Transition in a swept-boundary layer subject to surface roughness and free-stream turbulence

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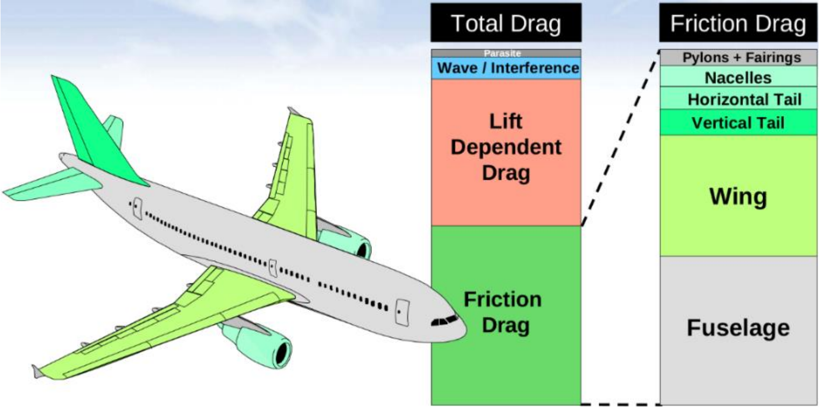
[1] *Linné FLOW Centre, KTH Mechanics*

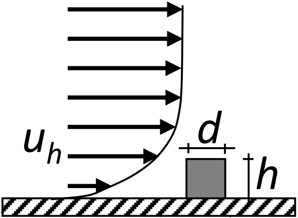
Introduction



D. Hills, Airbus Challange Future Aircraft Technology and Challenges, Flight Physics Center of Competence, Airbus

Introduction

$$Re_{hh} = \frac{U(h)\,h}{\nu}$$



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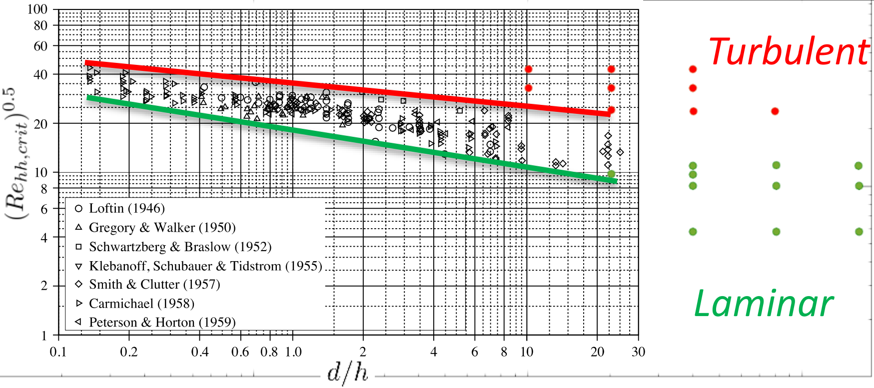
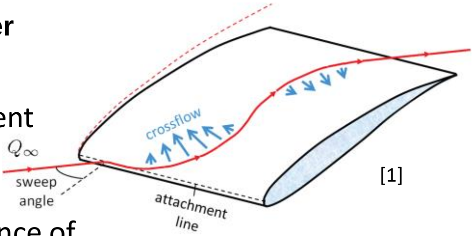


[1] Von Doenhoff, A.E., Braslow, A.L., The effect of distributed surface roughness on laminar flow, Boundary Layer and Flow Control- Its Principles and Application, 657-681 (1961)

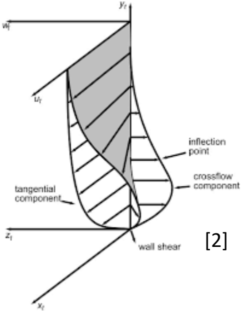
Swept wing boundary layer

- Sweep angle and pressure grandient results in curved streamlines.



- Inside the boundary layer imbalance of centrifugal and pressure forces creates a crossflow.

- The crossflow profile has an inflection point.



[1] D. Tempelmann, Receptivity of crossflow-dominated boundary layers , Ph.D. Thesis, 2011 .

[2] S. Saric *et al.*, Stability nad Transition of Three-Dimensional boundary layers, Annual Review of Fluid Mechanics, 2003

RECEPT Experiment

Main goal: Critical size roughness element.

Parameters:

- Sweep angle = 35°
- Angle of attack = -5°
- Velocity (m/s) = 9, 18, 27
- Height R-E (mm) = 0.2, 0.4, 0.8
- Diameter R-E (mm) = 8, 16, 32
- Turbulence level = 0.03%, 0.3%, 0.8%

[1]

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[1] R. Örlü , N. Tillmark, P. H. Alfredsson, Measured critical size of roughness element, RECEPT project Technical Report TR D1.14, (2015)

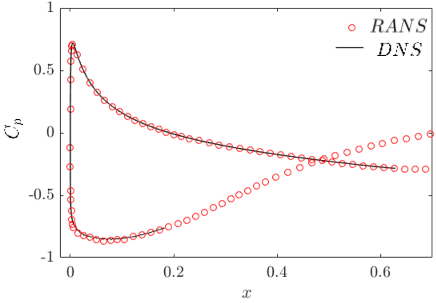
RECEPT Experiment

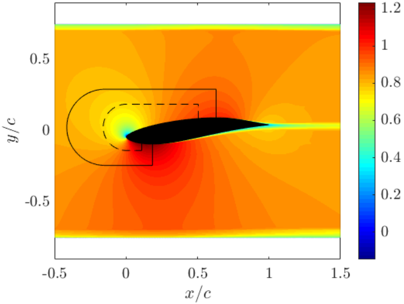
Test cases, roughness elements (R-E) diameters (mm) within the red boarder										
R-E height [μm]	Grid #: / Speed U_{MTL} [m/s]	0 (Tu =0.03%)			1 (Tu =0.3%)			2 (Tu =0.8%)		
200	9	8	16	32	8	16	32			
	18	8	16	32	8	16	32			
	27	8	16	32	8	16	32	8	16	32
400	9	8	16	32	8	16	32	8	16	32
	15								16	
	17	8								
	18	8	16	32	8	16	32	8	16	32
	22		16			16				
	27	8	16	32	8	16	32	8	16	32
800	9	8	16	32	8	16	32			
	18	8	16	32	8	16	32			
	27	8	16	32	8	16	32			
	No observable effect:		Slight effect:		Effect:		Transition:			

[1] R. Örlü , N. Tillmark, P. H. Alfredsson, Measured critical size of roughness element, RECEPT project Technical Report TR D1.14, (2015)

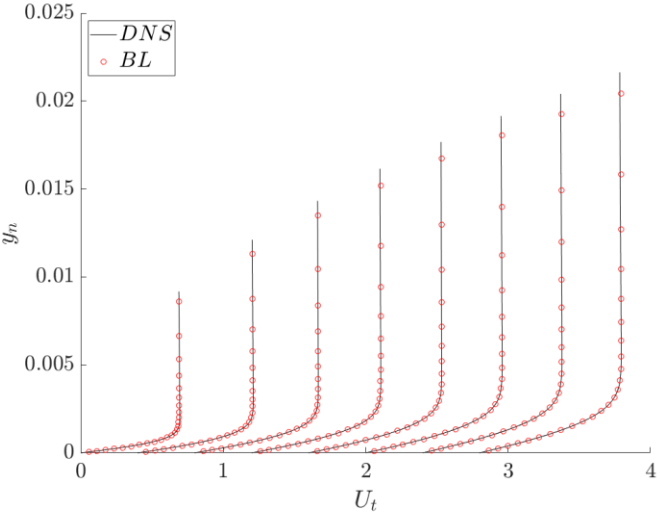
Simulation Setup

1. Reynolds-Averaged Navier-Stokes simulation to get initial and boundary condition for direcet numerical simulations (DNSs)
   - Numerical domain equal to dimensions of the wind tunnel
   - Rans performed with Fluent using $k-\omega$ as turbulence model
   - Transition imposed at x/c = 0.7 on upper surface and x/c = 0.1
2. Two dimensional DNSs to obtain the reference flow field.

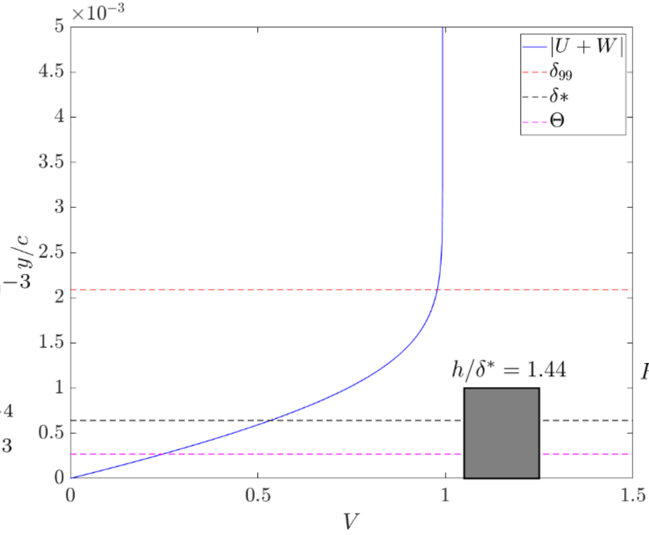




Comparison Boundary layer solver and 2D DNSs



Boundary layer at the roughness element location



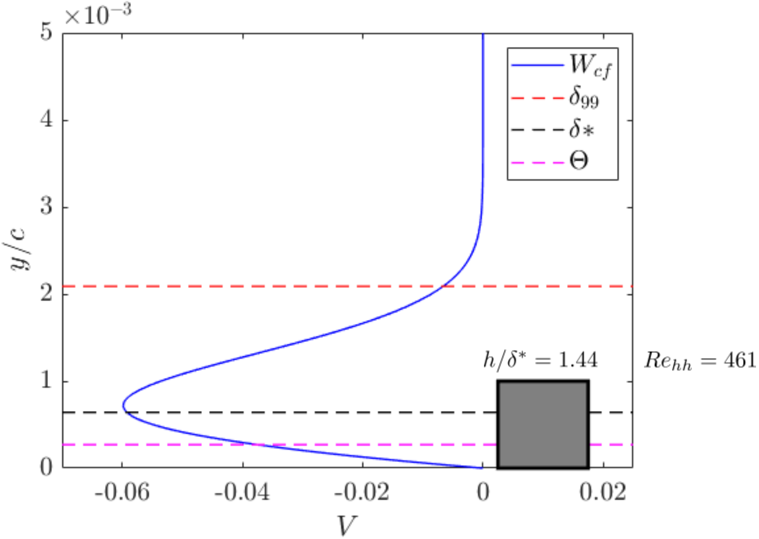
$\delta_{99} = 2.2 \cdot 10^{-3}$

$\delta^* = 6.96 \cdot 10^{-4}$

$\theta = 2.21 \cdot 10^{-3}$

$Re_{hh} = 461$

Boundary layer at the roughness element location



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Results: Direct Numerical Simulations

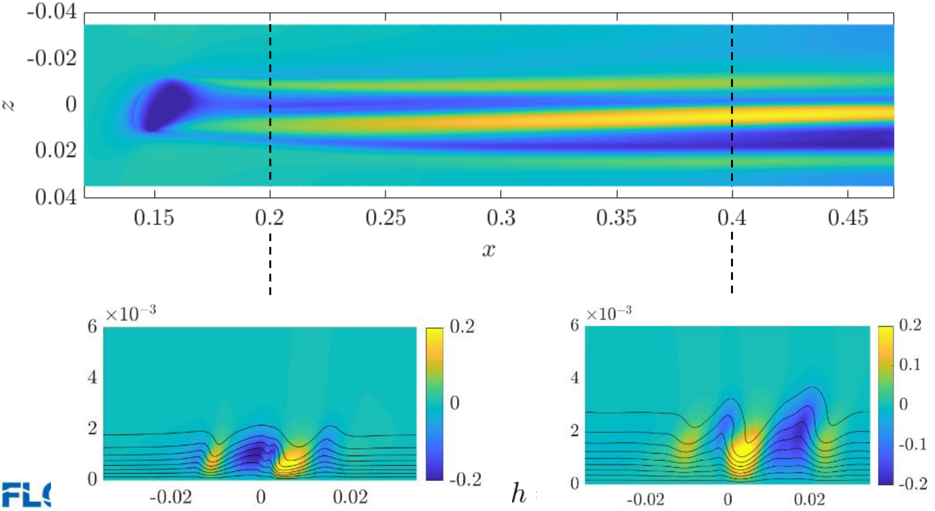
$d/h = 10 \quad h = 1.44\,\delta^*$

$d/h = 20 \quad h = 1.44\,\delta^*$

$d/h = 40 \quad h = 1.44\,\delta^*$

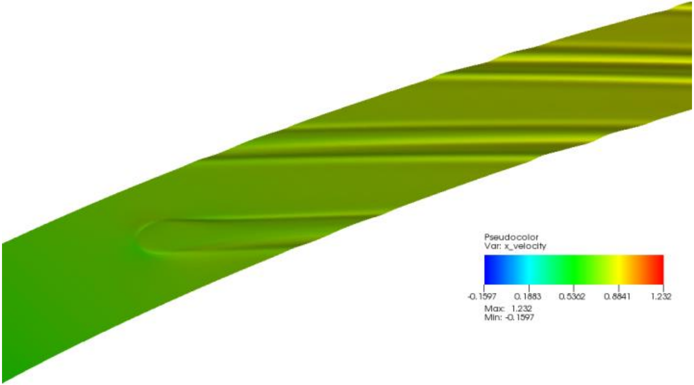
Results: Direct Numerical Simulations

We can observe high and low speed streaks behind the roughness



Results: Direct Numerical Simulations

For the case $d/h = 20 \quad h = 2.0\,\delta^*$ transition is observed



Isosurface of spanwise velocity coloured by x velocity

Results: Direct Numerical Simulations

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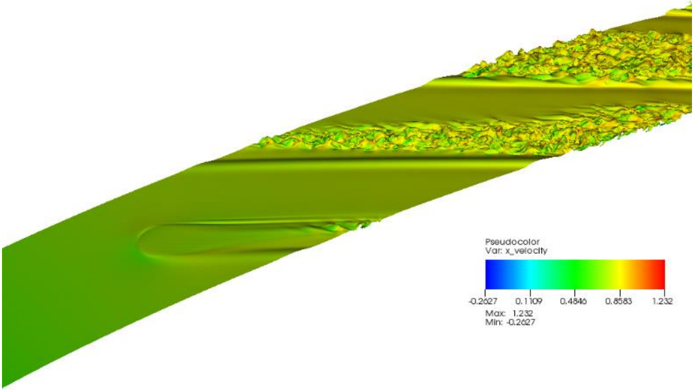

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Results: Direct Numerical Simulations

$$d/h = 20$$
$$h = 1.44\delta^*$$
$$Tu \approx 0.0\%$$

$$d/h = 20$$
$$h = 2.0\delta^*$$
$$Tu \approx 0.0\%$$

Friction coefficient

Impulse-Response

Linear analysis:

Initial condition: Wave-packet disturbance

$$\psi = xy^3 e^{-(x^2+y^2+z^2)} \qquad (u, v, w) = (\psi_y, -\psi_x, 0)$$

placed upstream the RE and alligned with streamline.

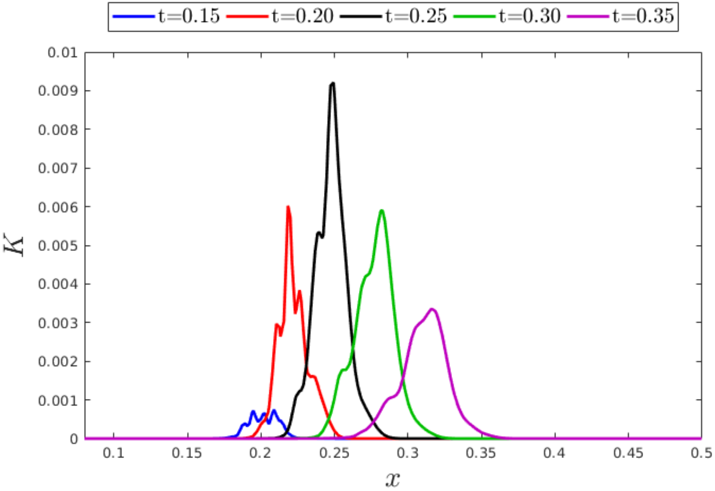
We studied the evolution of the initial disturbance .

Brynjell-Rahkola *et al*, Stability and sensitivity of a cross-flow-dominated Falkner–Skan–Cooke boundary layer with discrete surface roughness, JFM, 2017.

Bech *et al*, Linear and non linear development of localized disturbances in zero and adverse pressure gradient boundary-layers, Phys. Fluids, 1998.

Linear Analysis: Impulse-Response

$$d/h = 20 \quad h = 1.44\,\delta^*$$



Linear Analysis: Impulse-Response

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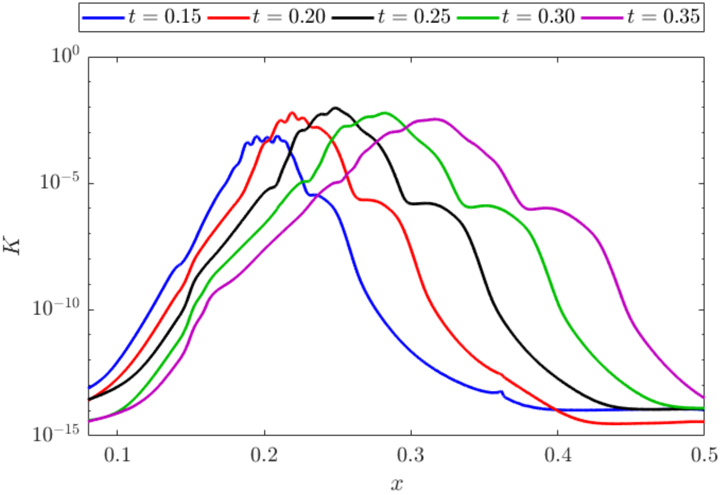

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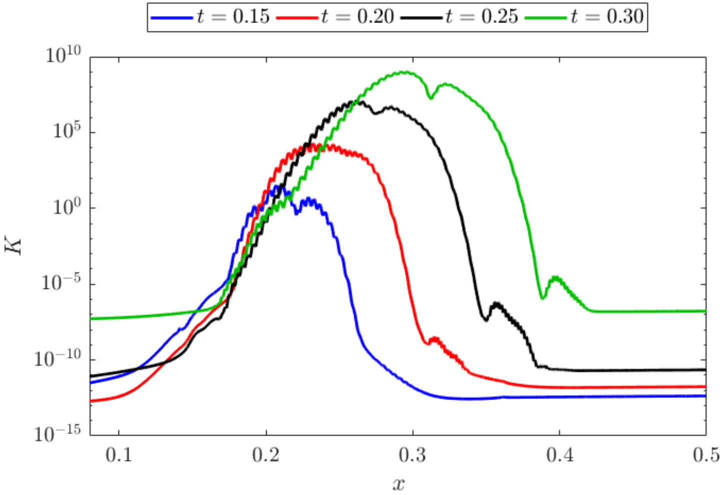

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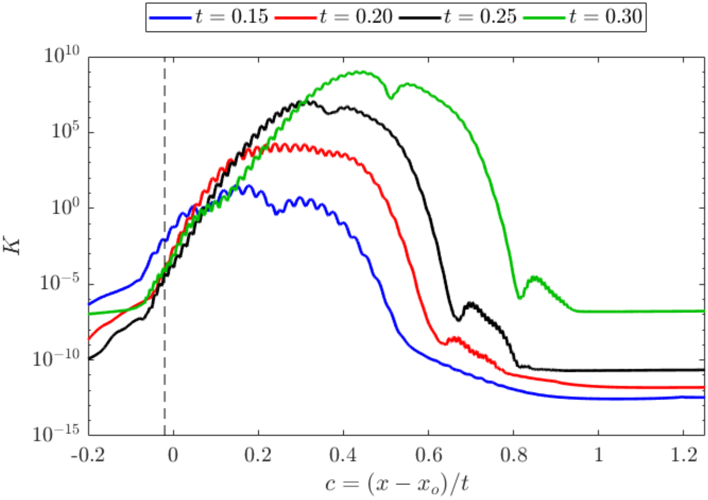
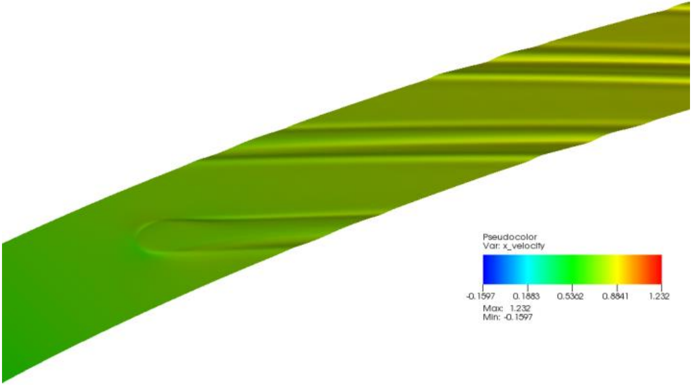


Results: Direct Numerical Simulations

For the case $d/h = 20 \quad h = 1.44\,\delta^* \quad Tu \approx 0.3\%$ transition is observed



Isosurface of spanwise velocity coloured by x velocity

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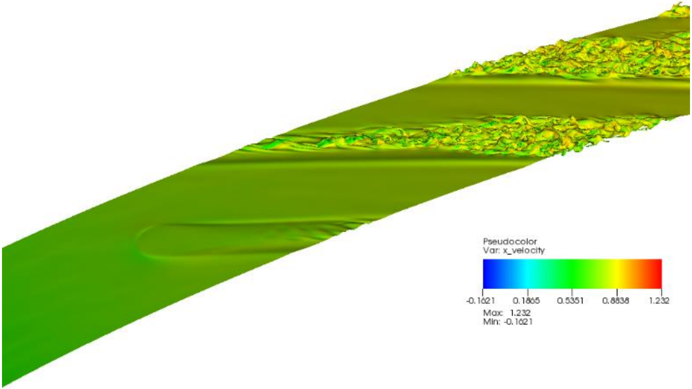

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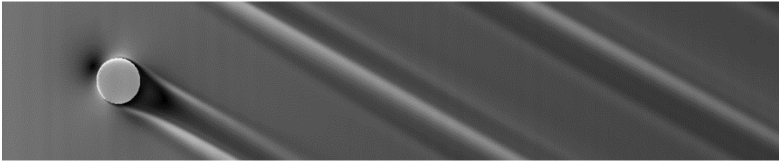

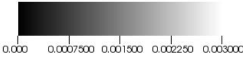

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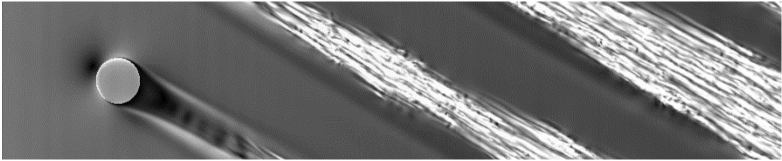

Friction coefficient

Results: Direct Numerical Simulations

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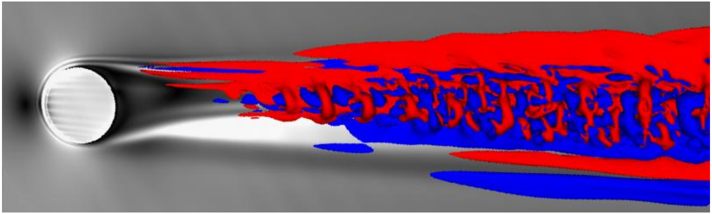

Isosurface of negative (blue) and positive (red) streamwise velocity.

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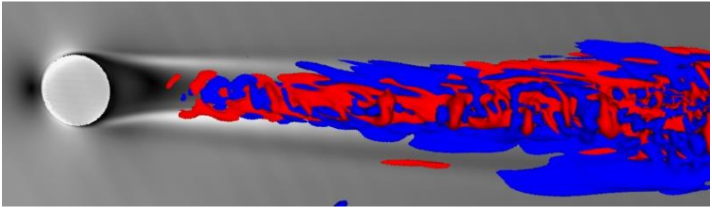

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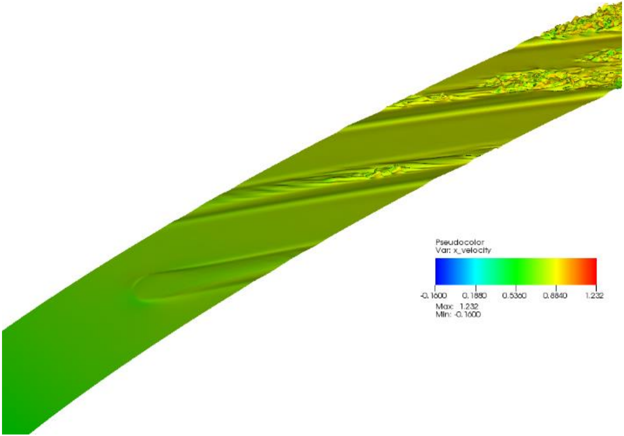
Results: Direct Numerical Simulations

$$d/h = 20, \quad h = 1.44\delta^*, \; Tu \approx 0.03\%$$



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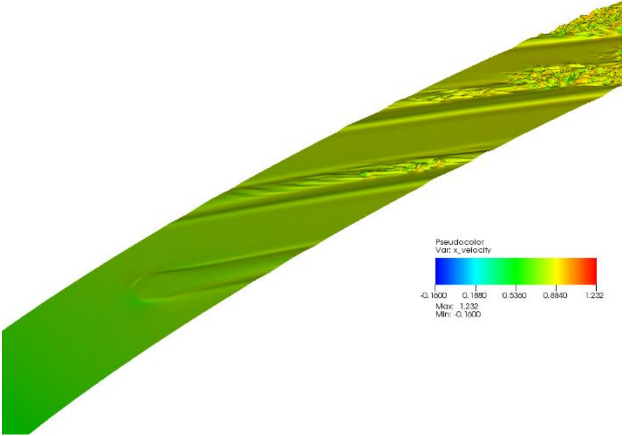

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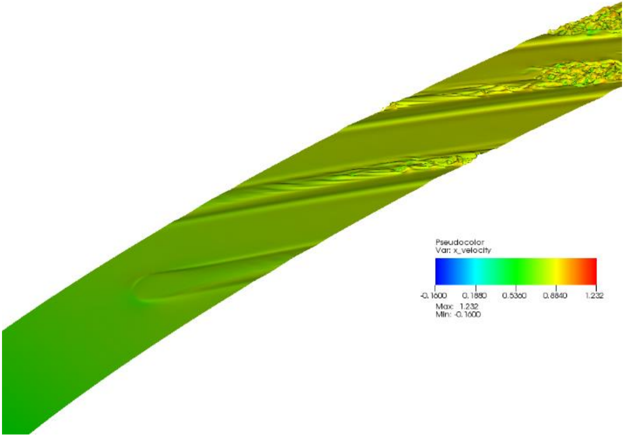

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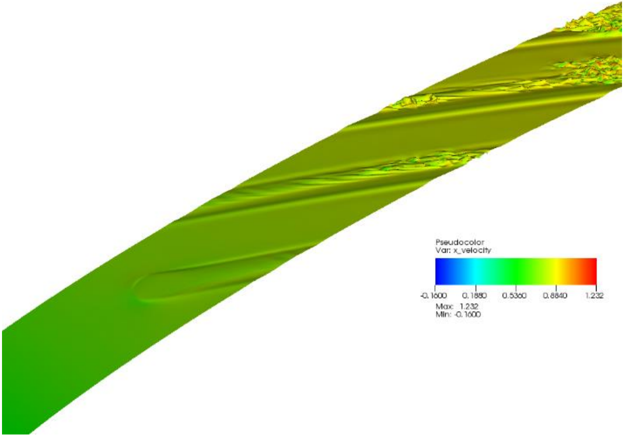

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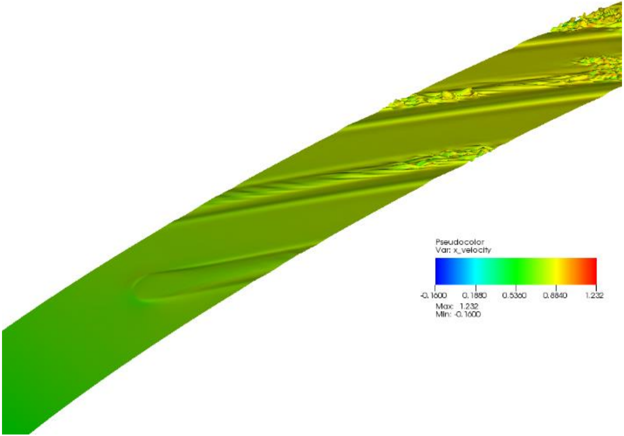

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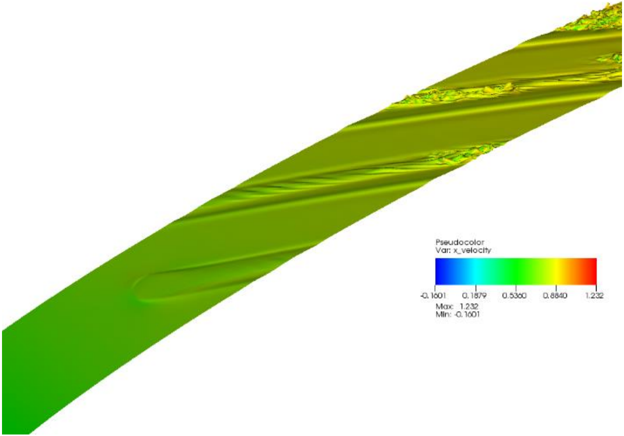

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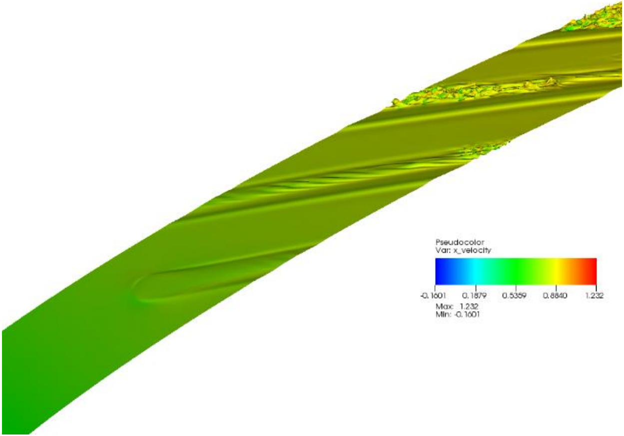

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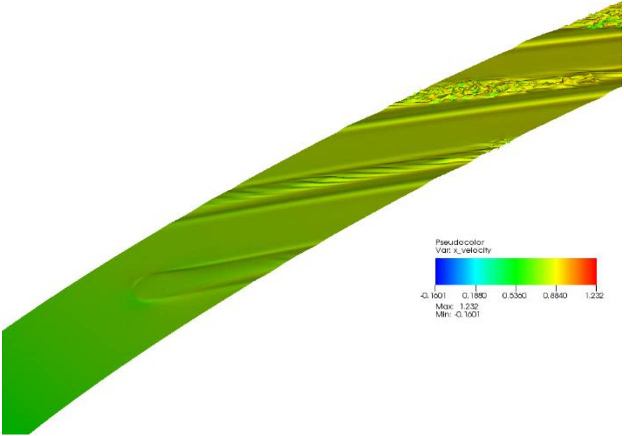

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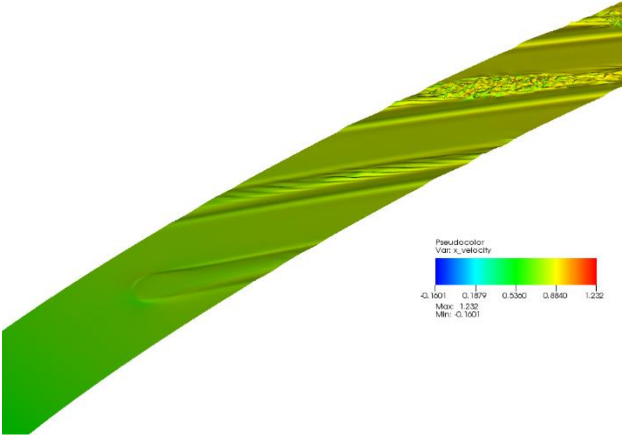

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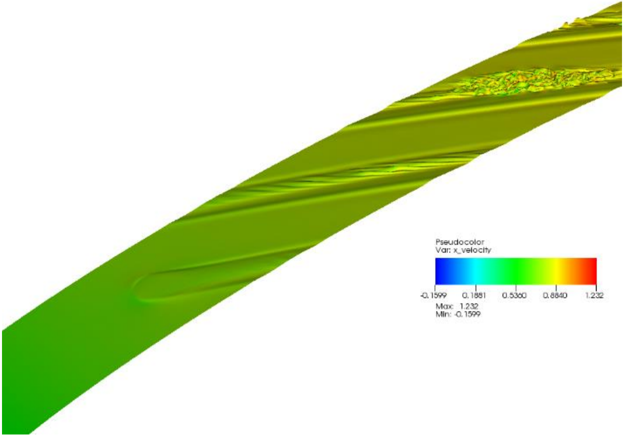

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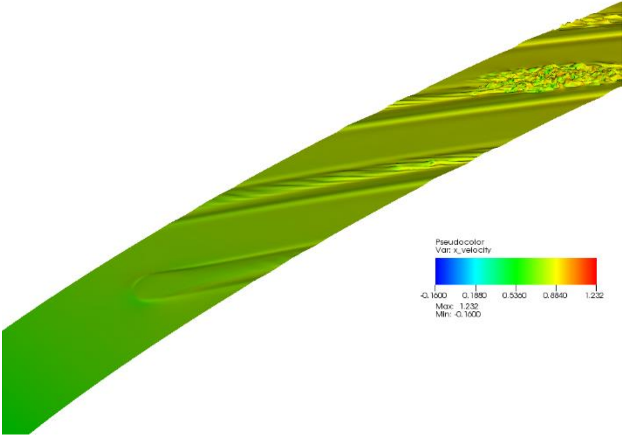

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FLOW

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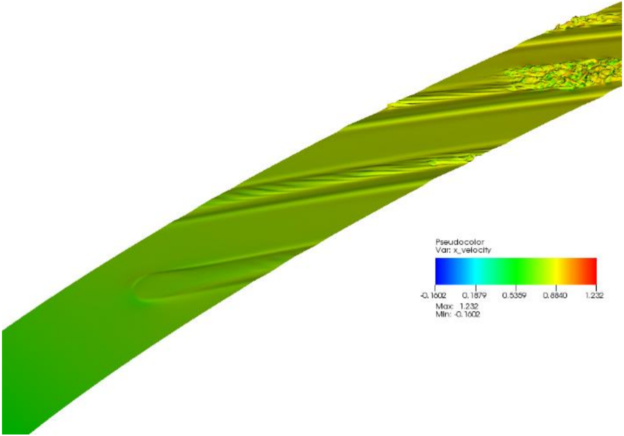

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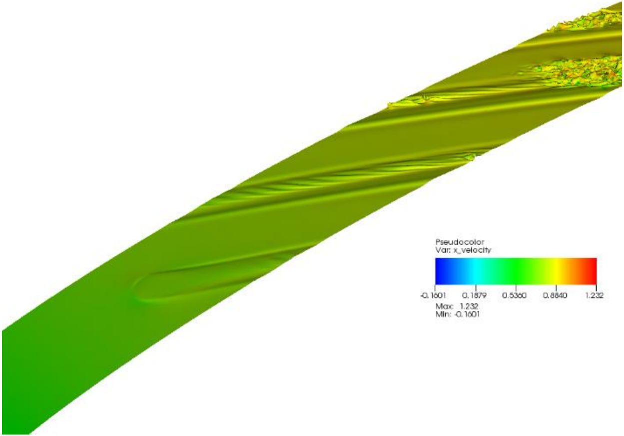

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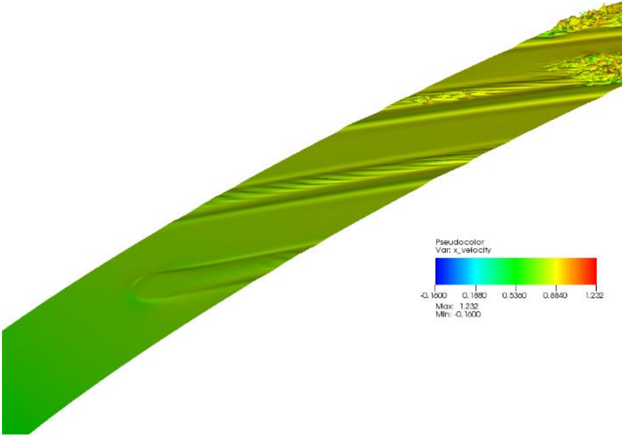

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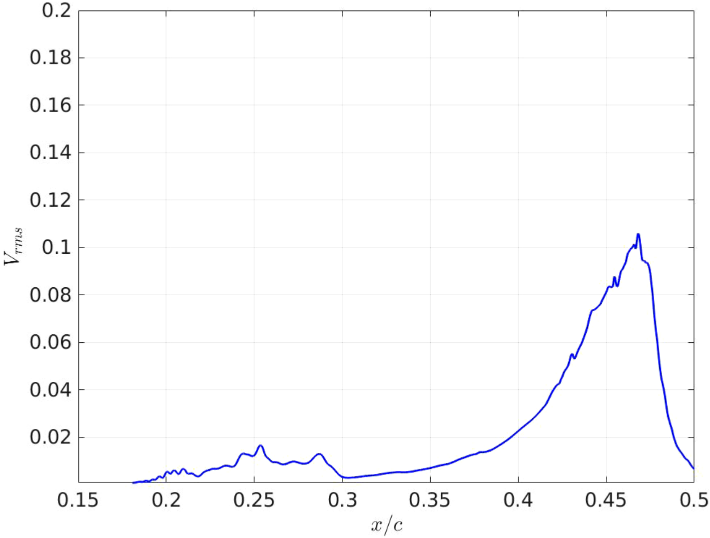


Conclusions

For $h = 1.44\delta^* \; (Re_{hh} = 461)$ we can observe different scenario depending on the level of disturbance :

For $Tu \approx 0\%$ a steady solution is found for every aspect ratio investigated.

For $Tu \approx 0.03\%$ disturbances grows traveling downstream and forms turbulent spots.

For $Tu \approx 0.3\%$ transition take places in the low speed region behind the roughness.

For $h = 2.0\delta^* \; (Re_{hh} = 712)$ transition take place without introducing any disturbance.

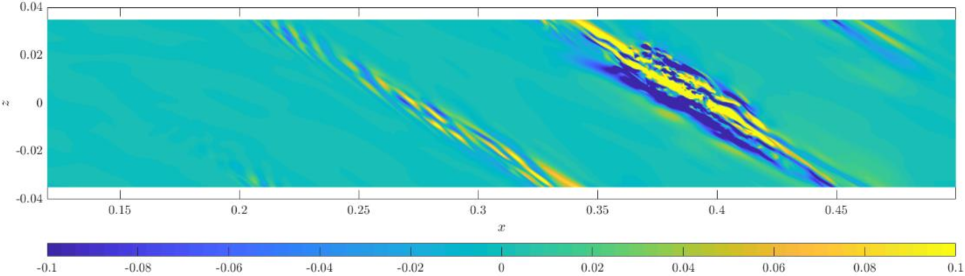
Thank you for your attention.

Any questions?

Conclusions

- For $h = 1.44\delta^* \; (0.8\,mm)$ steady solutions are obtained for all diameters.
- Impulse response analysis showed that the disturbance weakly grows up to $x/c = 0.1$ downstream the roughness and that the disturbance is adavected dowstream.
- For $h = 2\delta^*$ we can observe transition without introducing any other disturbance.
- Transition take place for $h = 1.44\delta^*$ when a we introduce a free stream turbulence $Tu \approx 0.3\%$
- When we consider a turbulence level $Tu \approx 0.03\%$ turbulent spots are generated and then advected downstream
- For both turbulence levels of free stream turbulence the results are consistent with the observation of the experiment

Results: Direct Numerical Simulations



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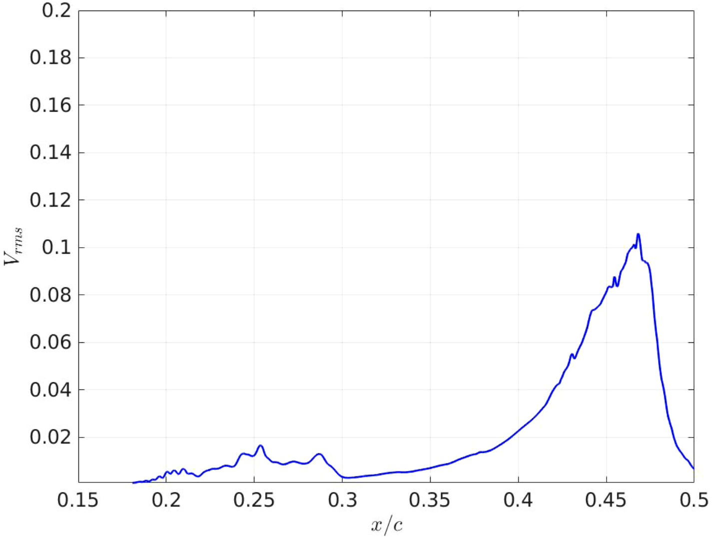

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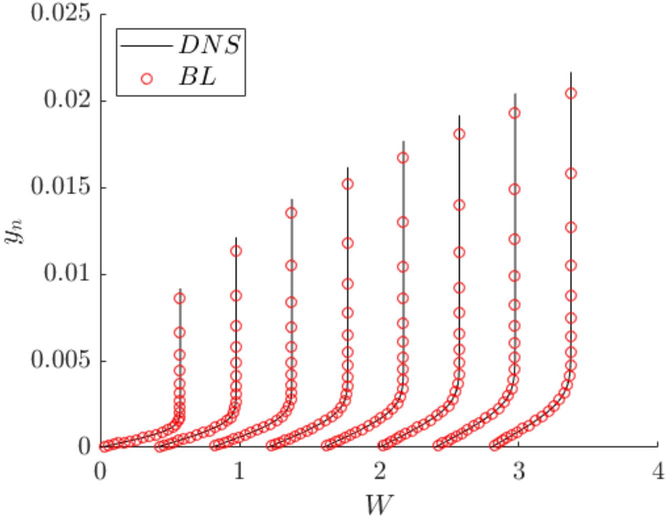
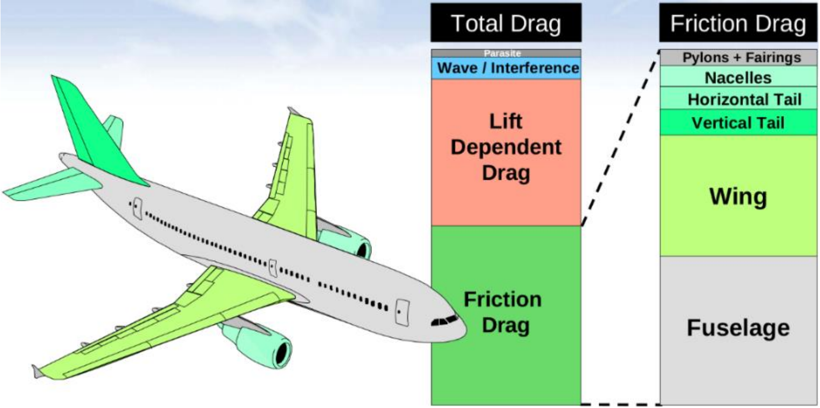


Introduction



D. Hills, Airbus Challange Future Aircraft Technology and Challenges, Flight Physics Center of Competence, Airbus

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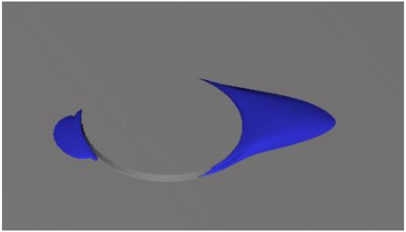
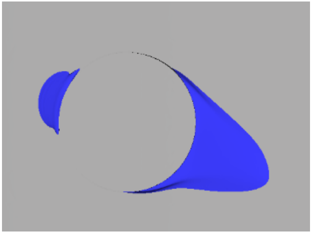
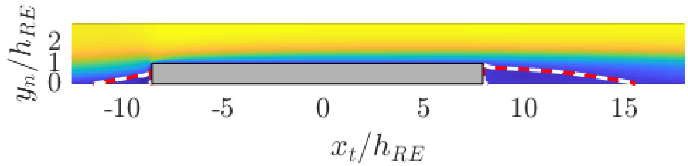
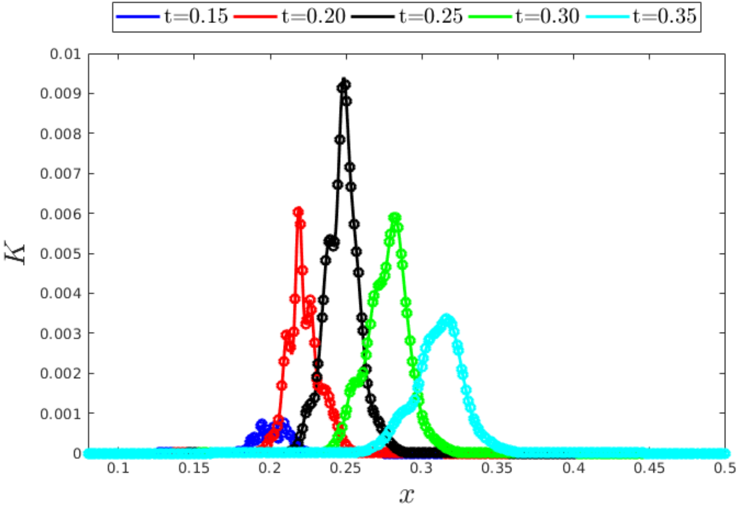




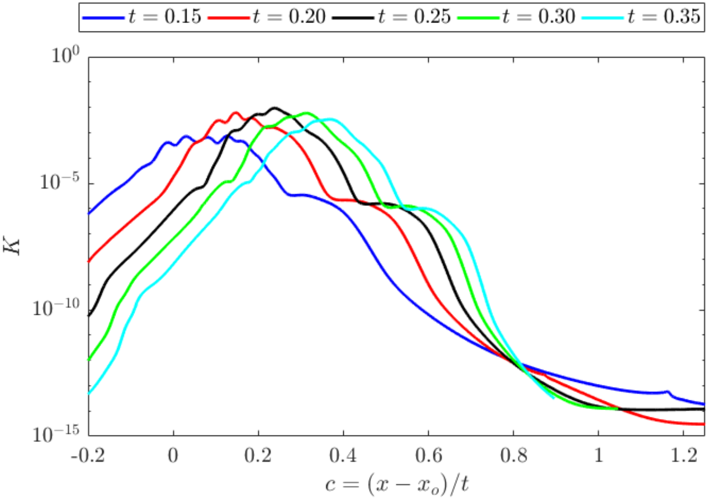


Linear Analysis: Impulse-Response



Linear Analysis: Impulse-Response

$$\phi = 16\,mm, \quad h = 1.44\delta^*$$



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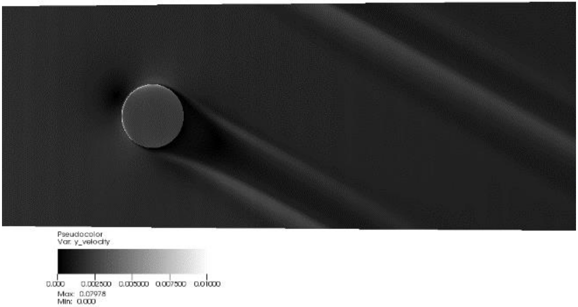
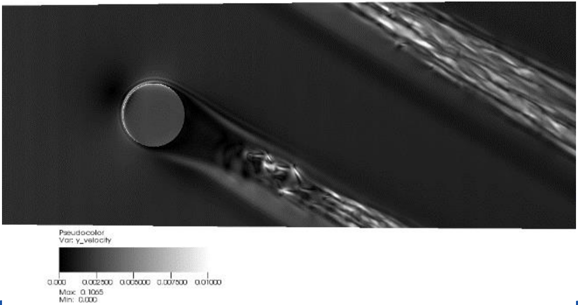
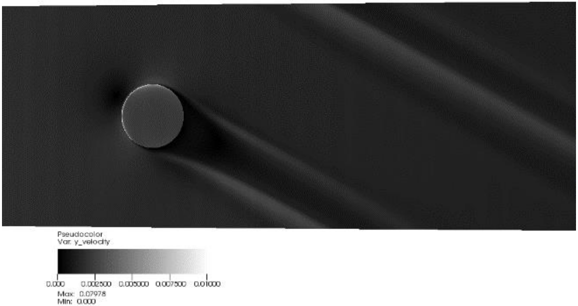


$$d/h = 20$$
$$h = 2.0\delta^*$$
$$Tu \approx 0.0\%$$

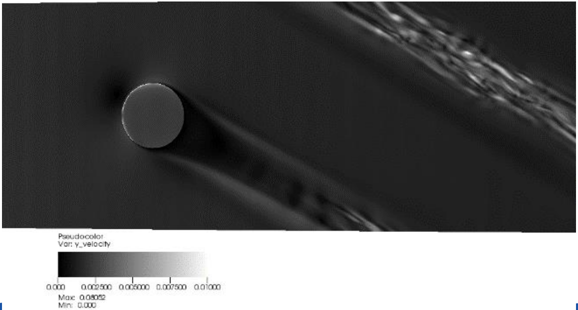


Results: Direct Numerical Simulations

$$d/h = 20$$
$$h = 1.44\delta^*$$
$$Tu \approx 0.0\%$$



$$d/h = 20$$
$$h = 1.44\delta^*$$
$$Tu \approx 0.3\%$$



Results: Direct Numerical Simulations

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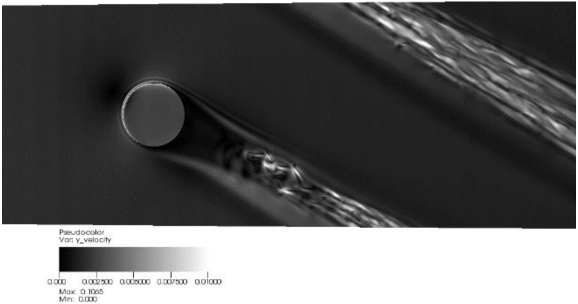

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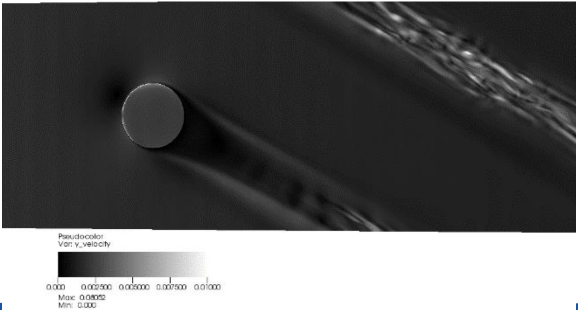
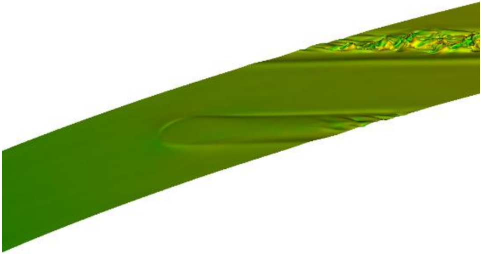
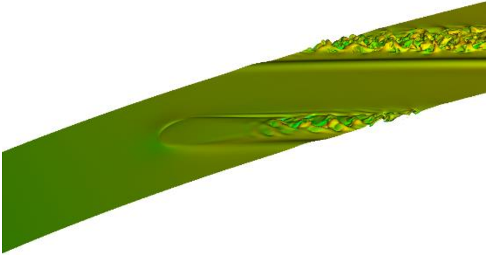


Results: Direct Numerical Simulations



$$d/h = 20, \quad h = 1.44\delta^*$$
$$Tu \approx 0.3\%$$



$$d/h = 20 \quad h = 2\delta^*$$

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- Von Doenhoff, A.E., Braslow, A.L., The effect of distributed surface roughness on laminar flow, Boundary Layer and Flow Control- Its Principles and Application, 657-681 (1961)

- Loiseau, J., Robinet, J., Cherubini, S., Leriche, E., Investigation of the roughness-induced transition: global stability analyses and direct numerical simulations, J. Fluid Mech., 760, 175-211 (2014)

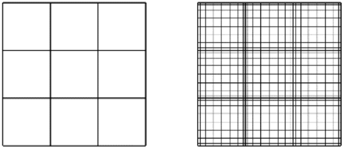
- Bucci, M., Puckert, D., Andriano, C., Loiseau, J., Cherubini, S., Robinet, J., & Rist, U. Roughness-induced transition by quasi-resonance of a varicose global mode. Journal of Fluid Mechanics, 836, 167-191 (2018)

Nek5000

Numerical domain decomposed in hexahedral elements

Variables expressed in terms of Lagrange interpolants on the Gauss-Lobatto-Legendre quadrature points.

$$u(\mathbf{x}) = \sum_{i=1}^{n} \hat{u}_i \phi_i(\mathbf{x})$$



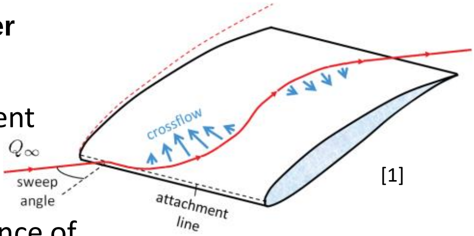
Continuity enforced at the boundaries of each element

N points used for velocity, N-2 for pressure to avoid spurious modes

Third-order implicit discretization in time for viscous terms and third-order explicit for the non-linear terms

Swept wing boundary layer

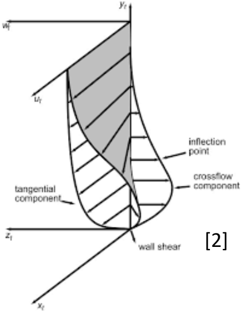
- Sweep angle and pressure grandient results in curved streamlines.



[1]

- Inside the boundary layer imbalance of centrifugal and pressure forces creates a crossflow.

- The crossflow profile has an inflection point.



[2]

[1] D. Tempelmann, Receptivity of crossflow-dominated boundary layers , Ph.D. Thesis, 2011 .

[2] S. Saric *et al.*, Stability nad Transition of Three-Dimensional boundary layers, Annual Review of Fluid Mechanics, 2003

Nek5000 [1]

Incompressible Navier-Stokes solver

$$\frac{\partial u_i}{\partial x_i} = 0$$

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{\partial p_i}{\partial x_i} + \frac{1}{Re}\frac{\partial^2 u_i}{\partial x_i^2} + f_i$$

The equations are solved using a Spectral Element Menthod [2]

Complex geometries and high order method

Highly scalable code [3]

[1] Fisher *et al.* Nek5000 web page. http://nek5000.mcs.anl.gov, 2008
[2] Patera, A.T. "A spectral element method for fluid dynamics : laminar flow in a channel expansion." J. Comput. Phys. 54:468–488, 1984
[3] Offermans *et al.*, On the strong scaling of the spectral element solver Nek5000 on petascale systems. Proceedings of the EASC '16 conference, 2016

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- Von Doenhoff, A.E., Braslow, A.L., The effect of distributed surface roughness on laminar flow, Boundary Layer and Flow Control- Its Principles and Application, 657-681 (1961)

- Kurz, H., & Kloker, M. Mechanisms of flow tripping by discrete roughness elements in a swept-wing boundary layer. Journal of Fluid Mechanics, 796, 158-194, (2016).

- Brynjell-Rahkola, M., Shahriari, N., Schlatter, P., Hanifi, A., & Henningson, D. Stability and sensitivity of a cross-flow-dominated Falkner–Skan–Cooke boundary layer with discrete surface roughness. Journal of Fluid Mechanics, 826, 830-850, (2017).

Simulation Setup

1. Reynolds-Averaged Navier-Stokes simulation to get initial and boundary condition for direcet numerical simulations (DNSs)
    - Numerical domain equal to dimensions of the wind tunnel
    - Rans performed with Fluent using $k-\omega$ as turbulence model
    - Transition imposed at x/c = 0.7 on upper surface and x/c = 0.1

2. Two dimensional DNSs to obtain the reference flow field.

- v:

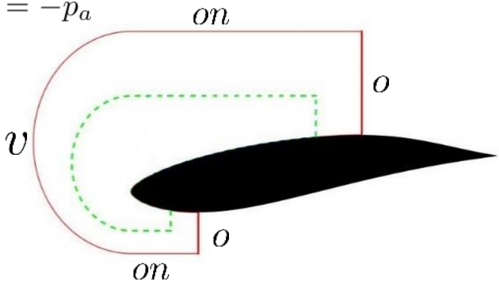
$$u = u_{sim}$$
$$v = v_{sim}$$
$$w = w_{sim}$$

- on:

$$u = u_{sim}$$
$$\frac{1}{Re}\frac{\partial v}{\partial y} - p = -p_a$$
$$w = w_{sim}$$

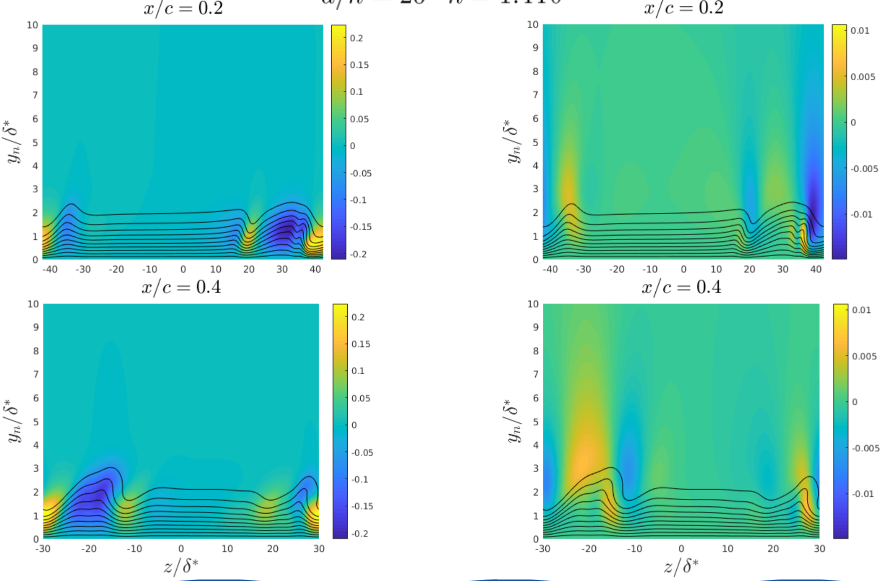
- o:

$$\frac{1}{Re}\frac{\partial u}{\partial x} - p = -p_a$$
$$\frac{\partial v}{\partial x} = 0$$
$$\frac{\partial w}{\partial x} = 0$$



Results: Direct Numerical Simulations

$d/h = 20 \quad h = 1.44\,\delta^*$



Results: Direct Numerical Simulations

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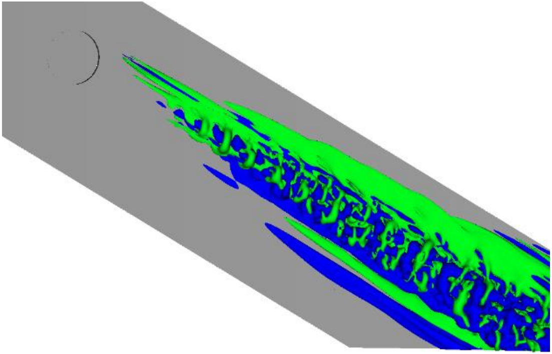
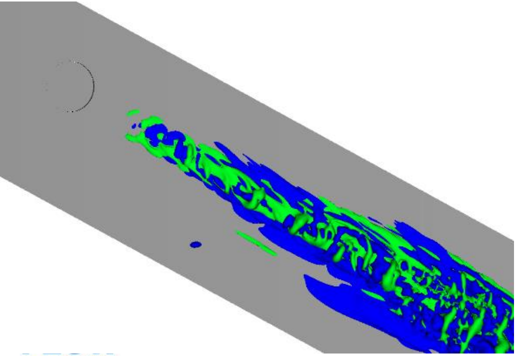
$Tu \approx 0.0\%$

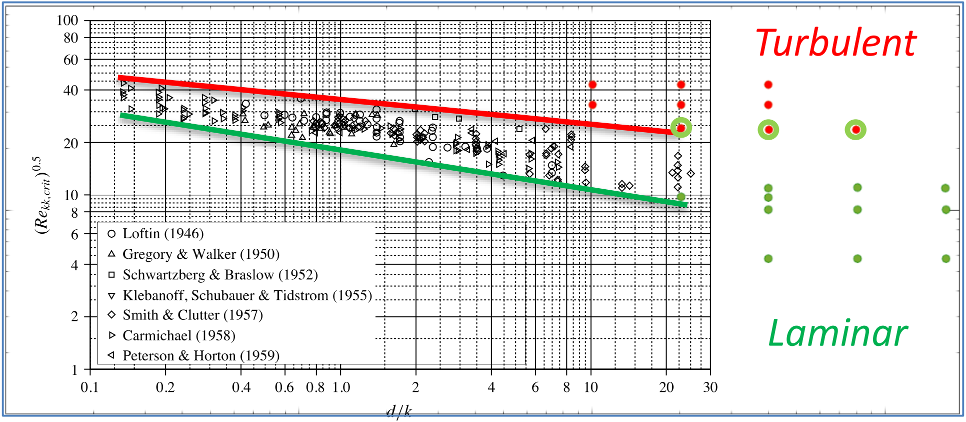




$d/h = 20$

$h = 1.44\delta^*$

$Tu \approx 0.3\%$

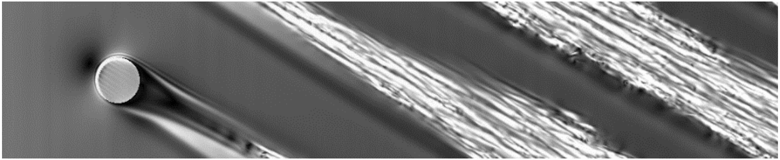


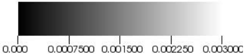
Turbulent
Laminar
$(Re_{kk,crit})^{0.5}$
d/k
Loftin (1946)
Gregory & Walker (1950)
Schwartzberg & Braslow (1952)
Klebanoff, Schubauer & Tidstrom (1955)
Smith & Clutter (1957)
Carmichael (1958)
Peterson & Horton (1959)

FLOW

Results: Direct Numerical Simulations

$$d/h = 20$$
$$h = 1.44\delta^*$$
$$Tu \approx 0.0\%$$





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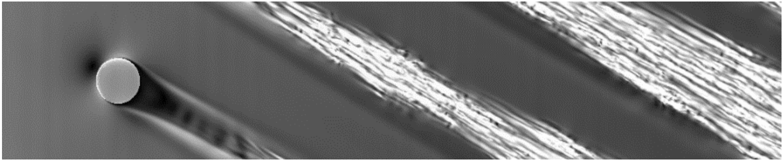
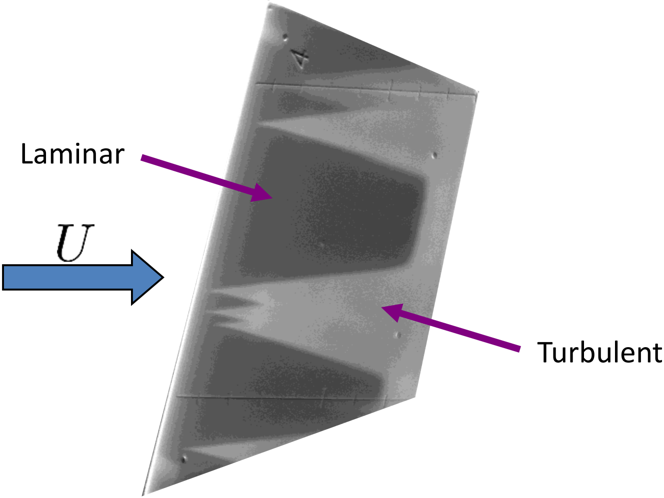


FLOW

Introduction



Roughness induced transition