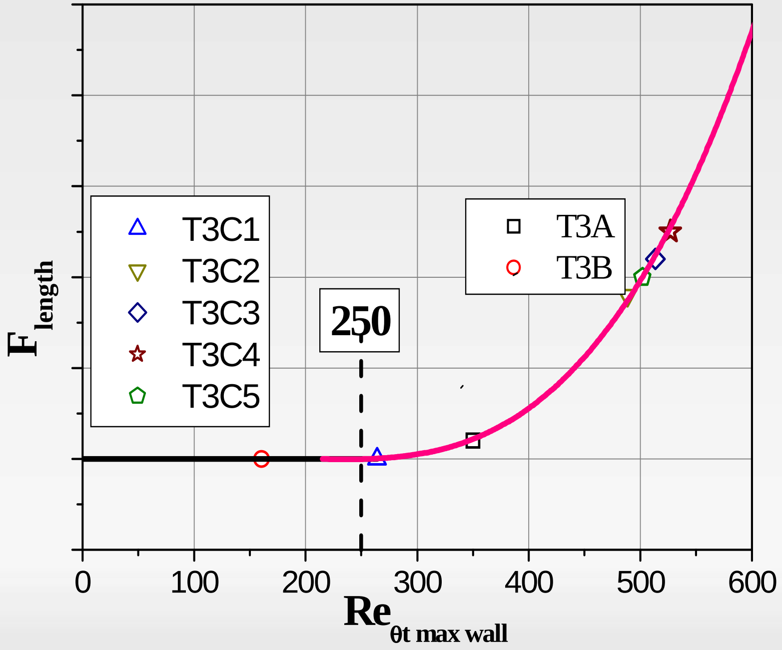
The key element of the methodology is a relation between $Re_{\theta c}$ and F_{length} and local momentum thickness Reynolds number $Re_{\theta t}$?

Those relations were obtained based on numerical experiment!

$$Re_{\theta c} = f\left(\tilde{Re}_{\theta t}\right) \Longrightarrow \mathrm{Re}_{\theta c} = F_P \cdot \tilde{\mathrm{Re}}_{\theta t}$$







Intermittency Transport Model - modifications to account for wall roughness (ITM$_R$)

Introduced modifications:

✓ For turbulent boundary layer: modification of wall boundary condition for ω and for turbulent eddy viscosity (Hellstein&Laine,1997)

$$\mu_T = \frac{a_1 \rho k}{MAX(A_1 ; |\Omega| F_2 \boxed{F_3})}$$

$$\omega_w = \frac{u_\tau^2}{\nu} S_R \qquad K_s^+ = \frac{u_\tau k_s}{\nu}$$

$$S_R = \left[50/\max(K_S^+; K_{S\min}^+)\right]^2 \qquad dla \quad K_S^+ < 25$$

$$S_R = 100/K_S^+ \qquad dla \quad K_S^+ \geq 25$$

$$F_3 = 1 - tanh\left[\left(\frac{150\nu}{\omega d^2}\right)^4\right]$$

$$(F_3 = 1 \rightarrow 0 \ in \ near \ wall \ region)$$

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$$F_3 = 1 - tanh\left[\left(\frac{150\nu}{\omega d^2}\right)^4\right]$$

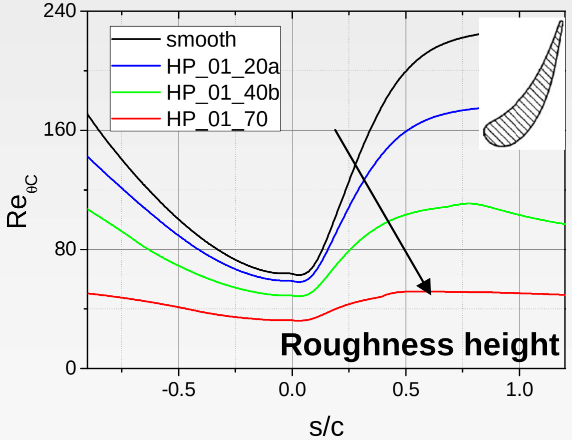
$$(\,F_3 = 1 \rightarrow 0 \ in \ near \ wall \ region\,)$$

✓ For transitional boundary layer: combination of Re$_{\theta t}$ transport equation with the onset correlation of Stripf at al. (2008).

for $k_r/\delta^* > 0.01$

$$Re_{\Theta t} = MIN\left[\left(\frac{1}{\boxed{Re_{\Theta twall}}} + 0.0061\, f_\Lambda \left(\frac{k_r}{\delta^*} - 0.01\right)^{f_{Tu}}\right)^{-1}\right]$$

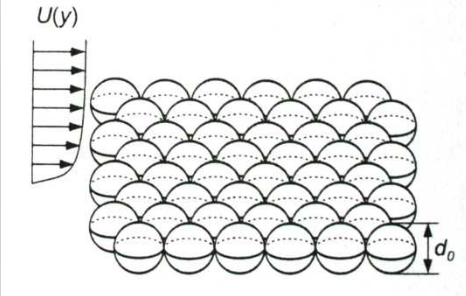
$$f_{Tu} = f(Tu) \qquad f_\Lambda = f(\Lambda_R)$$



The correlation accounts for the effects of roughness height and density as well as turbulence intensity.

Calculations of simple flows with rough walls

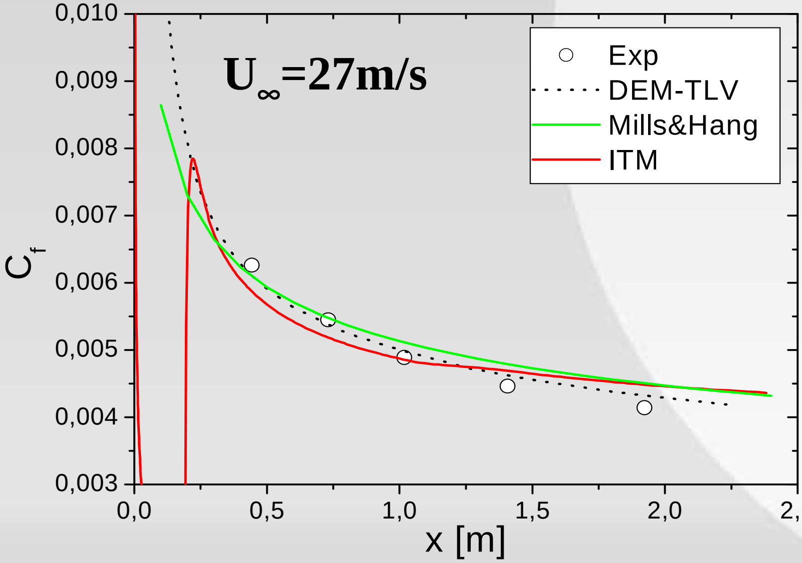
Flat plate flow with zero gradient (Halzer,1974)

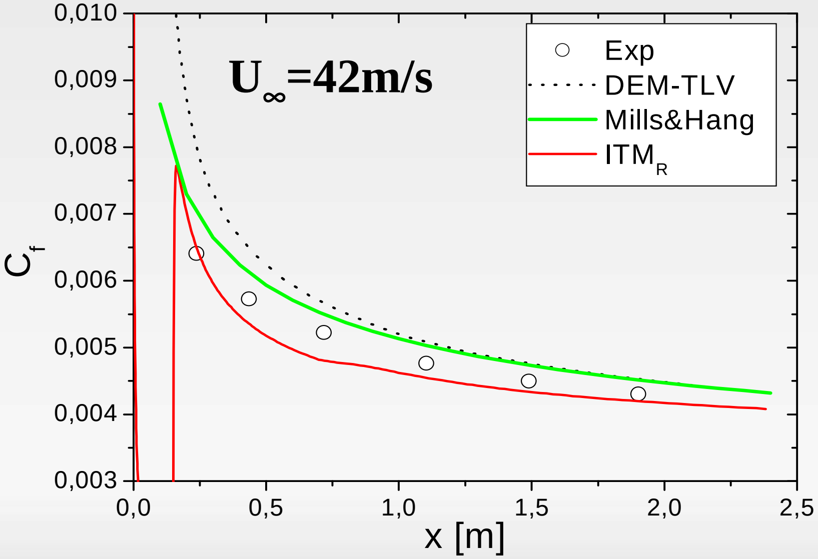


copper balls with a diameter of d_0 = 1.27 mm
equivalent sand roughness k_s=0.62·d_0=0.79 mm
Tu=0.4%; U_∞=27, 42, 58 m/s

Calculations verified against DEM-TLV (Stripf, 2007) and correlation by Mills and Hang (1983)

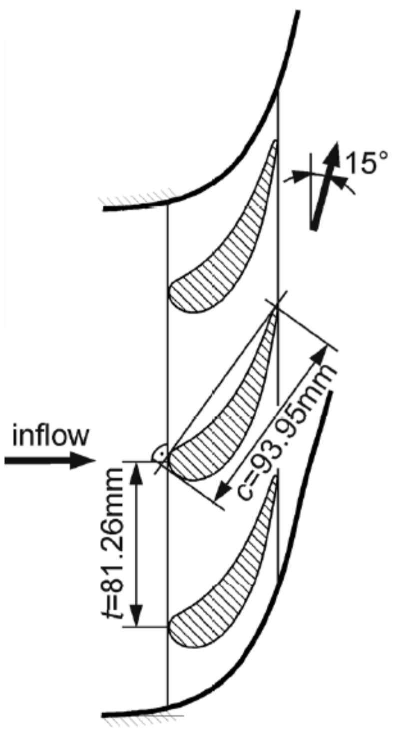
$$c_f = (3.476 + 0.707\ln(x/k_s))^{-2.46}$$



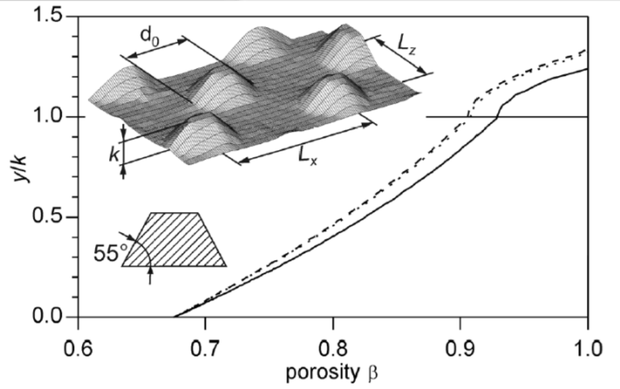


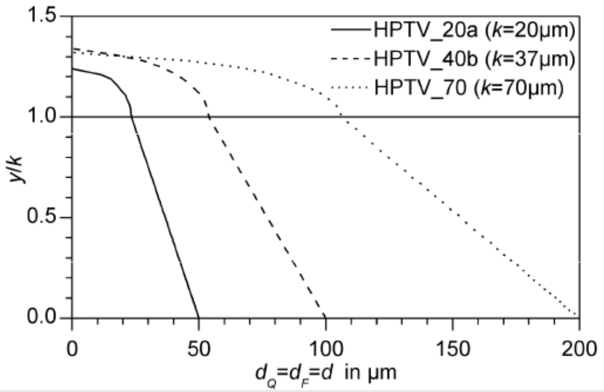
Verification of ITM procedure for turbine blade with wall roughness

High pressure turbine vane (Stripf, 2007).



Type of surface roughness



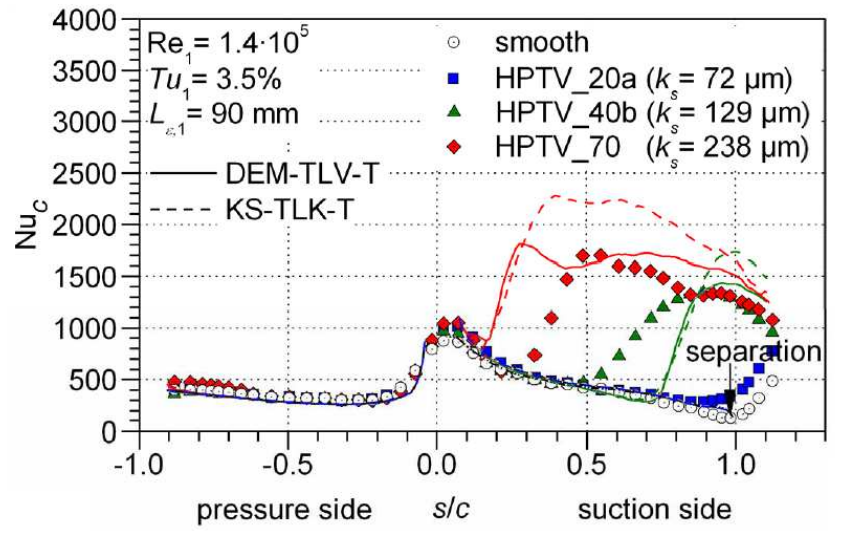


***Tu*=3.5 %; U$_\infty$=29.8 m/s**

Test case	$K_S^+ [-]$	$k_s [mm]$	$\tau [Pa]$	$u_\tau [m/s]$	$\delta^* [mm]$	$Tu_{eff} [\%]$	Λ_R	k_s/δ^*
HP_01_20a	22.05	0.072	39	6.21	0.157	0.98	5.7	0.46
HP_01_40b	48.13	0.129	57.9	7.57	0.102	1.0	5.4	1.26
HP_01_70	99.03	0.238	72	8.44	0.073	1.19	5.2	3.26

Condition to induce the response of b.l. (acc. to Zhang, Hodson'04): k_s> 0.15% chord >> HP_01_40b

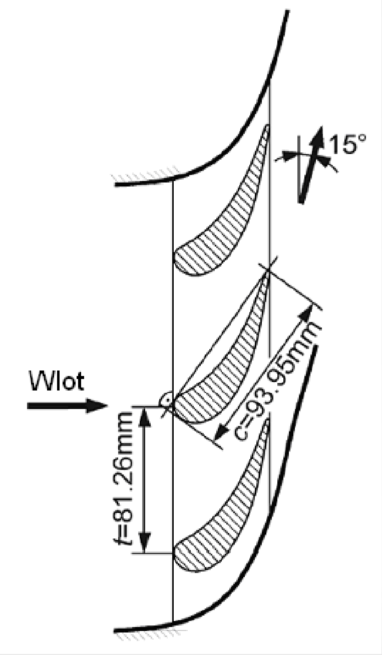
Verification of ITM procedure for turbine blade with wall roughness



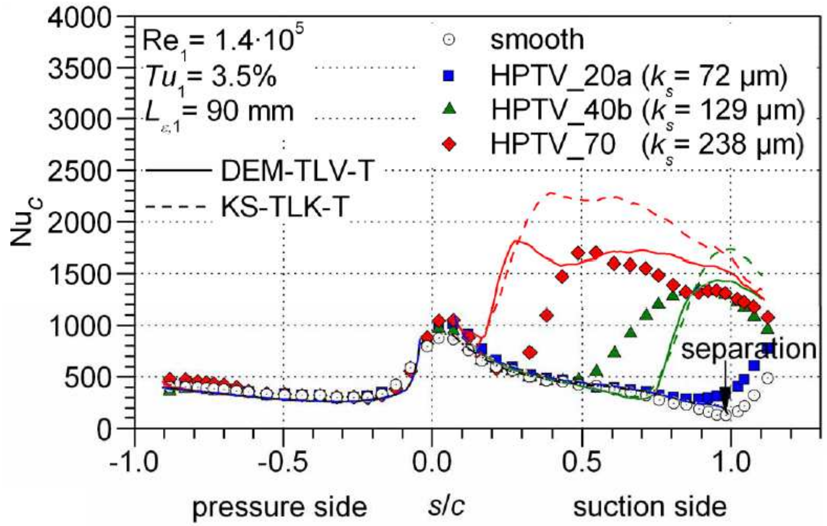
Symbols – experimental data

Lines - num. results (Stripf'08)

Parameter –Nusselt Number Nu_c



Verification of ITM procedure for turbine blade with wall roughness



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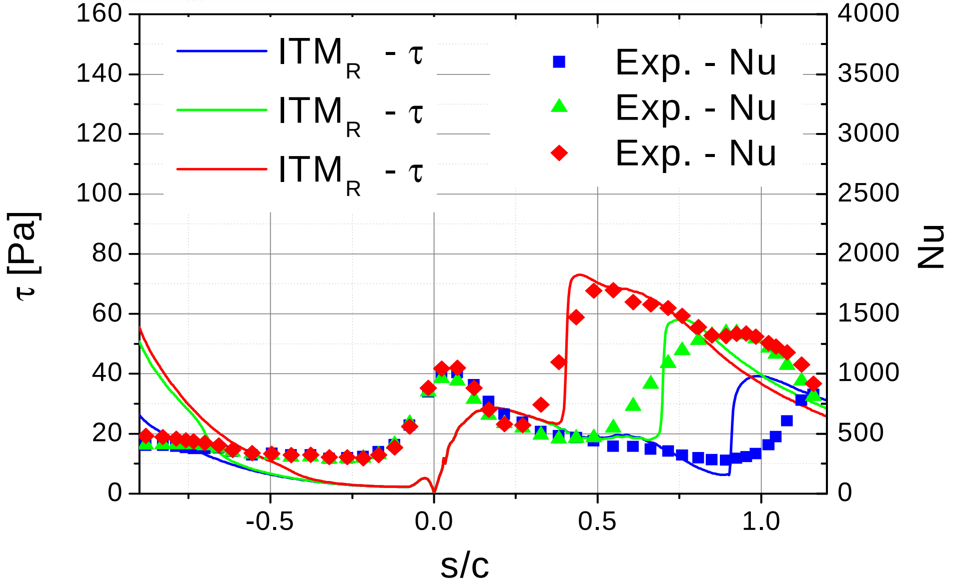
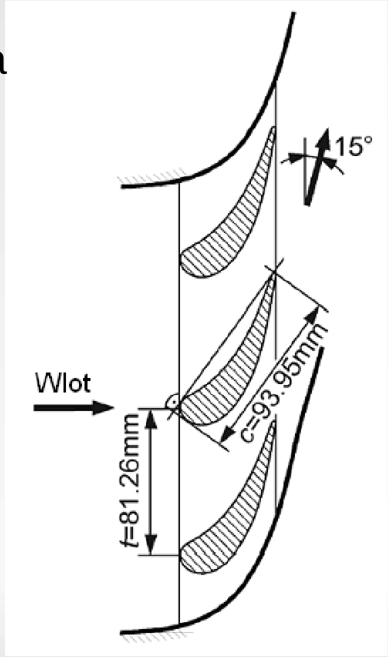


Symbols – experimental data

Lines - own num. results

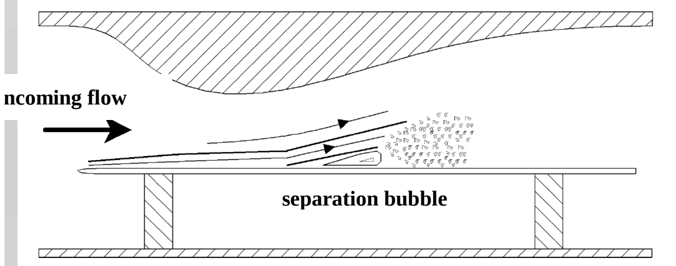
Parameter –shear stresses

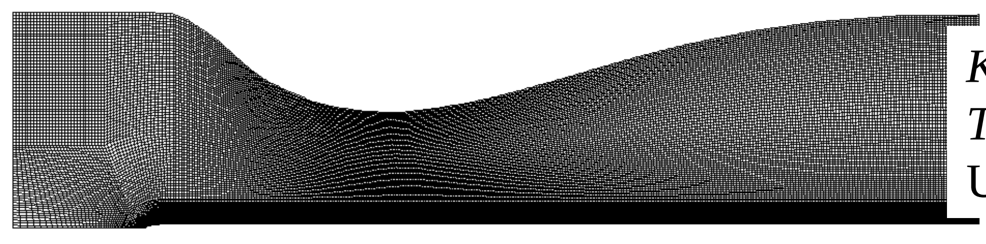
$\tau\,[Pa]$



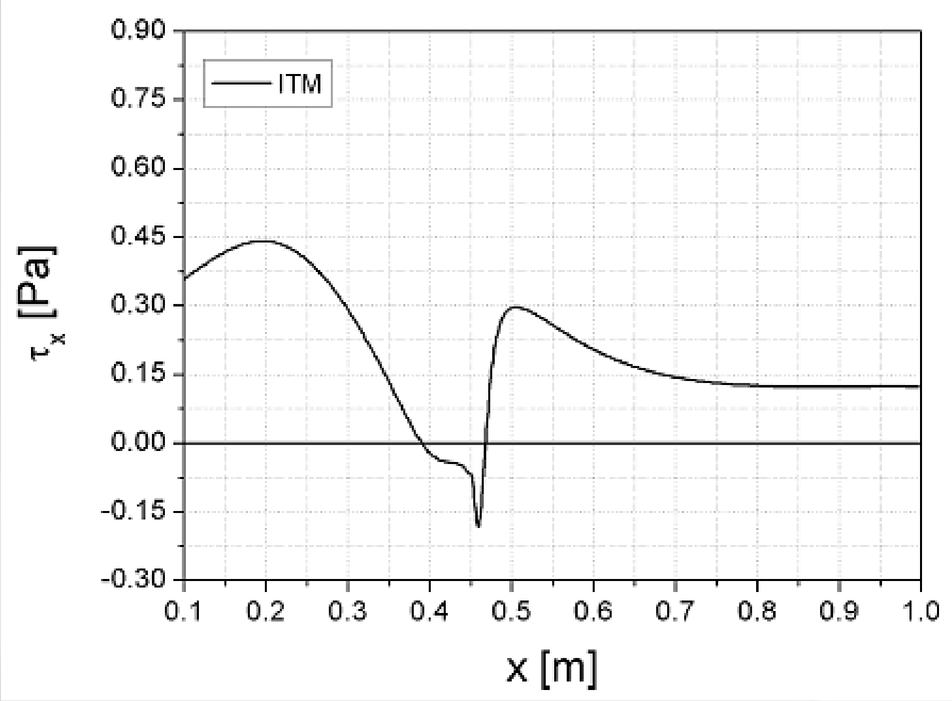
Steady and unsteady calculations of simple flows with rough walls

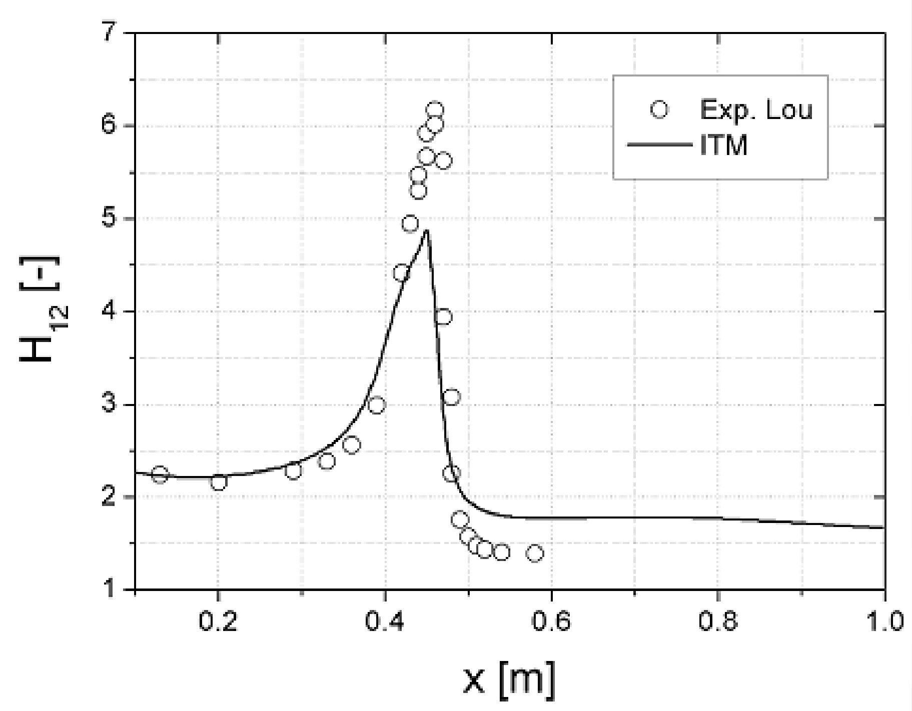
Calculations for flat plate with pressure gradient (Lou, Hourmouziadis, 2000)





K_s^+=10-50;
Tu=0.6%;
U_∞=9 m/s





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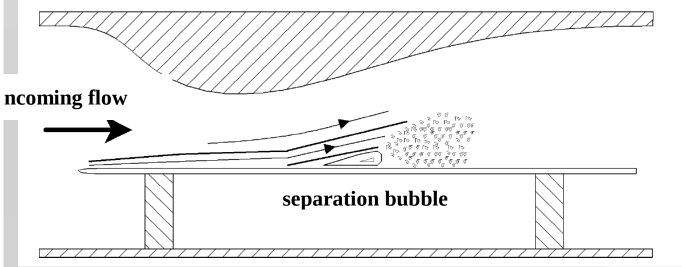

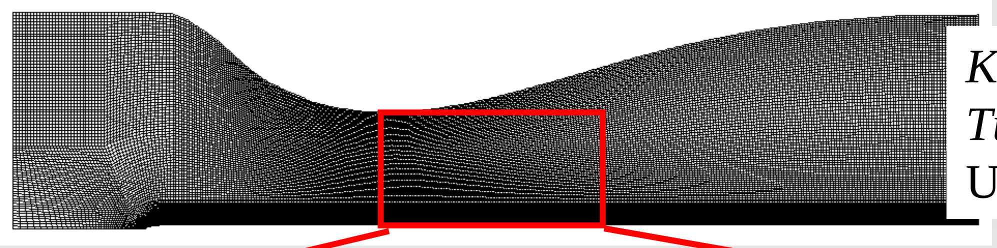

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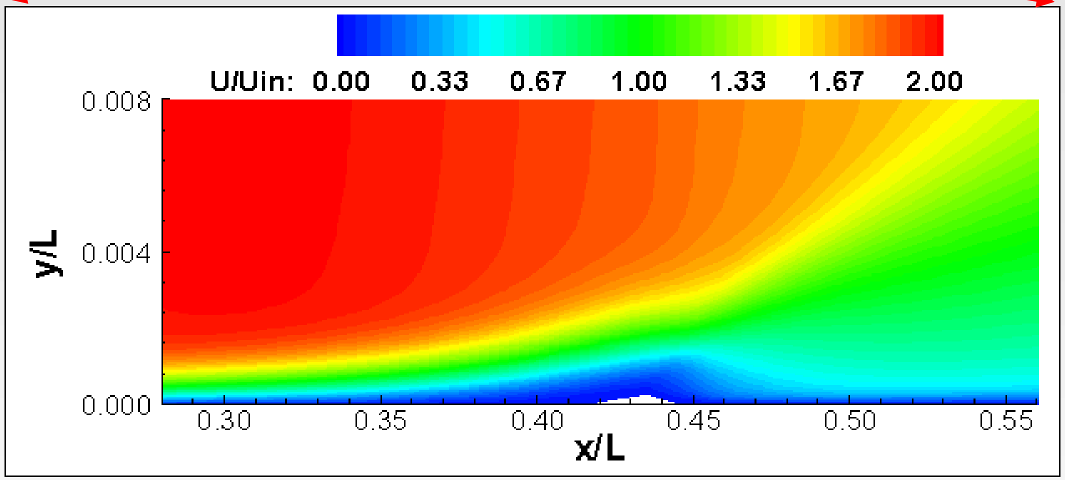


Unsteady results: oscillating inflow conditions

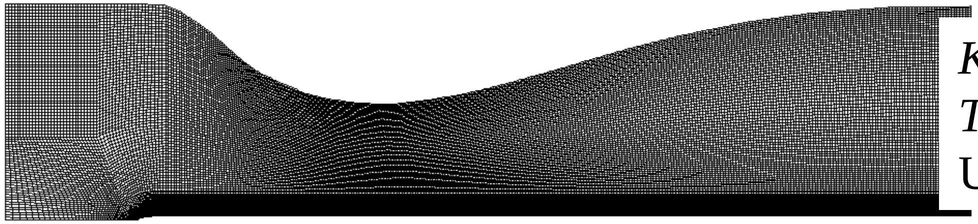
$$U_\infty(t) = \overline{U}_{in}\left[1 + A\sin(2\pi f t)\right]$$

A=13%, f=7Hz

Steady and unsteady calculations of simple flows with rough walls

Calculations for flat plate with pressure gradient (Lou, Hourmouziadis, 2000)

Influence of surface roughness



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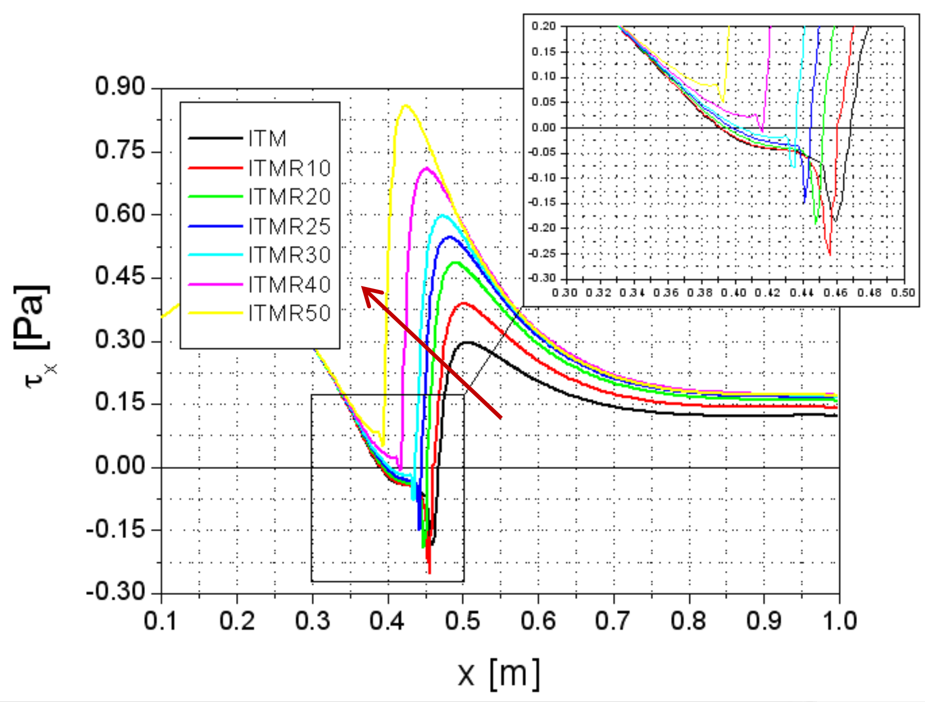
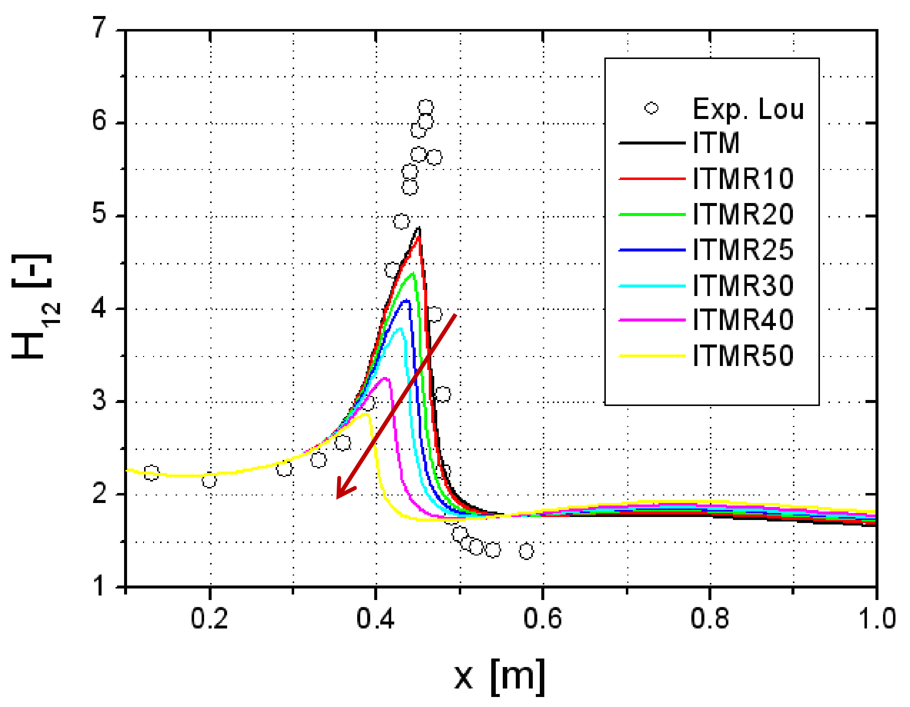
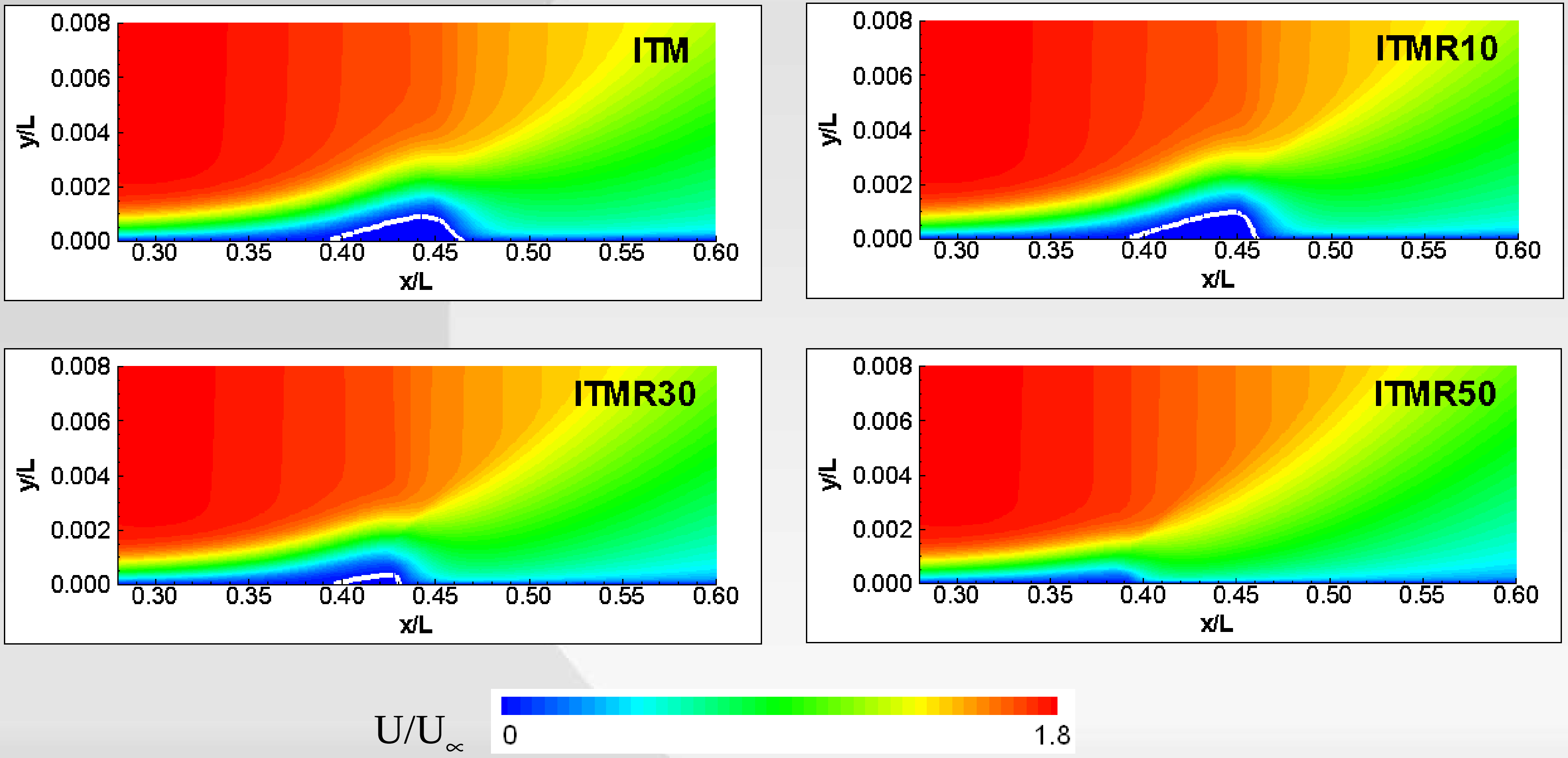




Steady and unsteady calculations of simple flows with rough walls

Calculations for flat plate with pressure gradient (Lou, Hourmouziadis, 2000)

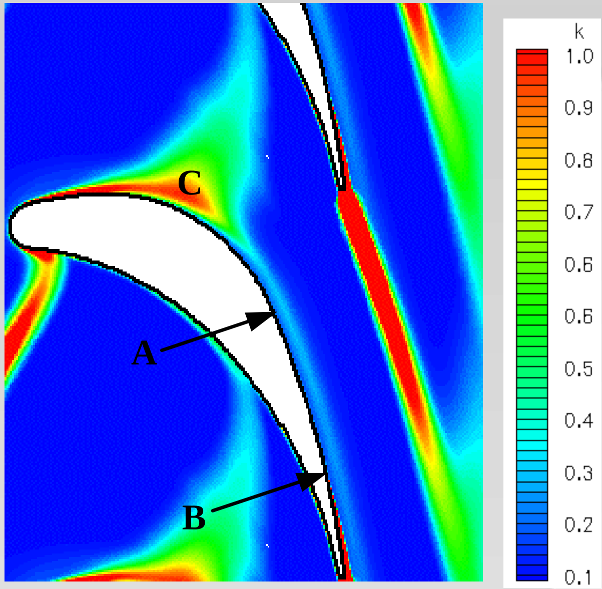
Velocity distributions for chosen surface roughness



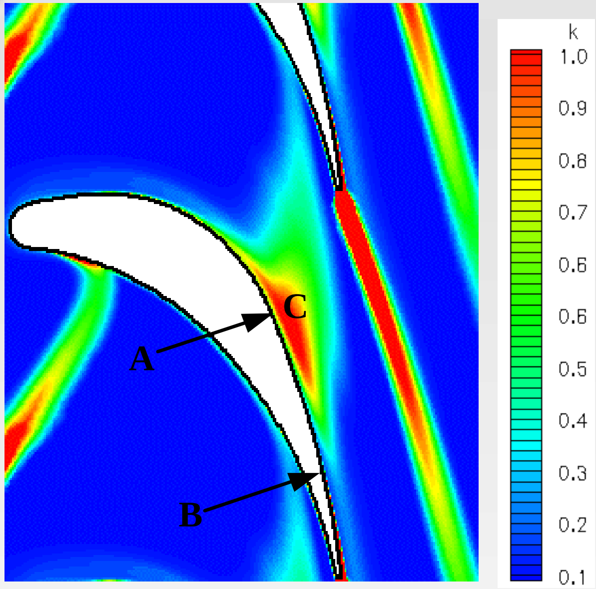
Unsteady calculations of N3-60 blade

Unsteady results: instantaneous solutions $Tu_{in}=0.4\%$ and d=4mm

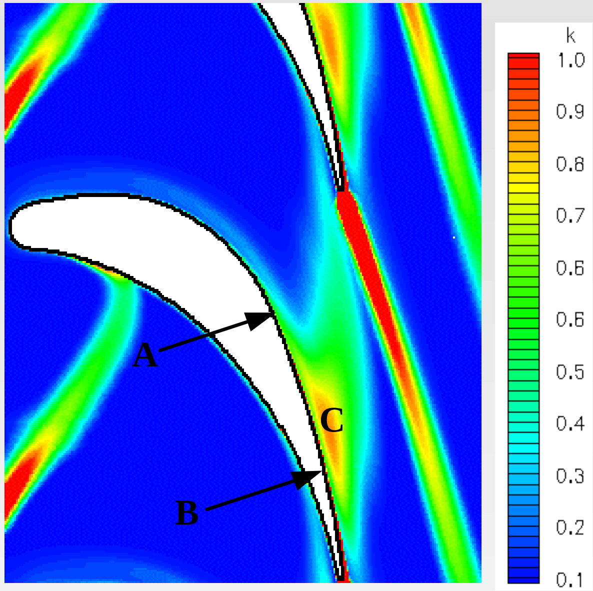
$\tau/T \approx 0.20$



$\tau/T \approx 0.49$



$\tau/T \approx 0.61$



Wake deformation and displacement towards the suction side

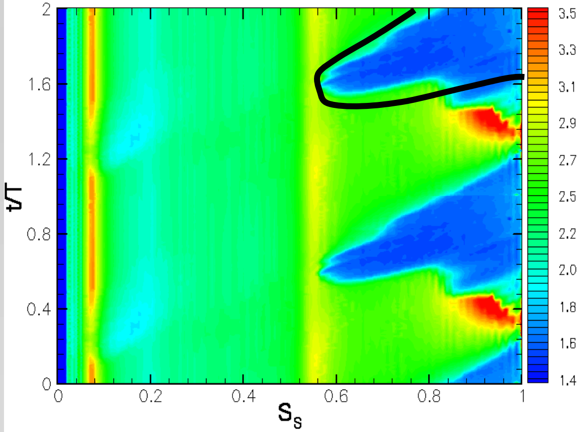
⇩

Difficult task for transition modelling

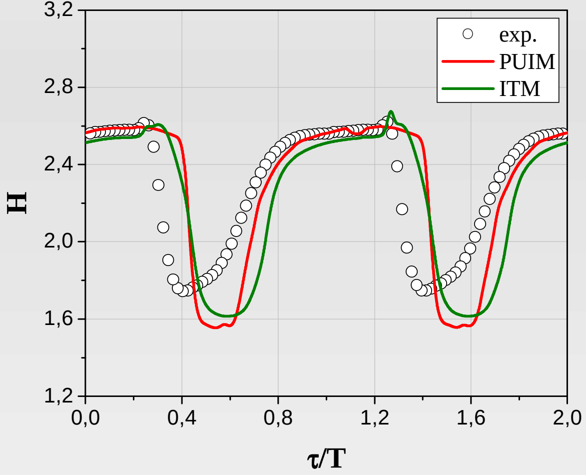
Unsteady calculations of N3-60 blade

Unsteady results: instantaneous solutions Tu_{in}=0.4% and d=4mm

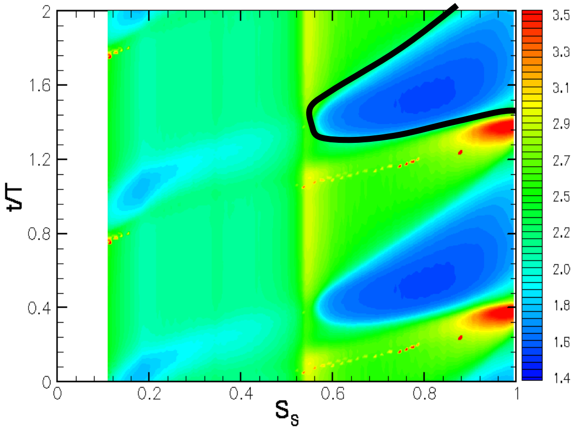
PUIM



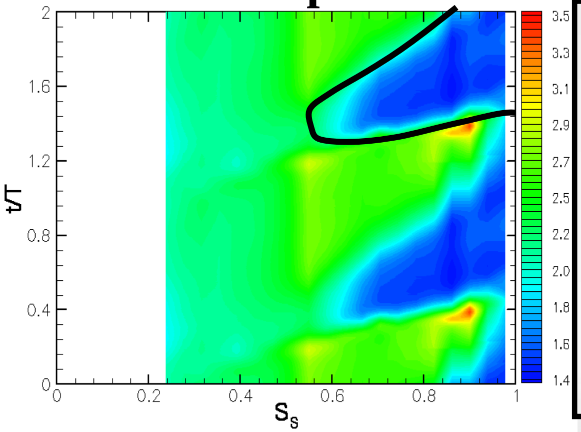
The time traces of H
at the location S_S=0.65



ITM



TUCz Experiment



The same start of transition under the wake

Some differences in the extend of the turbulent wedge

The model indicates transition in separated boundary layer

Concluding remarks

- the ITM procedure with proposed correlations for transition onset and transition length is able to predict the boundary layer development for simply as well as turbine blade test cases

- An approach to calculating roughness effect in the framework of transition model has been presented

- The results of simulations are consistent with experimental data, at least qualitatively

- The methodology needs further tests and evaluations