Direct Numerical Simulations of Transitional Flow in Turbomachinery

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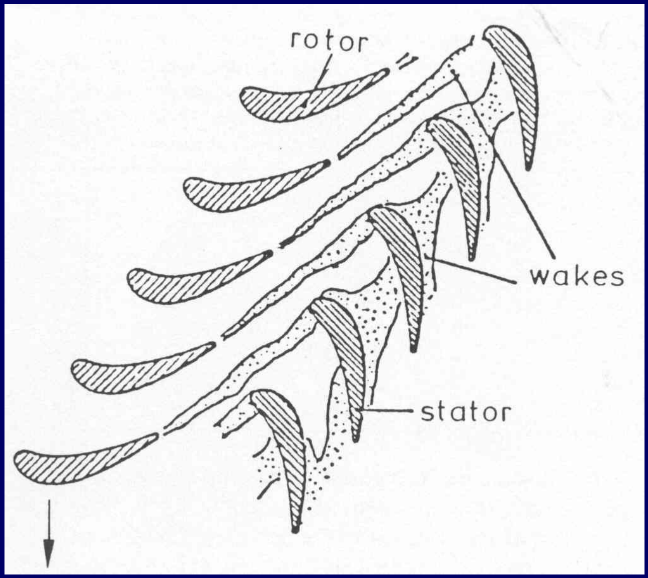
Unsteady transitional flow over turbine blades



- Periodic unsteadiness caused by rotor-stator interaction
- Relatively low Reynolds numbers
- Both phenomena directly affect blade boundary-layer transition, tendency to separation, heat transfer and losses

Overview of the Calculations

- Flow very complex and difficult to predict with RANS
- Phenomena need to be understood and reliable data need to be generated for improving transition models
- Because of low Re - this is possible with DNS – and calculations carried out in the DFG project are summarized here:

  (i) Flat plate boundary layer separation

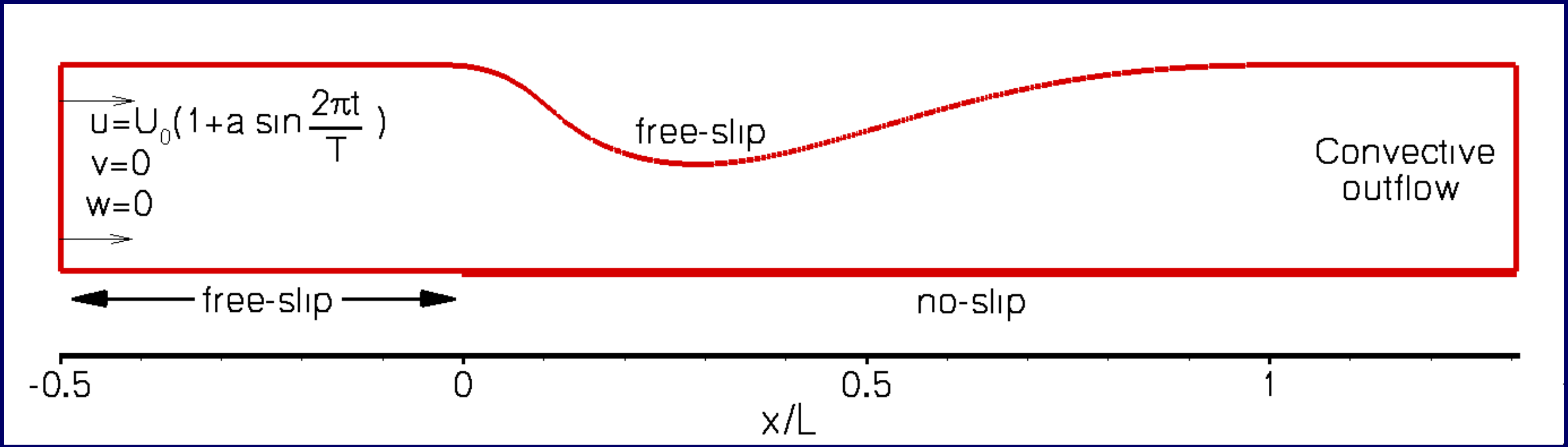
    1. Oscillating inflow
    2. Free-stream fluctuations

  (ii) Flow around turbine blades

    1. Separating flow past T106 blade
    2. Flow past and heat transfer to MTU blade

Flat plate boundary layer separation

Geometry

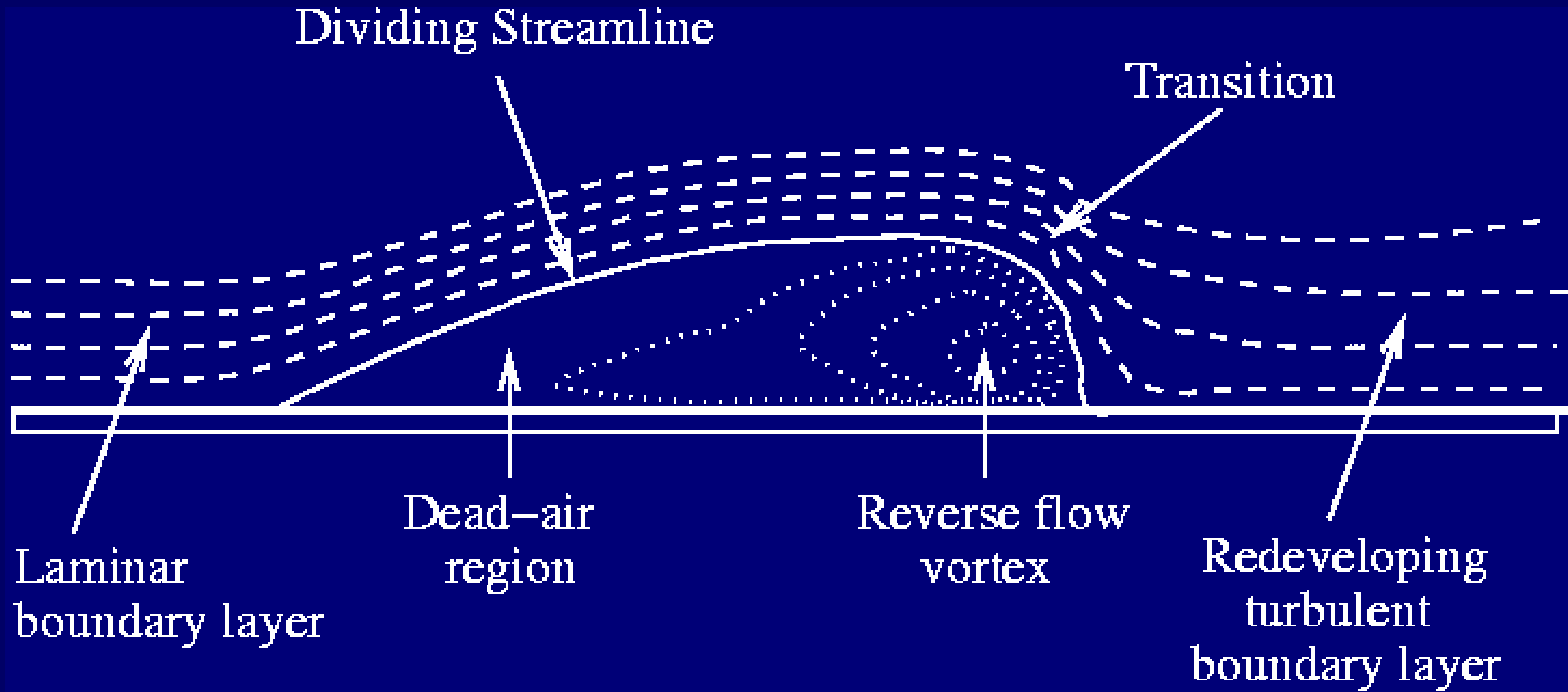


Periodic boundary conditions in spanwise direction

Reynolds number, Re=60 000, is based on the mean inflow velocity U_0 and the length-scale L (see figure).

At the inlet either a streamwise oscillation or free-stream disturbances

Structure of a Laminar Separation Bubble



Separating flow affected by inflow oscillations

Main Flow Features

- Without oscillating inflow, the shape of the upper wall generates an adverse pressure gradient for $x / L > 0.3$
- The adverse pressure gradient is alternately enhanced and decreased by the oscillating inflow
- As a result the location of separation moves back and forth
- Every period a new separation bubble is formed that moves downstream some time after the inflow accelerates
- Along the flat plate a pattern of turbulent patches, separated by becalmed flow, can be observed

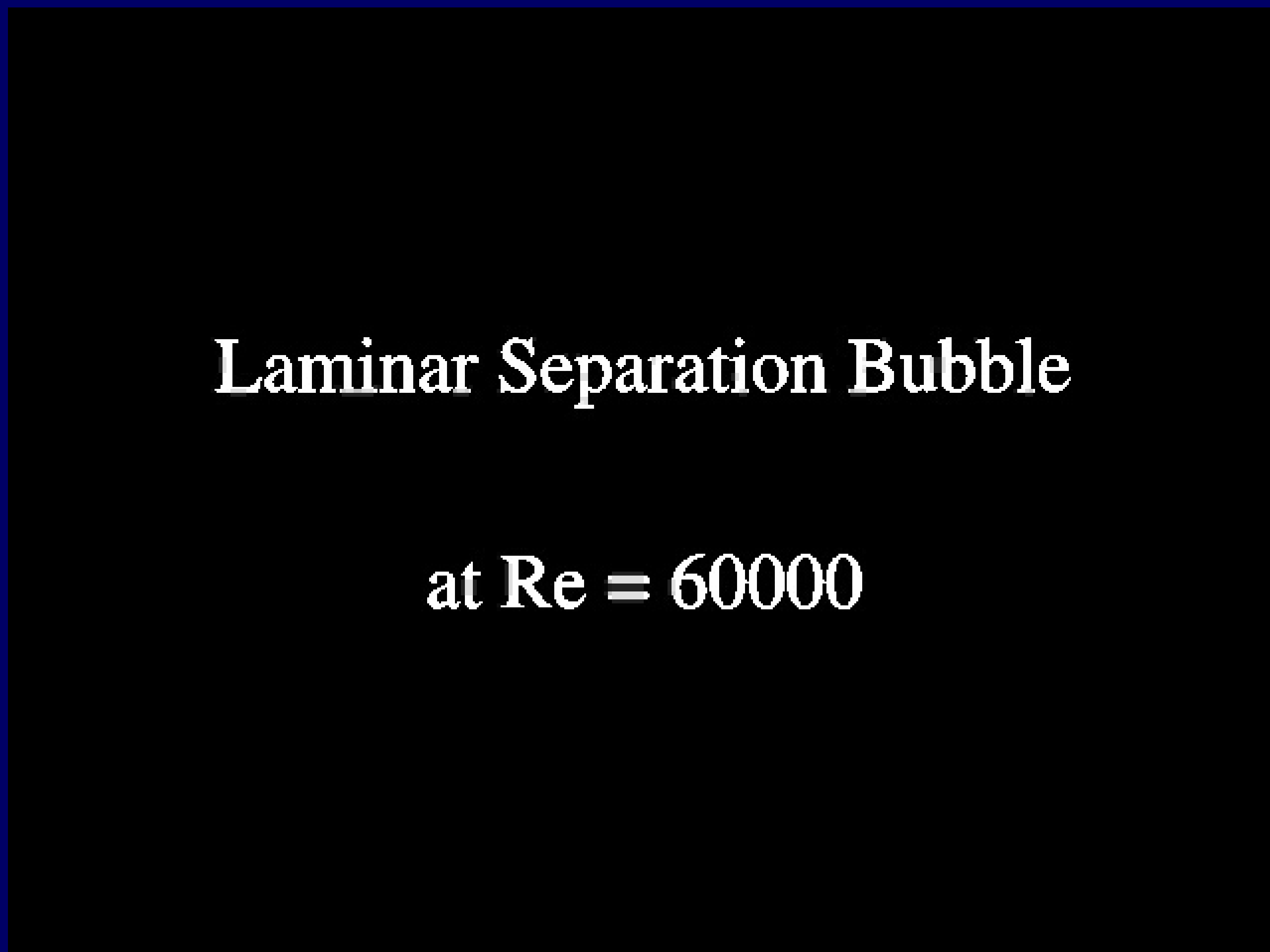
Separating flow affected by inflow oscillations

Simulations performed

Simulation	Grid	Size span	Amplitude	Period
O1	*966x 226 x 128*	*0.12L*	*0.20*	*0.61*
O2	*1286x 310 x 128*	*0.08L*	*0.10*	*0.30*
O3	*966x 226 x 128*	*0.12L*	*0.05*	*0.30*

Separating flow affected by inflow oscillations (3D film)

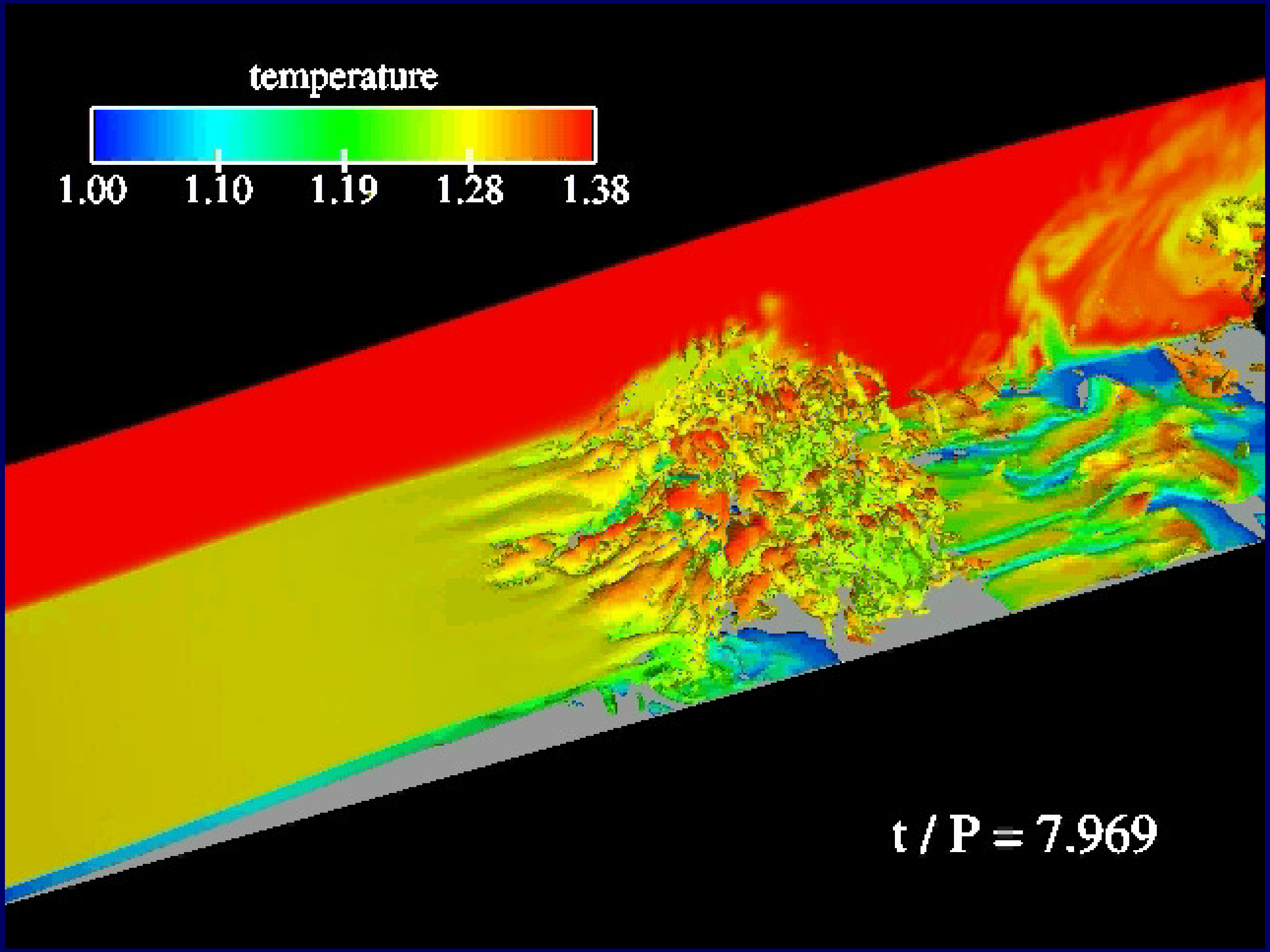
Simulation O1



Iso-surface of the spanwise vorticity at $\omega_z = -150$

Separating flow affected by inflow oscillations (3D film)

Simulation O3



Iso-surface of the spanwise vorticity at $\omega_z = -150$

DNS of a separating flow affected by inflow oscillations

Summary of Results

- The basic instability is a (2D inviscid) Kelvin-Helmholtz (KH) instability of the separated boundary layer.
- This instability is triggered by the inflow oscillation.
- The frequency of the most unstable (KH) mode is found to correspond to the inflow oscillation frequency or one of its higher harmonics.
- Increasing the amplitude of the inflow oscillation results in a stronger triggering of the KH instability.

DNS of a Laminar Separation Bubble at Re=60000 with Free-Stream Disturbances

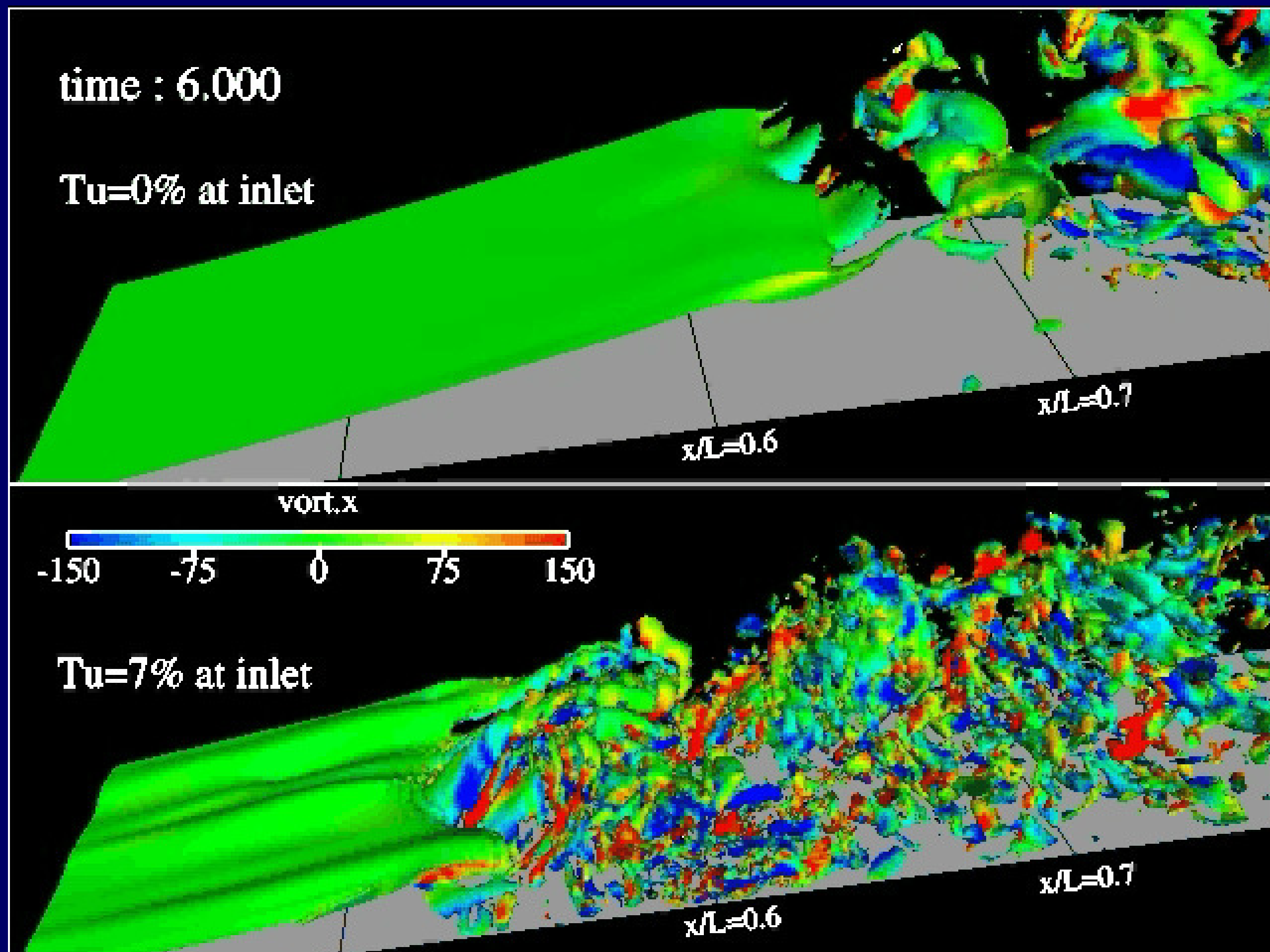
Simulations performed

Sim.	grid	Spanwise size	l_x	Inlet disturbances
F1	*1038 x 226 x 128*	*0.08L*	*1.6L*	*none*
F2	*1926 x 230 x 128*	*0.08L*	*3.0L*	*Tu=5%*
F3	*1926 x 230 x 128*	*0.08L*	*3.0L*	*Tu=7%*
F4	*966 x 226 x 128*	*0.08L*	*1.4L*	*oncoming wakes, period=0.6L/U_e*

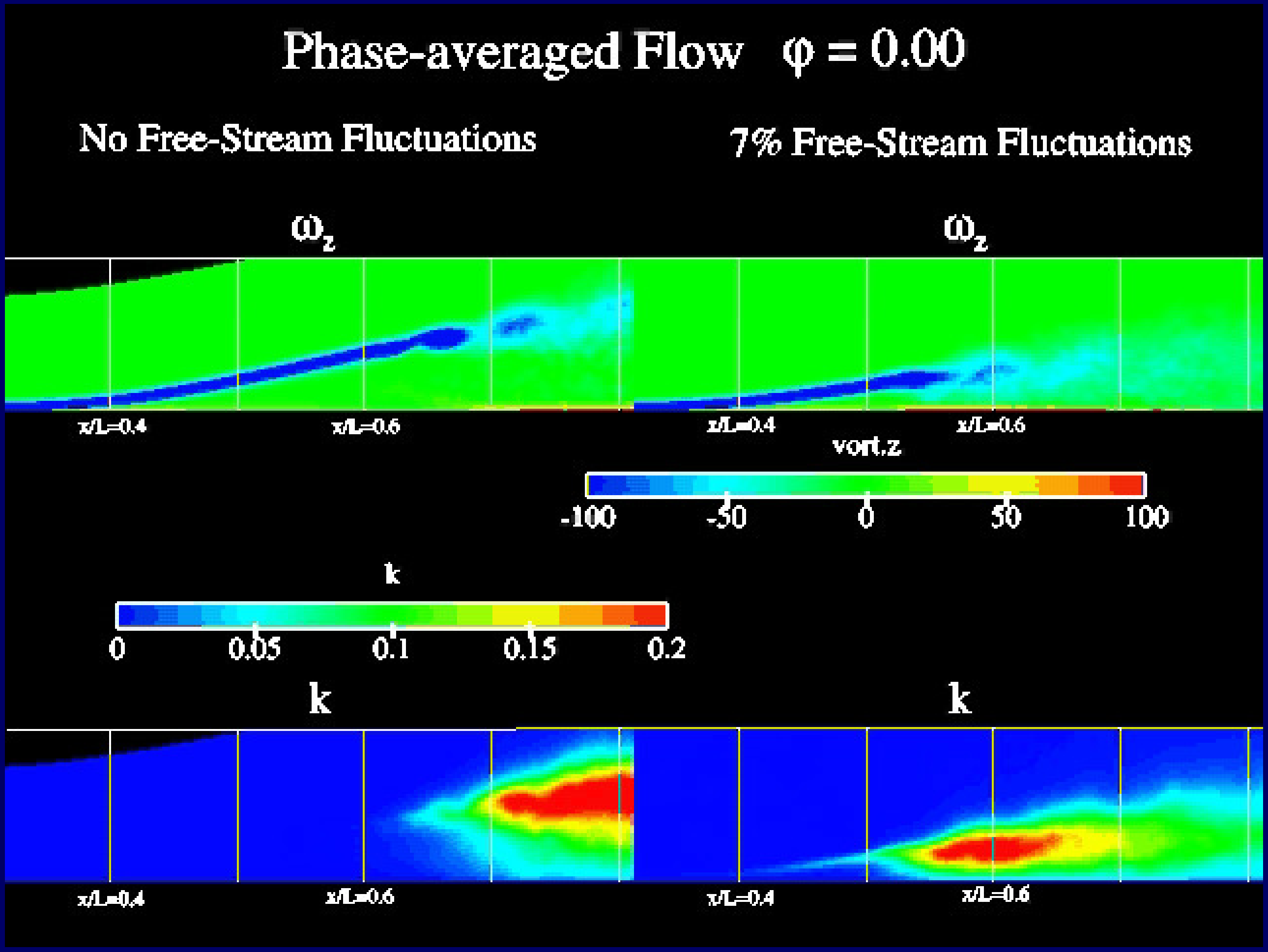
Tu: turbulence level

l_x: actual length of flat plate as employed in the DNS

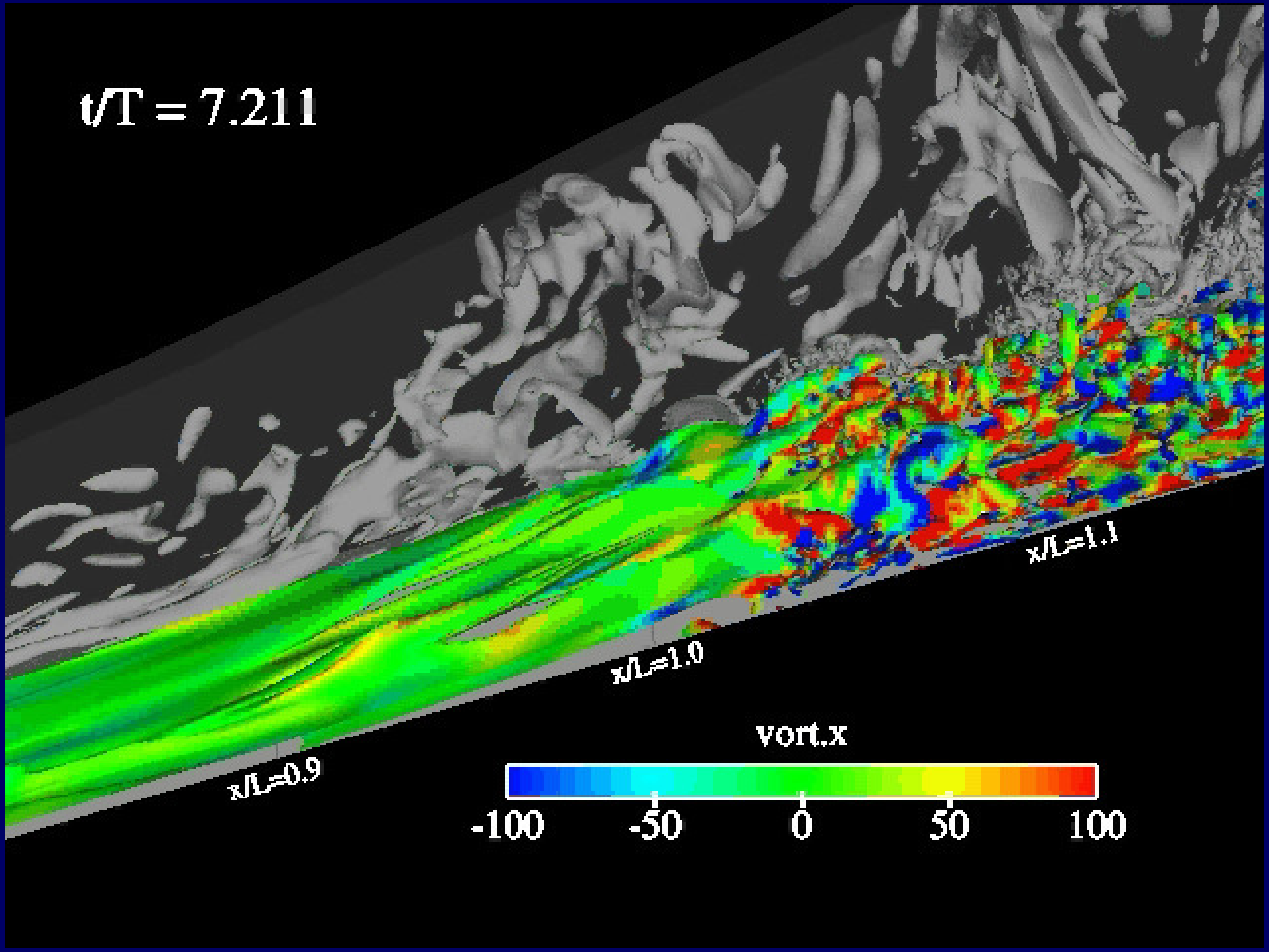
DNS of a Laminar Separation Bubble at Re=60000 comparison spanwise vort. iso-surfaces (Sim. F1 & F3)



Phase-averaged statistics (film)
Simulation F1 vs. Simulation F3

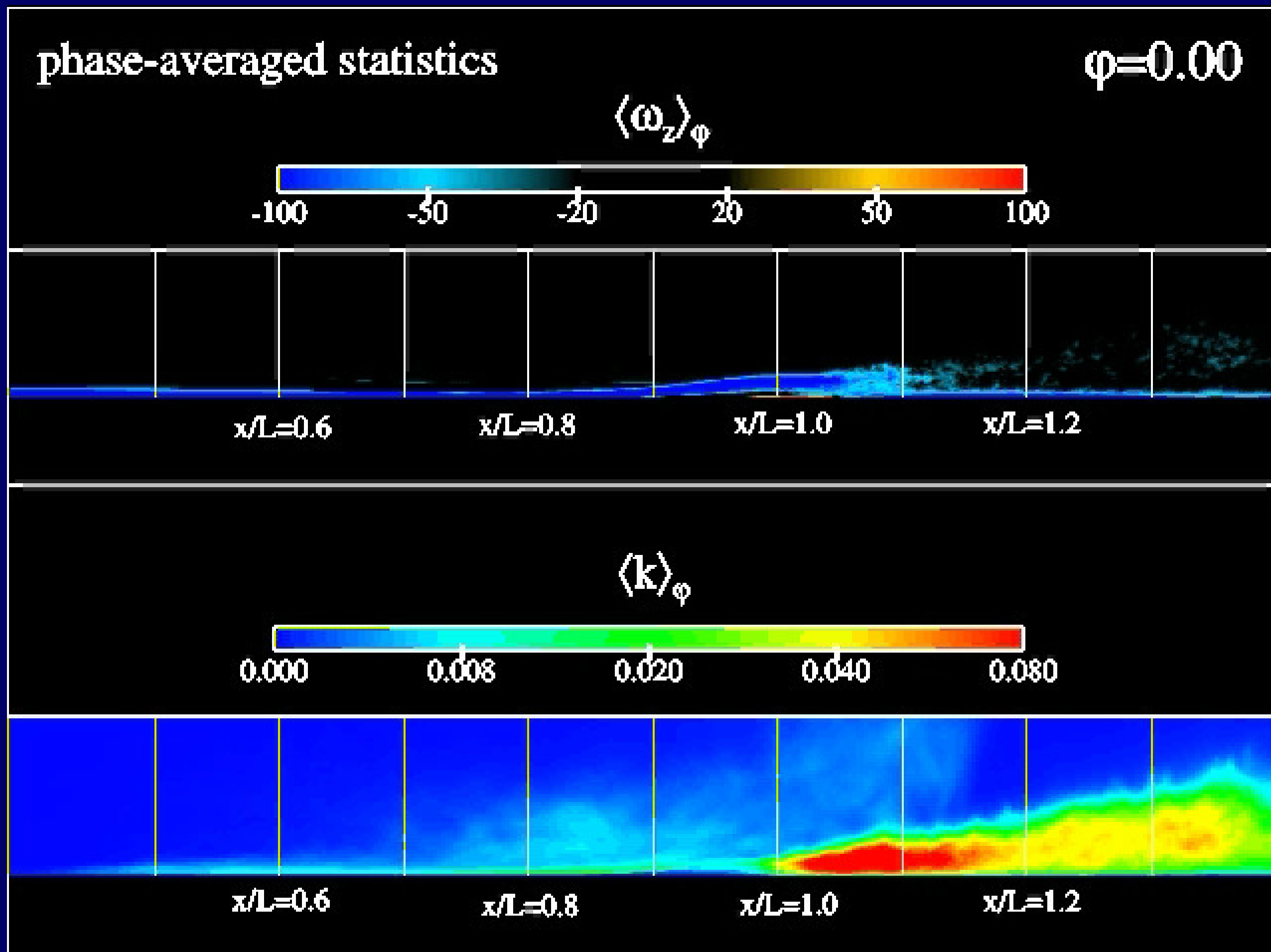


Boundary layer of Simulation F4
(made visible using an iso-surface of the spanwise vorticity)



Vortical structures in translucent box at the back belong to impinging wakes and are made visible with the λ_2-criterion

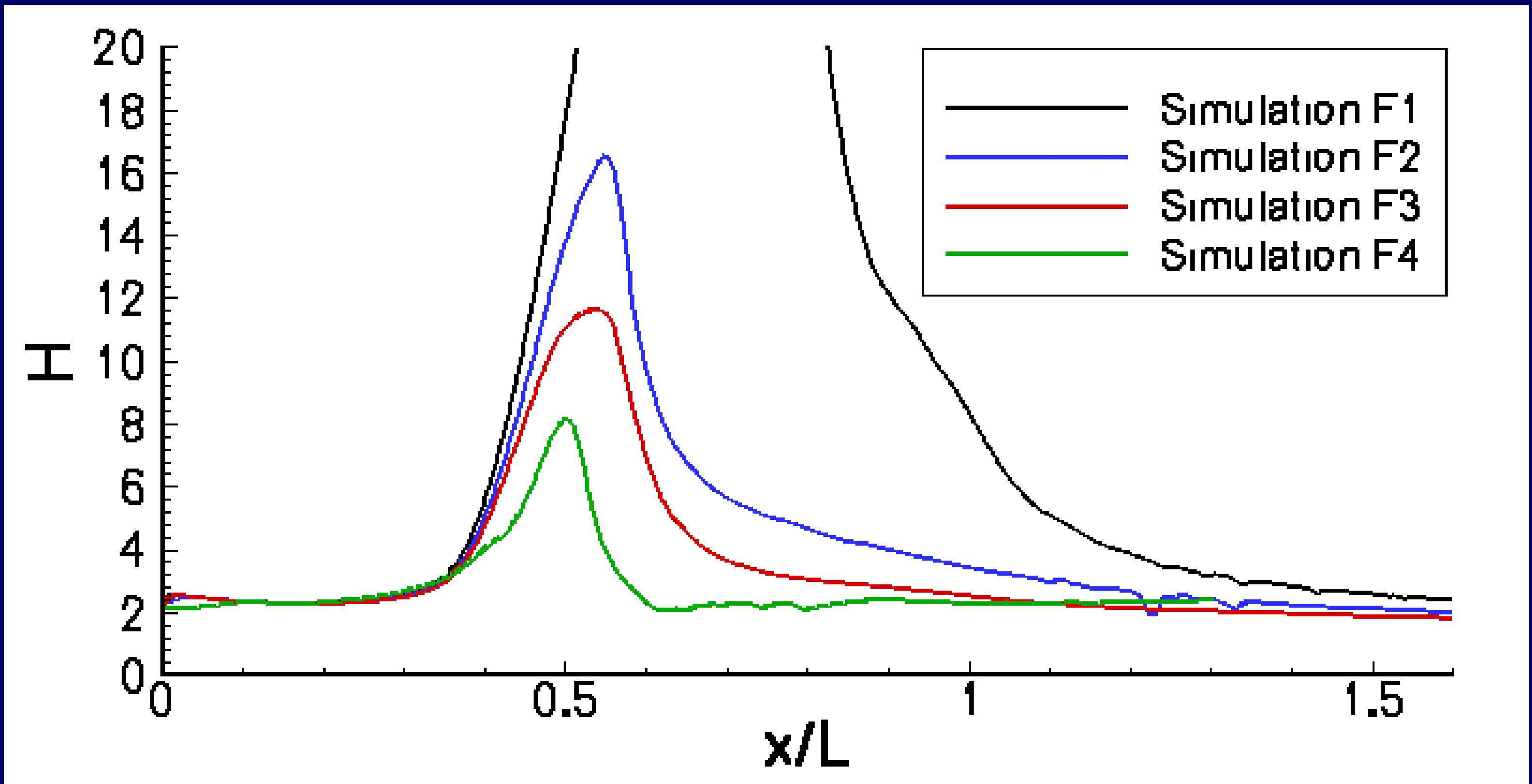
Phase-averaged statistics of Simulation F4



Passing wakes induce elevated levels of $\langle k \rangle_f$ in the free stream

DNS of a Laminar Separation Bubble at Re=60000 with Free-Stream Disturbances

Time-averaged shape factor



Shape factor of Simulation F1 reaches a peak value of H=77.3

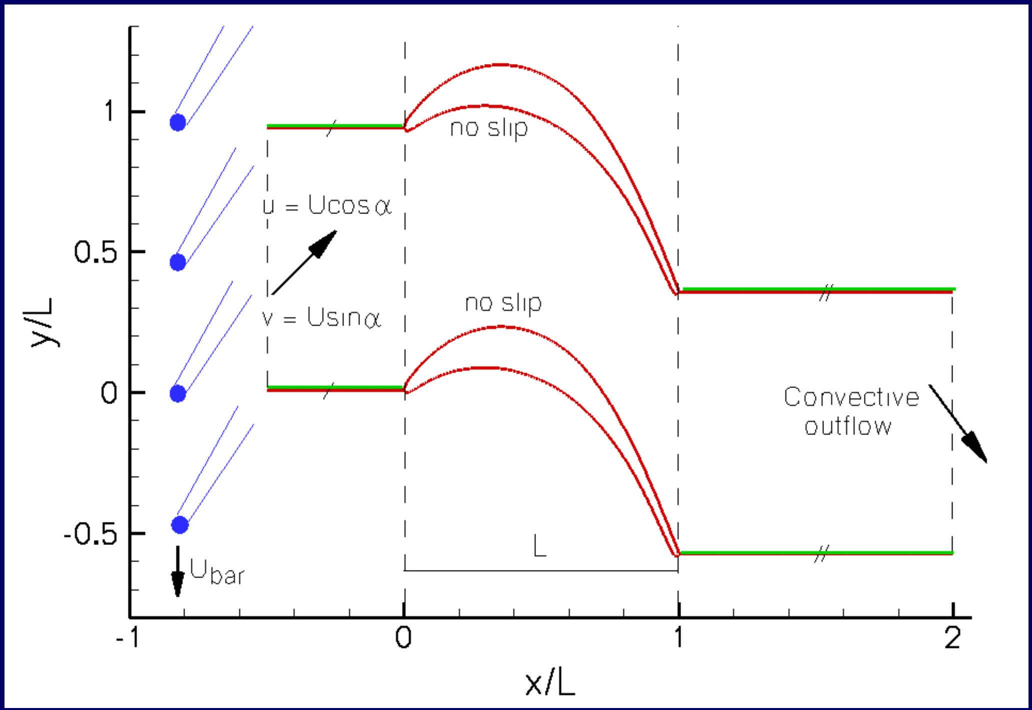
DNS of a Laminar Separation Bubble at Re=60000 with free-stream disturbances

Summary of Results and Discussion

- In all simulations, a Kelvin-Helmholtz instability is found to play an important role in the first stage of transition.
- With increasing level of free-stream fluctuations, the size of the separation bubble is found to decrease.
- Concentrated disturbances carried by periodically oncoming wakes are found to be more effective in decreasing the size of the bubble than the uniformly distributed disturbances
- In the simulation without free-stream fluctuations, numerical round-off error is responsible for triggering the K-H instability.

DNS of Separating Flow in a T106A Turbine Cascade at Re = 51 831

Geometry



Periodic boundary conditions in the spanwise direction

Reynolds number is based on the inflow velocity U and axial chord L

DNS of Flow in a T106A Turbine Cascade at Re = 51 831

Main Flow Features:

- The large angle of attack *(α=45.5°)* causes a strong adverse pressure gradient along the suction side for $x / L > 0.6$.
- In the absence of wakes, a large separation bubble is found along the downstream half of the suction side.
- Fascinating vortical structure is detected along the pressure side in a simulation with incoming wakes (also detected by Wu and Durbin (2001)).
- Periodically separating boundary layer flow along the downstream half of the suction side.

DNS of Flow in a T106A Turbine Cascade at Re = 51 831

Simulations performed

Simulation	grid	Span	WD	WHW
T1	*771 x 262 x 128*	*0.25L*	-	-
T2	*1014 x 266 x 64*	*0.20L*	*25%*	*0.03L*

WD: Mean wake deficit

WHW: wake half-width

LES generated inflow wake data have been kindly made available by Wu and Durbin of Stanford University

DNS of Flow in a T106A Turbine Cascade at Re=51831 with Periodically Passing Wakes

Close-up of Suction Side Separation near Trailing Edge

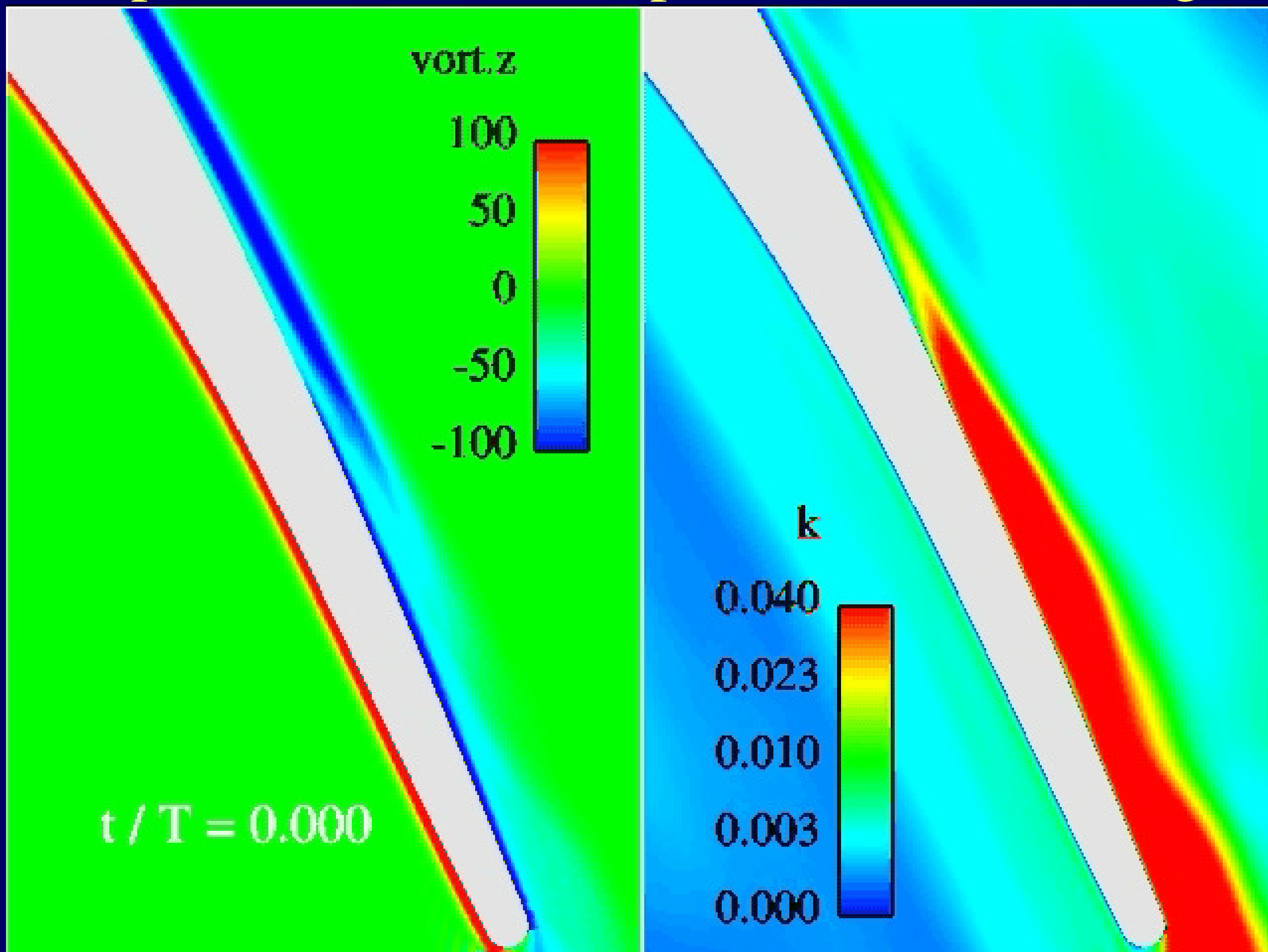
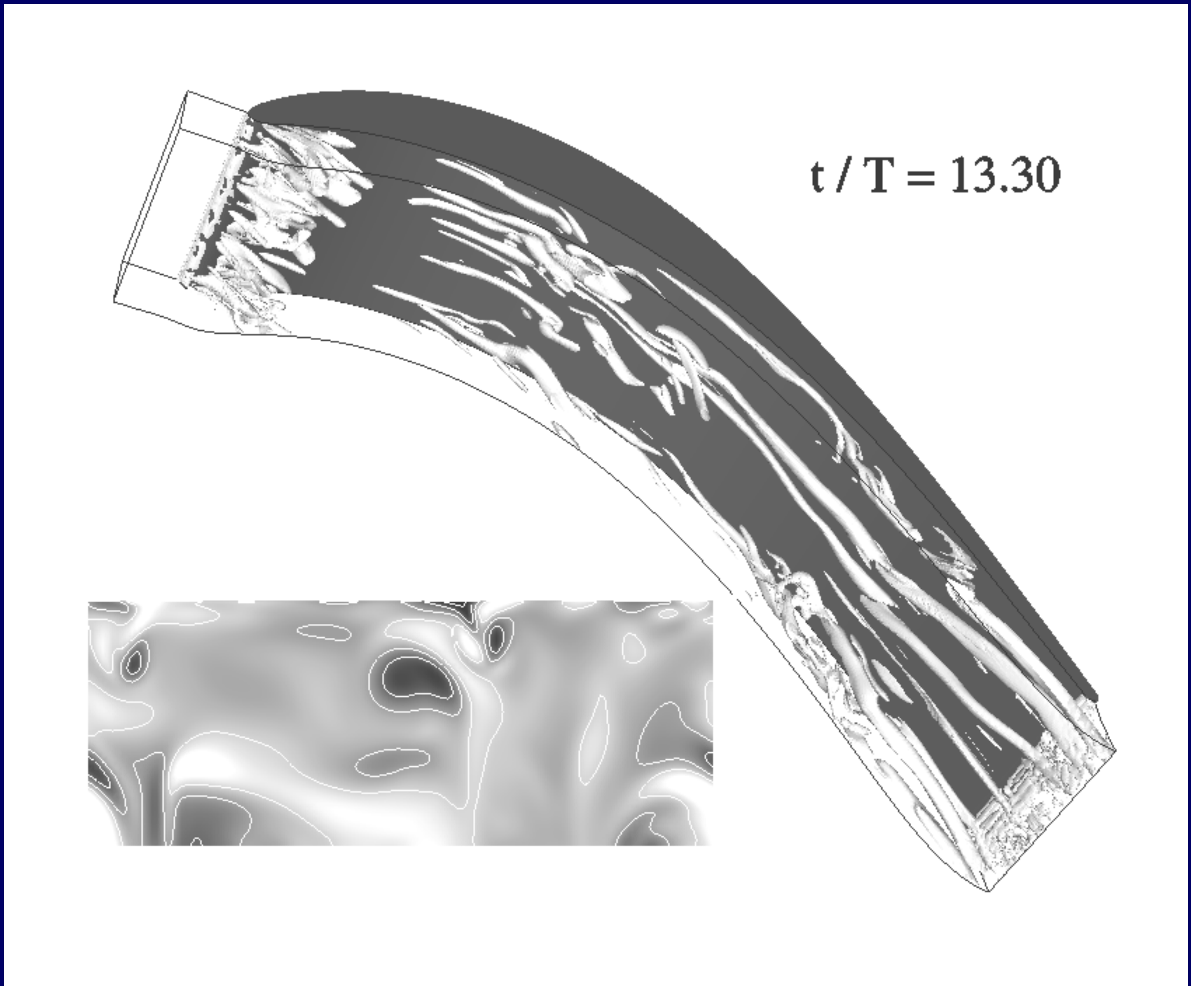


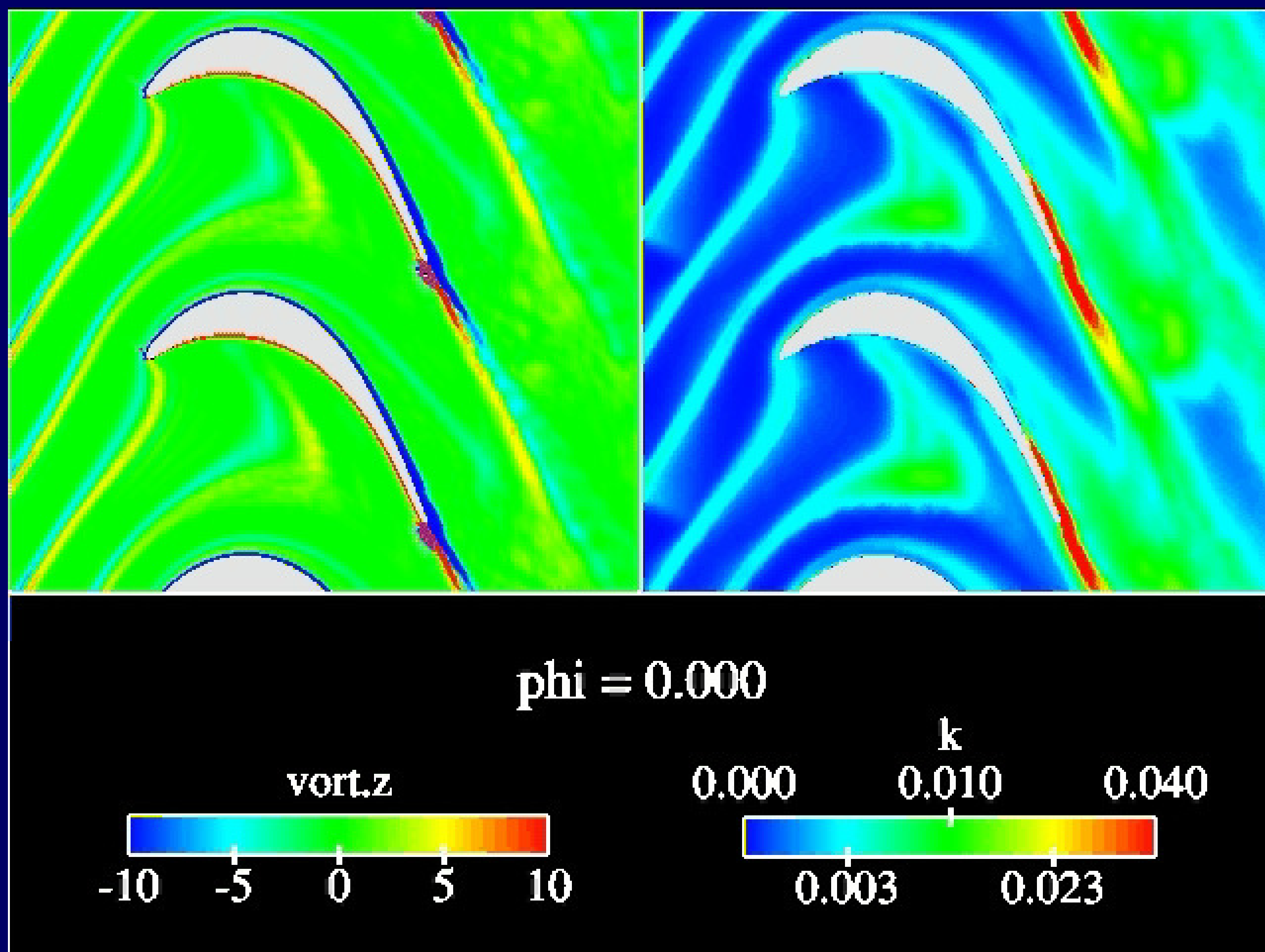
Illustration of Kelvin-Helmholtz Instability

DNS of Flow in a T106A Turbine Cascade at Re=51831 with Periodically Passing Wakes

Vortical Structures at the Pressure Side



DNS of Flow in a T106A Turbine Cascade at Re=51831 with Passing Wakes (Phase-Averaged Statistics)



694x230x64 mesh; lz=0.20

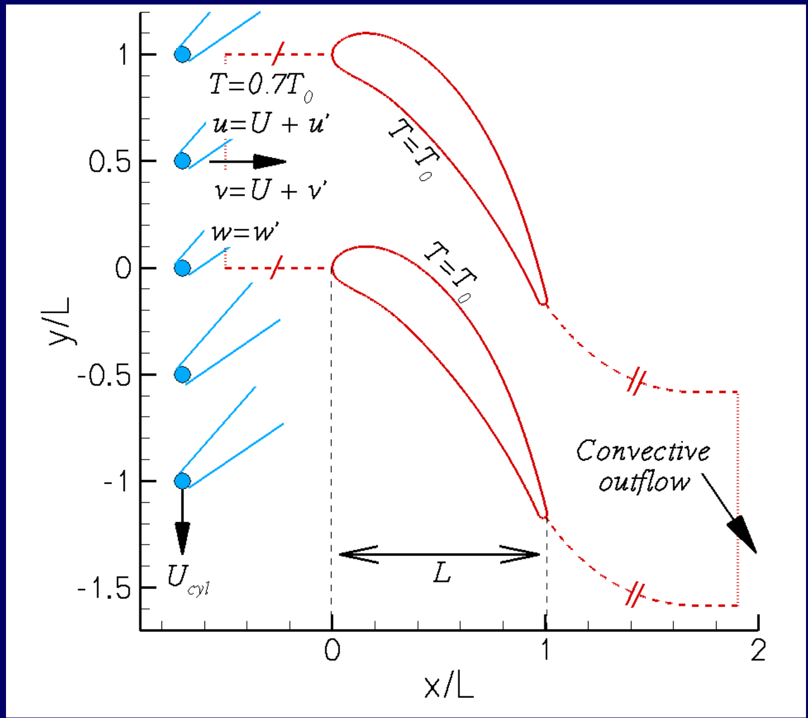
DNS of Flow in a T106A Turbine Cascade at Re=51831 with Periodically Passing Wakes

Summary of Results

- The presence of wakes hardly affects the wall static-pressure coefficient C_p distribution
- The Pressure side boundary layer remains laminar at all times
- Elongated vortical structures are found along the pressure side
- A large separation bubble is intermittently found to be present along the downstream half of the suction side.
- As a consequence separation induced transition is observed somewhat upstream of the trailing edge.
- The separation bubble is periodically suppressed by the impinging wakes
- As this happens, the location of transition moves downstream

DNS of Passive Heat Transport in a MTU Turbine Cascade at Re = 72000 (exp: Liu and Rodi)

Geometry

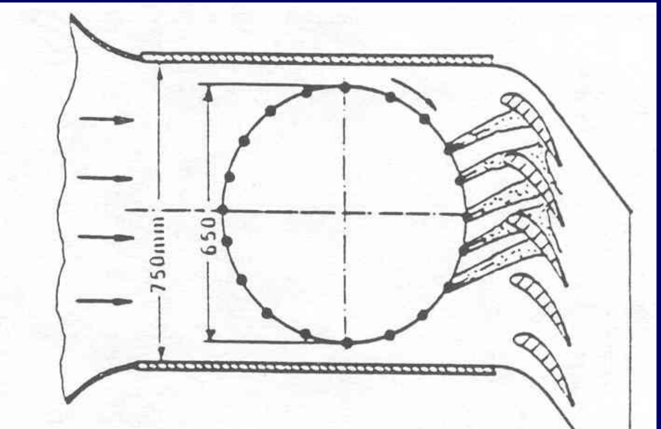


Periodic boundary conditions in the spanwise direction

Reynolds number is based on the inflow velocity U and the axial chord-length L (see figure)

MTU blade - test case

- Experimental study (Liu and Rodi 1992)

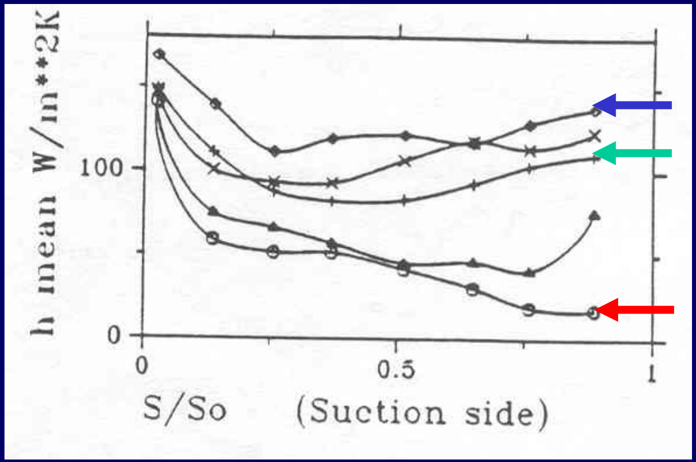


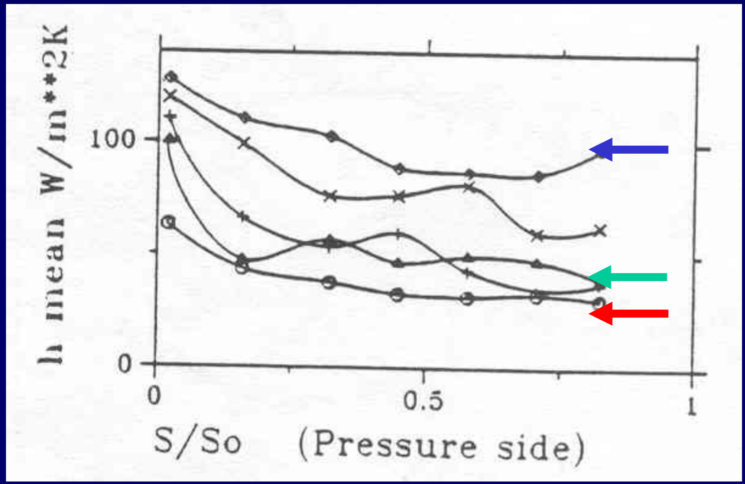
Test facility

case	A	B	C	D	E
f(Hz)	0	60	120	180	240
cyl. No:	0	24	24	48	48
cyl. pitch (mm)	inf	85	85	42.5	42.5
Vcyl. /m/s):	0	5.1	10.2	7.66	10.2
Str. No.	0	1.84	3.68	5.52	7.36
T (ms)	inf	16.667	8.33	5.56	4.167
Tu_{inf} (%)	0.9	2.3	2.8	3.1	4.8
dt (ms)	0.2	0.5	0.2	0.2	0.2

Cascade Test Cases

- Heat transfer measurements (time-mean $\bar{h}$)





Cases A (o), B (Δ), C (+), D (x), E (◇)

DNS of Passive Heat Transport in a MTU Turbine Cascade at Re = 72000 (exp: Liu and Rodi)

Overview of the simulations performed

Sim.	Wake Vel. deficit	Wake Half-width	D_{cyl}	Tu_{min}	Exp.
M1	-	-	-	0%	A
M2	30%	0.045L	½L	2.8%	C
M3	30%	0.045L	¼L	8.4%	E

Spanwise size: 0.20L

D_{cyl} is the distance between two wake-generating cylinders

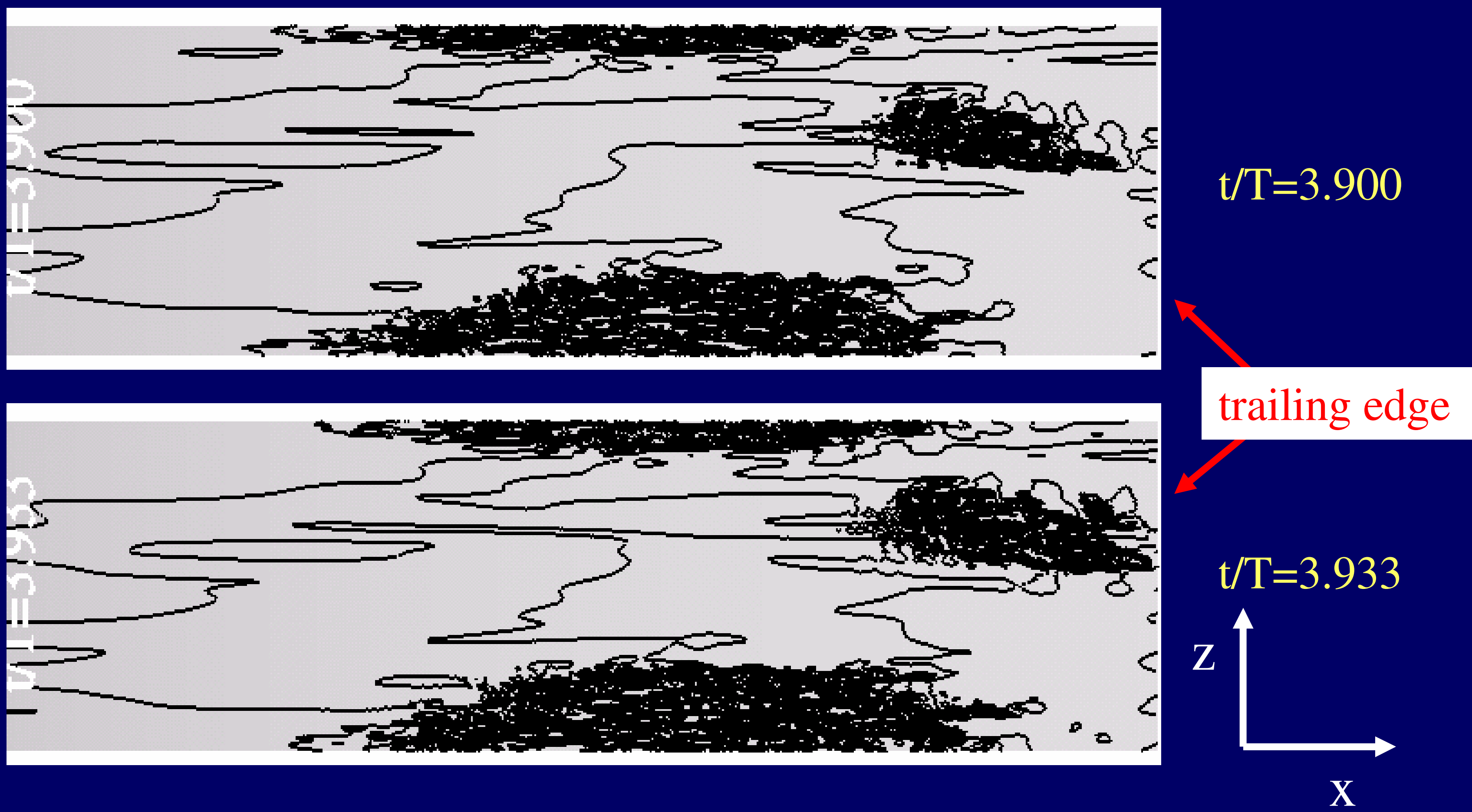
Tu_{min} is the minimum turbulence level in the plane x/L = –0.20

Re=72000 based on inflow conditions and axial chord-length L

1254x582x128 point mesh is employed in all simulations

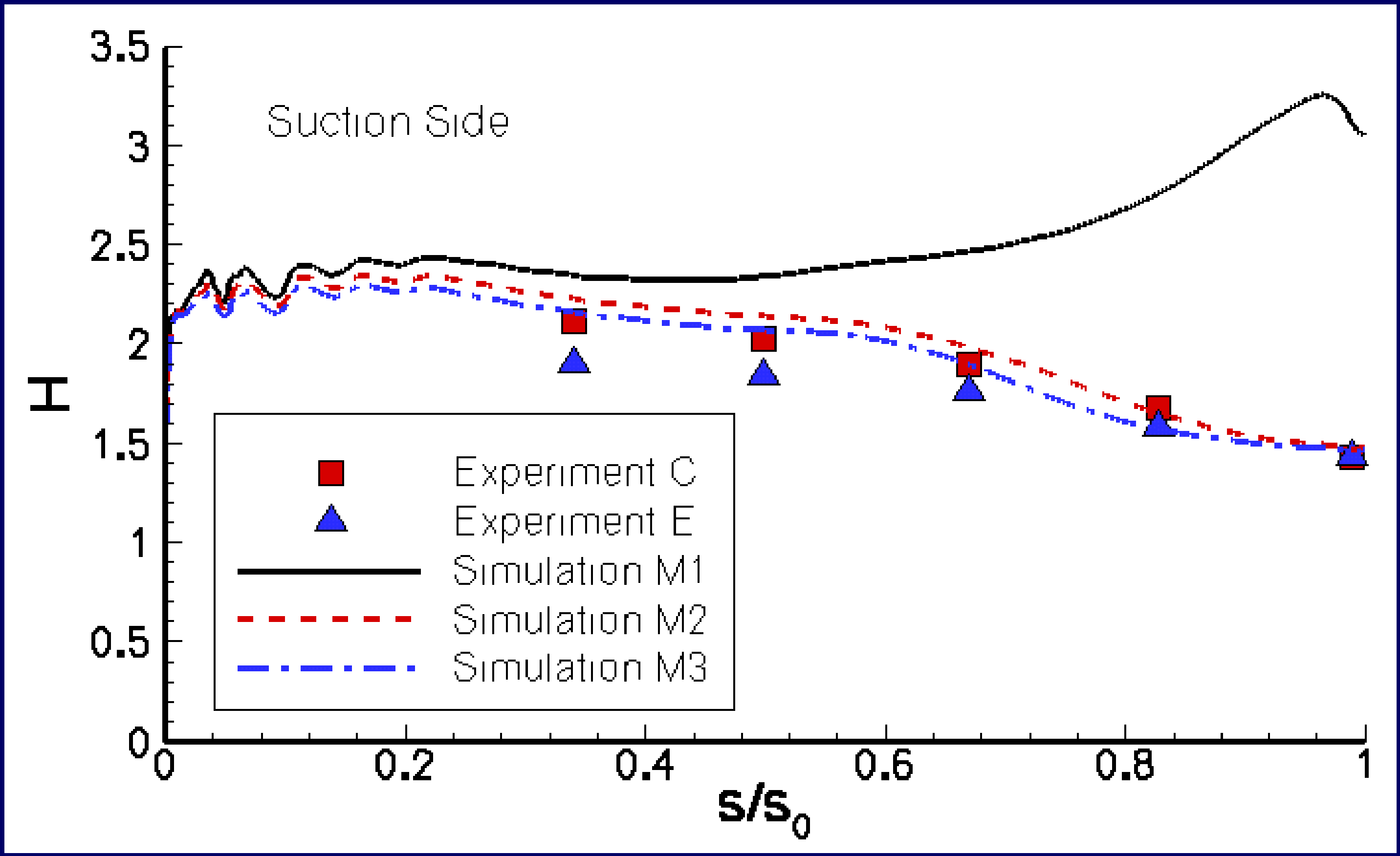
DNS of Flow in a MTU Turbine Cascade with Passive Heat Transport: turbulent spots

Contours of the instantaneous v-velocity along downstream half of suction side (Simulation M2)

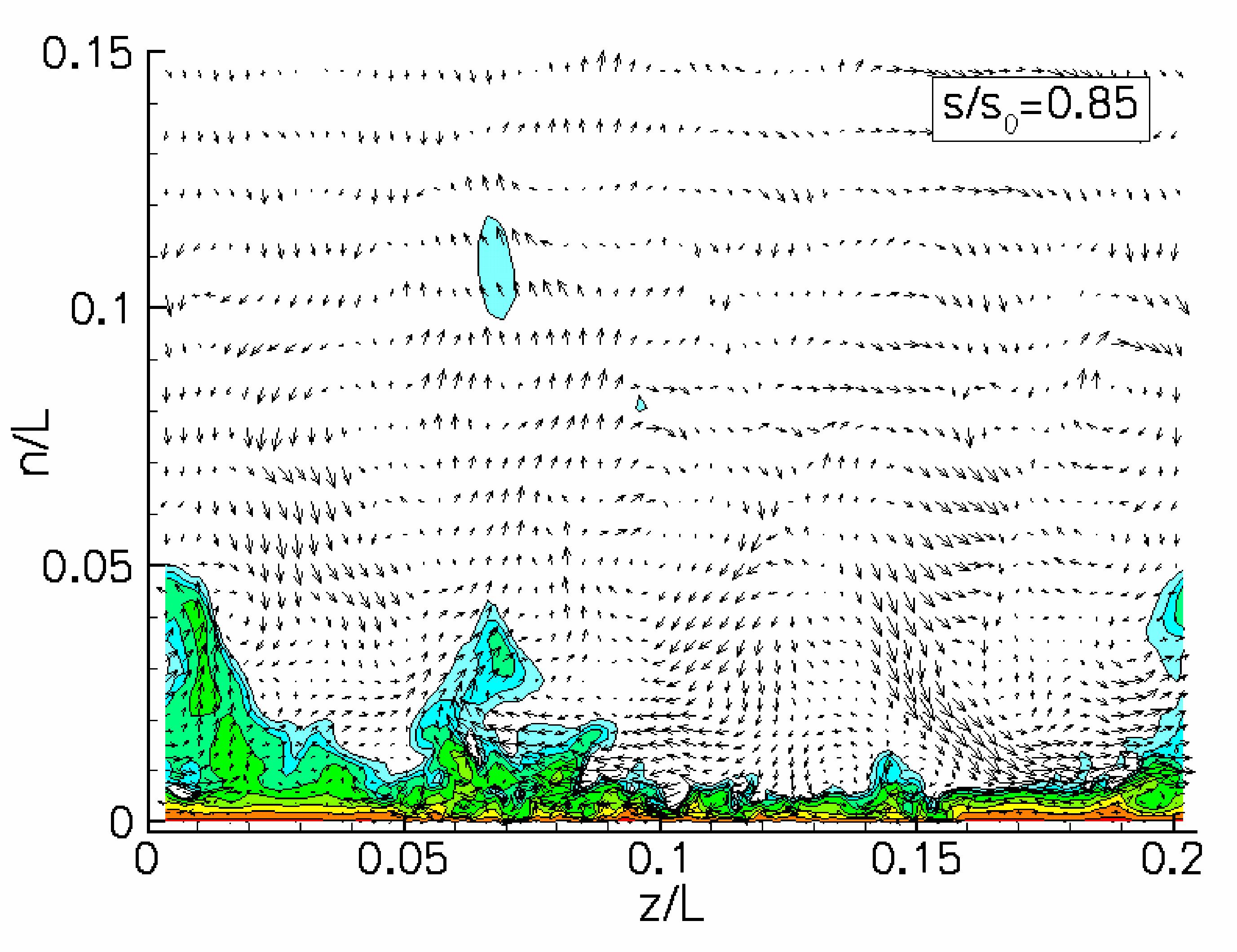


DNS of Flow in a MTU Turbine Cascade with Passive Heat Transport

Shape factor suction side BL (comparison to experiment C)

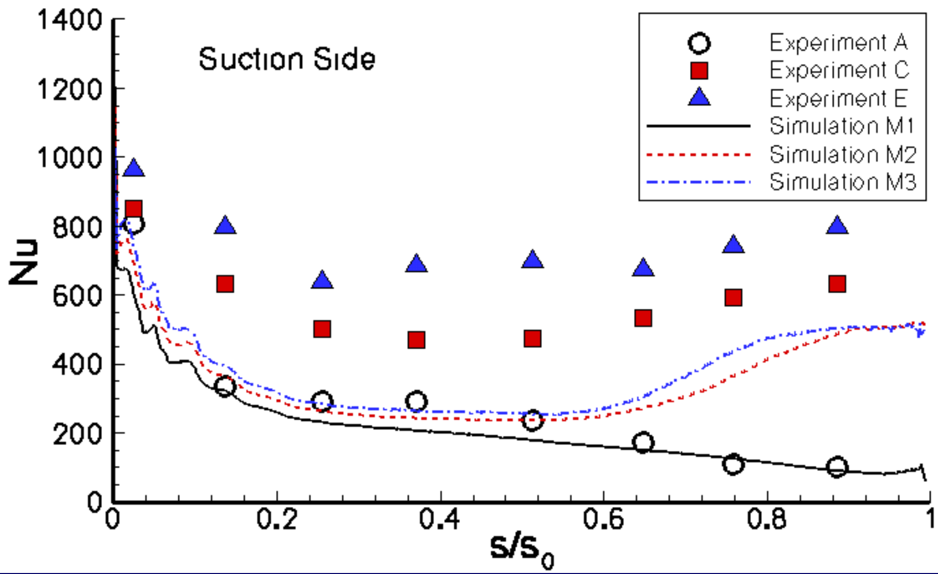


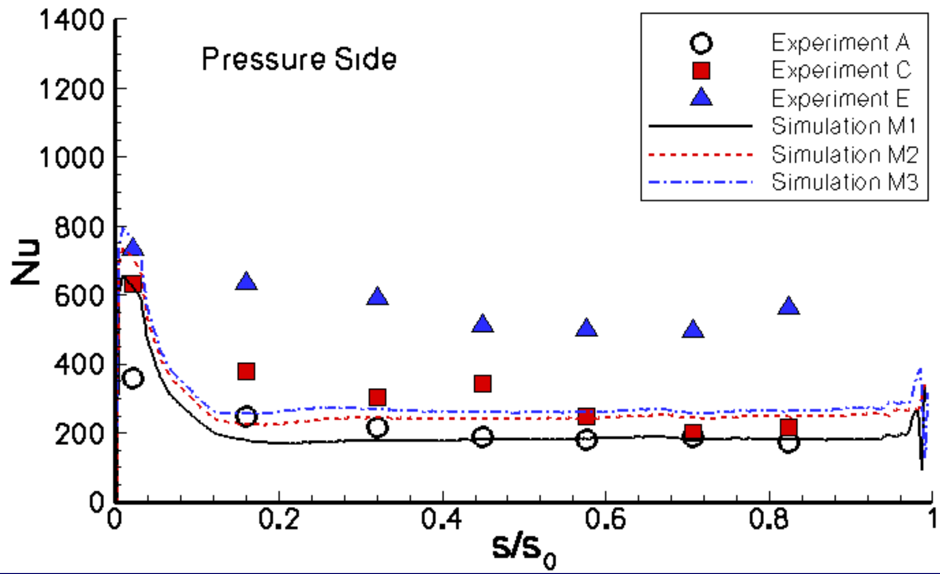
Simulation M3: Contours of the temperature and vector-field of the fluctuating velocity



DNS of Flow in a MTU Turbine Cascade with Passive Heat Transport

Nusselt number (comparison to experiments A, C, E)





Suction Side

Pressure Side

DNS of Flow in a MTU Turbine Cascade with Passive Heat Transport

Summary of Results

- The suction side boundary layer is predominantly laminar, only in the simulation with impinging disturbances transition is observed near the trailing edge.
- As a consequence, the transport of heat from the wall to the free stream is promoted, which is reflected in a locally increased Nusselt number.
- The pressure side remains laminar; with impinging wakes, vortical structures increase the heat transfer by 30%.
    - But the large increase at higher frequencies and in the pre-transitional suction side part could not be reproduced
    - This is most likely due to the fact that the incoming wake´s turbulence used has smaller scales, typical of the far-field of a wake, while in the experiment larger near-wake structures were present.

Conclusions

- DNS of transitional flow over turbine blades is possible
  - Still limited to moderate Re and simplified geometries (2D)
- Calculations are very expensive
  - Up to 100 Mio. grid points, $\Delta t \sim 10^{-5}$ L/U
  - Several months of clock time on supercomputers
- DNS not for practical applications, but increasingly important tool for studying transitional flows
  - Allows to extract all flow details
  - Provides valuable data for developing more economic/accurate transition models
- Further increase in computational power will allow to handle more complex geometries