Development and Application of LES for the Unsteady Flows in Turbomachinery

Recent progress in applying the Large Eddy Simulation (LES) to flow control in turbomachinery is reviewed. The development of flow control in turbomachinery requires accurate prediction of detailed three-dimensional flow structures including unsteady motion of various vortex systems. It has been shown that LES provides more realistic description of the complex flowfields compared to steady and unsteady Reynolds-averaged Navier-Stokes simulations (RANS & URANS).

Key note lecture, ISUAAAT 13

Development and application of LES for the unsteady flows in turbomachinery

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This lecture is based on two published papers

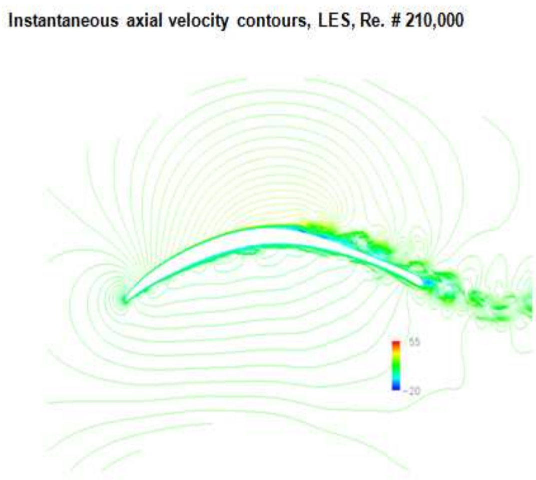
1. ISABE-2011-1220, “Study of near-stall flow behavior in a modern transonic fan.
2. ISORMAC-2012-120, “Investigation of laminar flow separation and transition in compressor/fan blades with a Large Eddy Simulation”.

The current work is supported by the NASA Fundamental Aeronautics Program, Subsonic Fixed Wing Project.

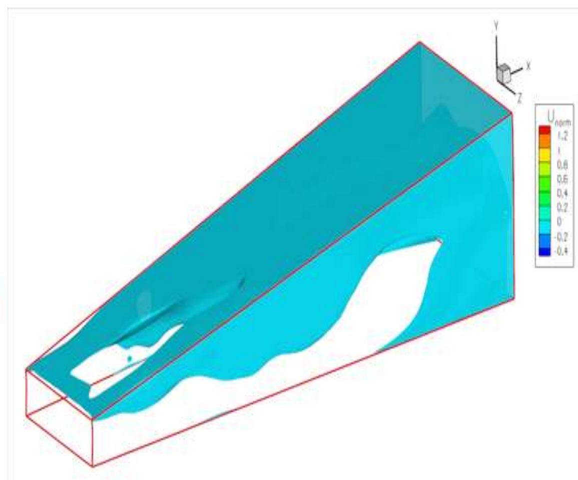
URANS and LES for unsteady flows in turbomachinery

- URANS : Effects due to entire turbulence scales are modeled. Solution depends on turbulence model. Difficult for separated flow, flow transition, Reynolds number effects.
- LES : Significant increase in computing cost. Requires large computational grid. Needs further development/validation for high speed flow.

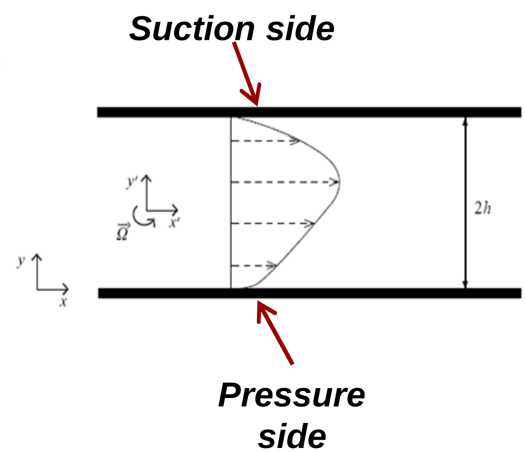
Example of flow problems



Flow transition



Flow separation



Effects of rotation

Objectives

- Development fan/compressor simulation tool based on LES approach.

Subgrid models

- Standard Dynamic model.
- Vreman’s model.
- A local dynamic one equation model.

Near-wall Treatment

- Hybrid LES/RANS.
- Generalized wall function.

Progress and current research issues with LES, examples

- Transonic fan flow at near stall operation (GEnx model fan).
- Flow transition and Reynolds number effects in a compressor cascade.

LES study of flow at near stall operation in a transonic fan (Genx model fan)

Why LES ?

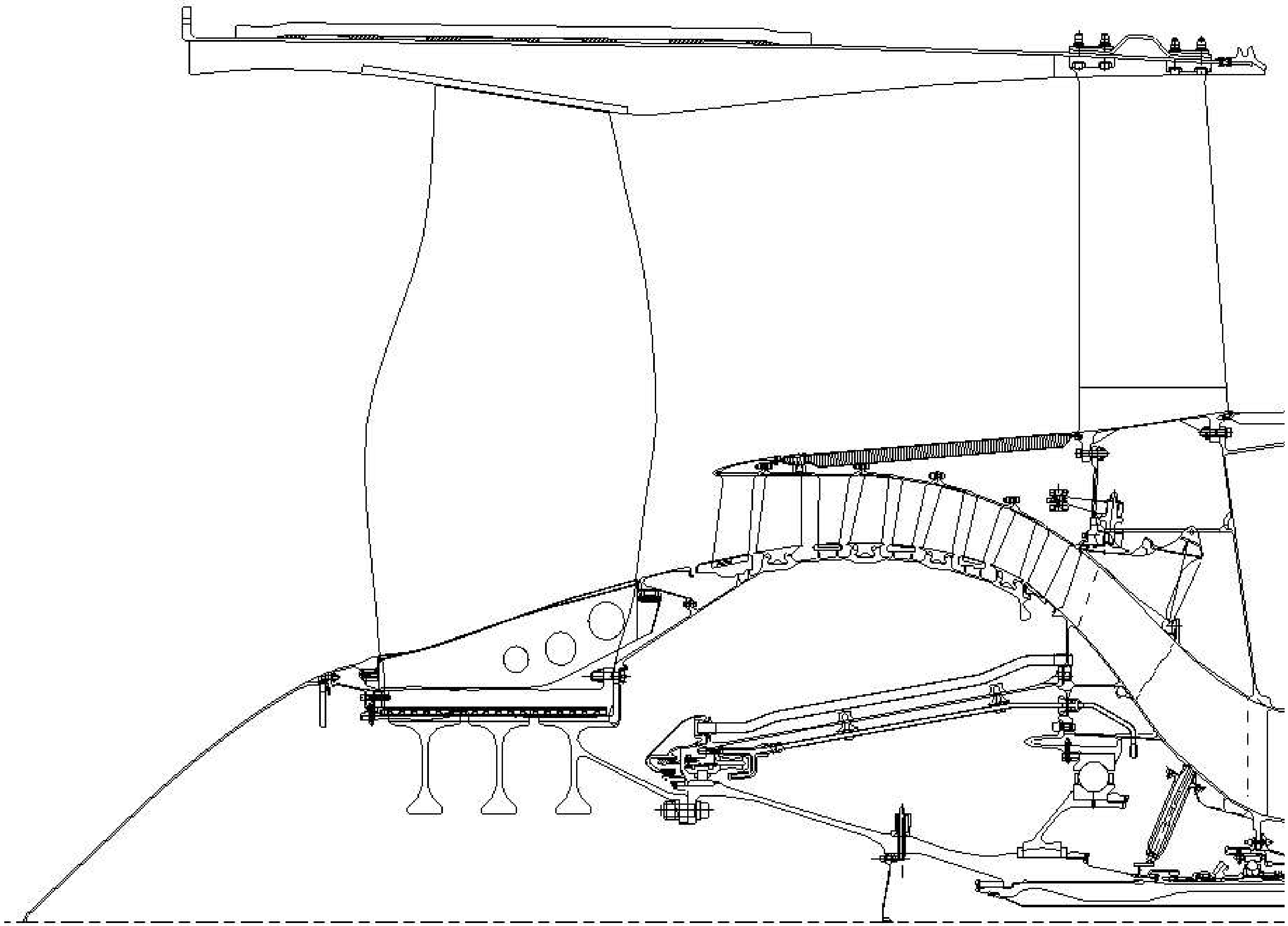
- Flow becomes highly transient when the transonic fan operates toward stall.
- Unsteady flow at near stall has not been investigated well.
- Accurate unsteady pressure field calculation requires adequate resolution of various vorticities.

Approach

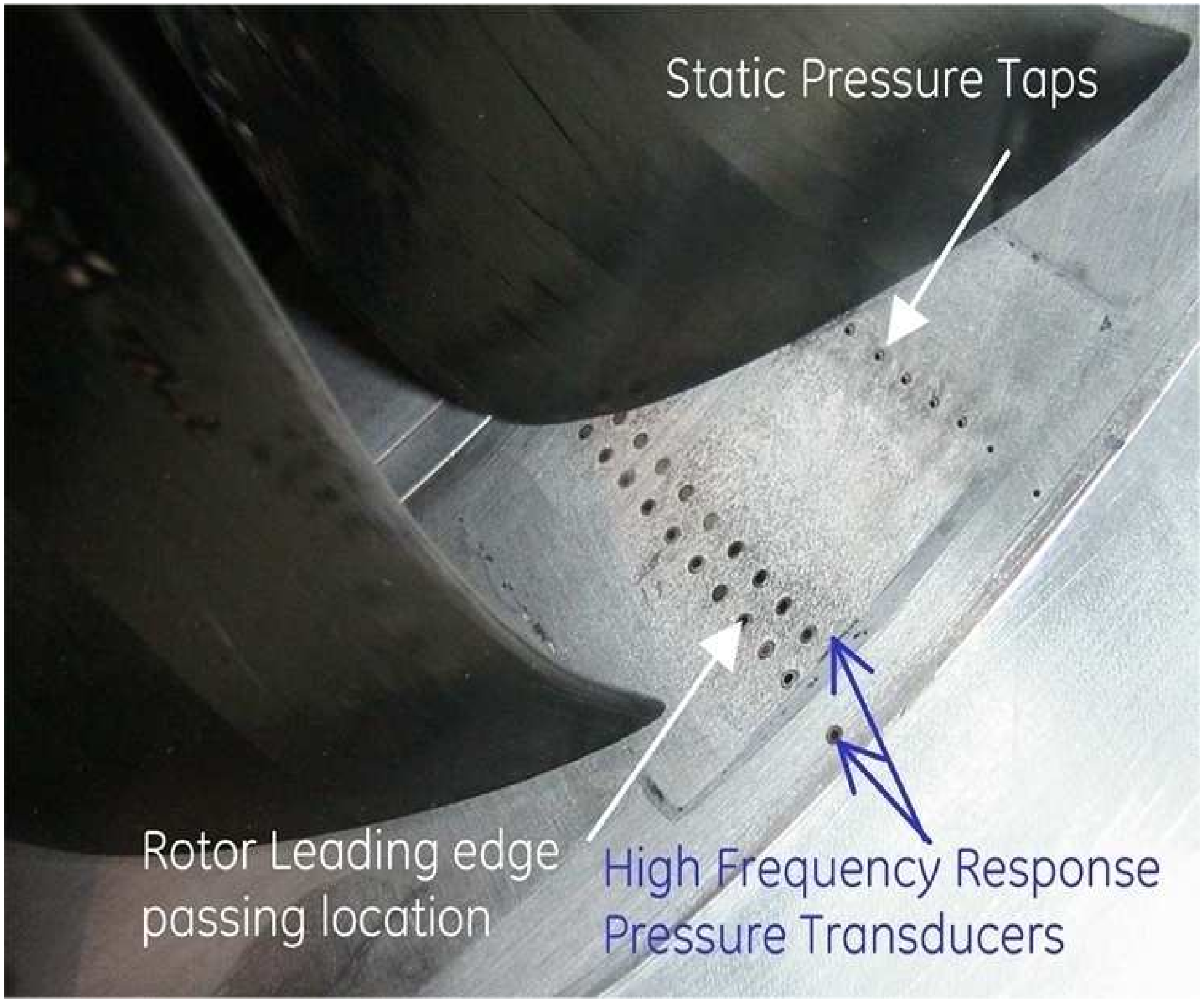
- Measurements : ultra-miniature high-frequency pressure transducers (for unsteady pressure) & pneumatic probe.
- Analysis : unsteady Reynolds-averaged Navier-Stokes (URANS) & Large Eddy Simulation (LES).

Genex fan flow field at near stall.

Cross section of test fan



Casing with pressure block



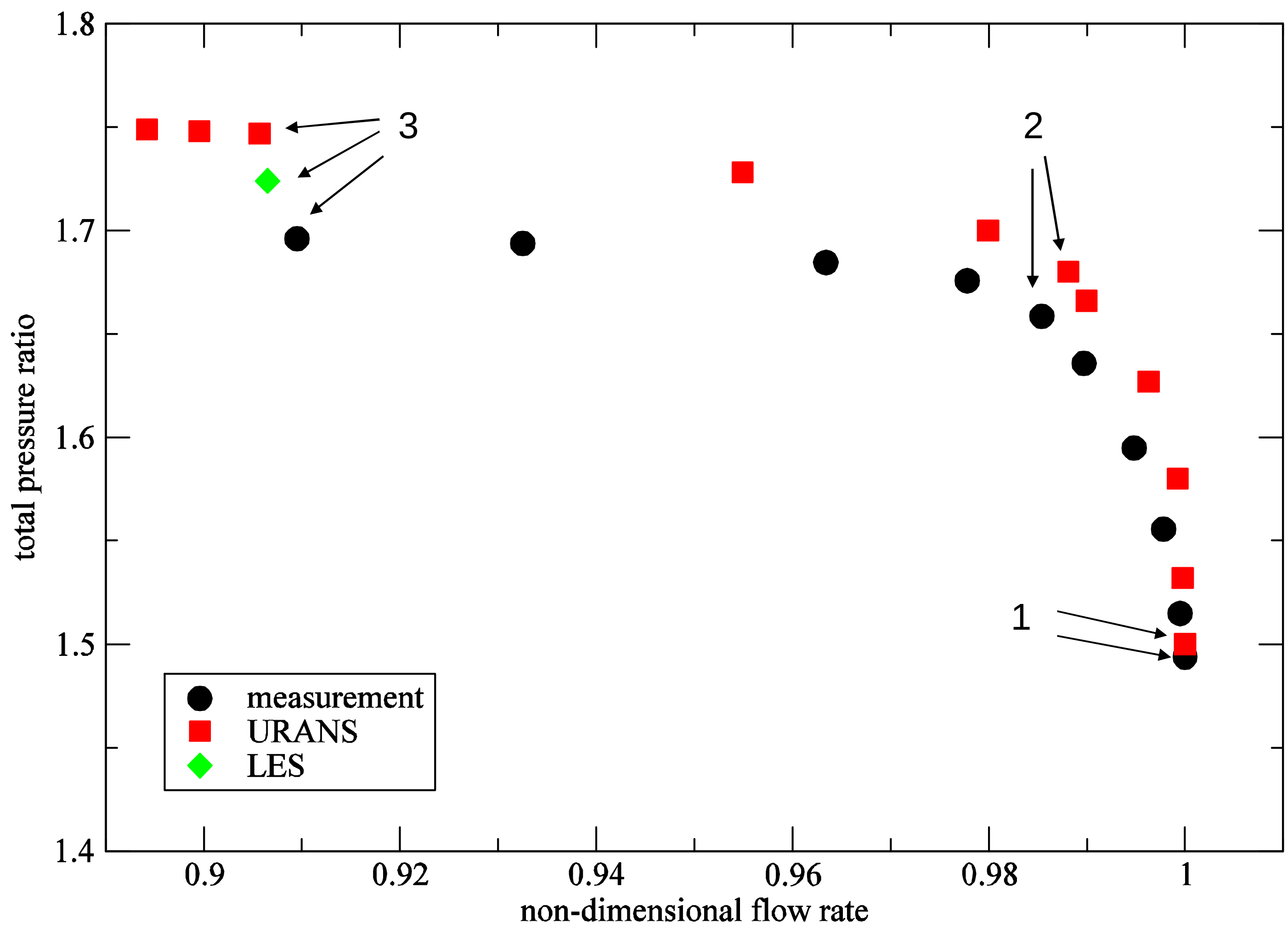
Objectives of numerical study

- Compare results from URANS and LES with measured data.
- Compare relative advantage and disadvantage.
- Recommend proper procedures for the design application.

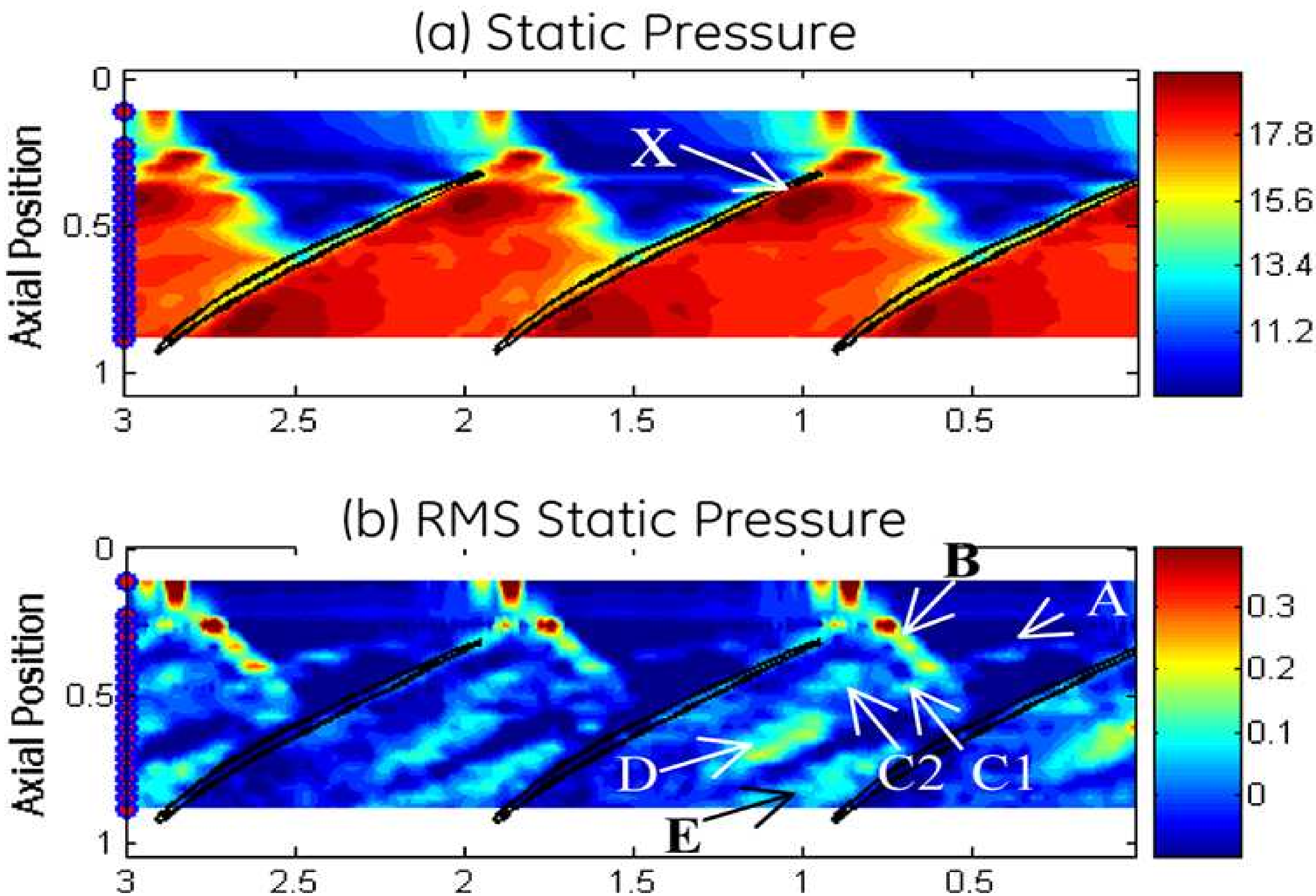
Numerical scheme

- 3^{rd}-order scheme for convection terms.
- 2^{nd}-order central differencing for diffusion terms.
- Sub-iteration at each time step.
- Dynamic model for sub grid stress tensor for Large Eddy Simulation.
- Standard two-equation model for URANS.
- A single block I-grid, 198x88x537 with 38 nodes inside tip gap for LES.
- 2,030,400 nodes for URANS.

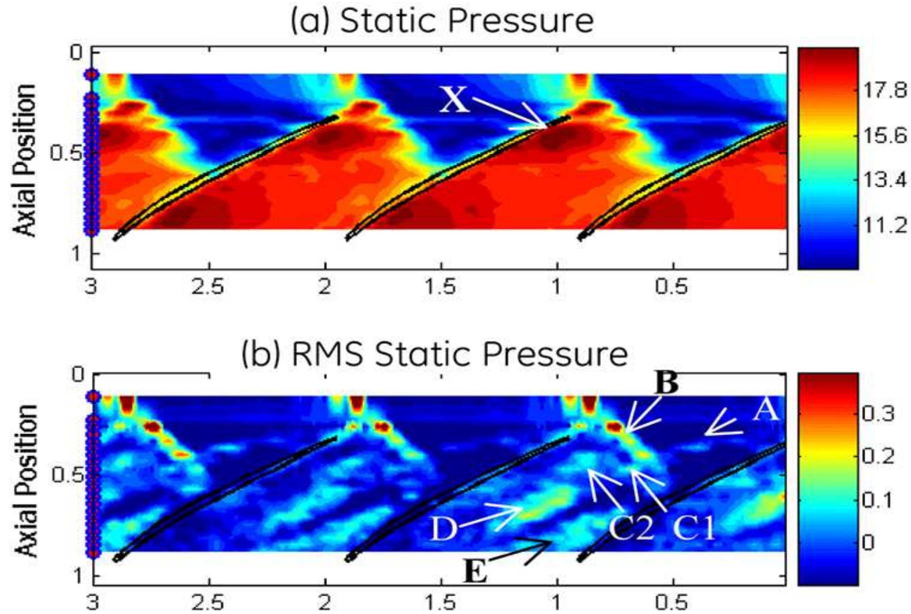
Three operating points for comparison



Measured static pressure and RMS static pressure at near stall

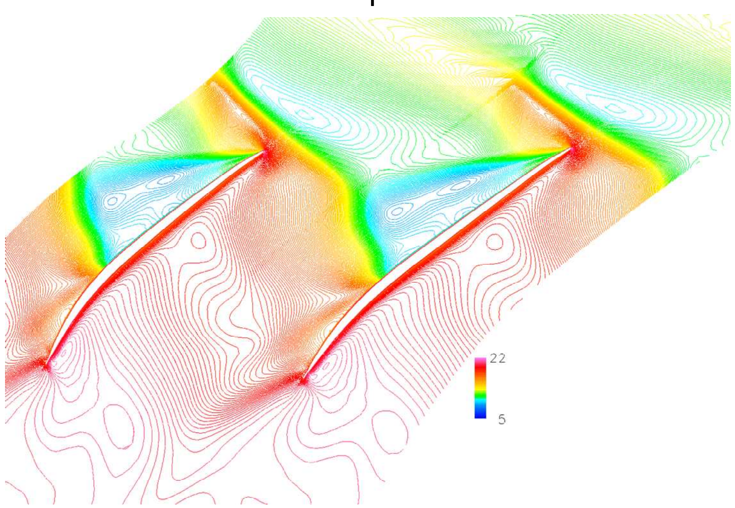


Calculated static pressure and RMS static pressure at near stall

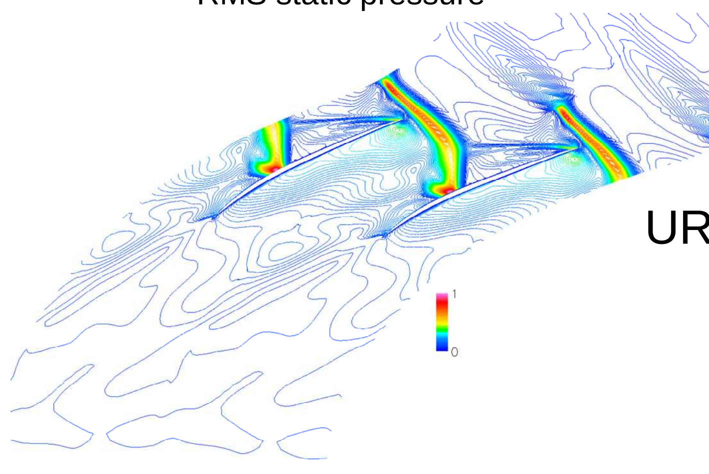


measurement

Static pressure

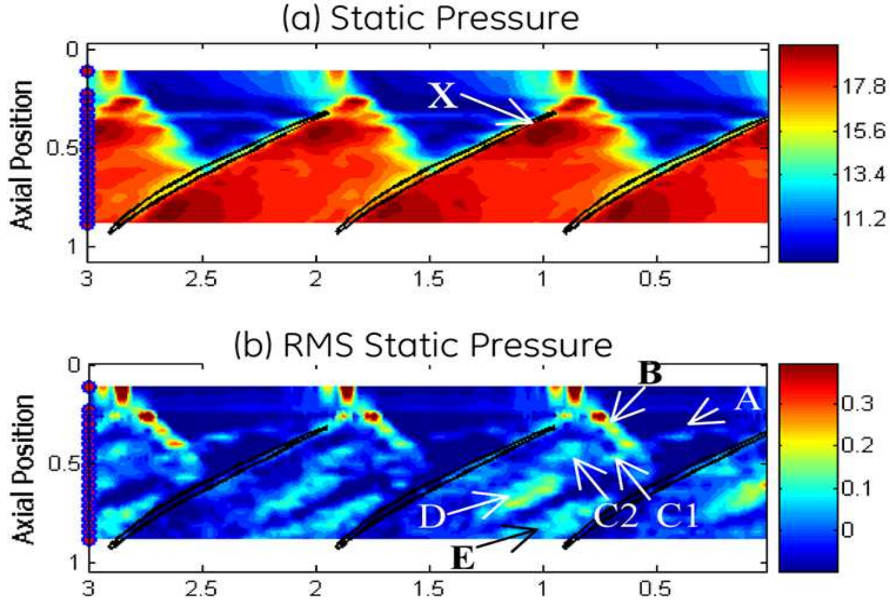


RMS static pressure



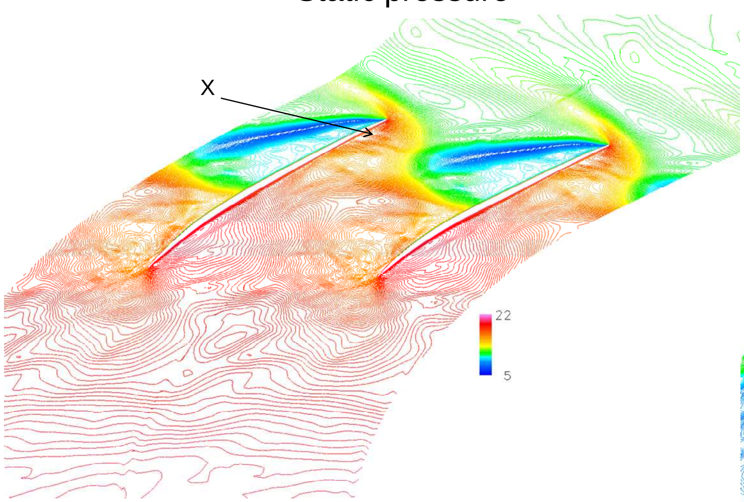
URANS

Comparison static pressure and RMS static pressure at near stall

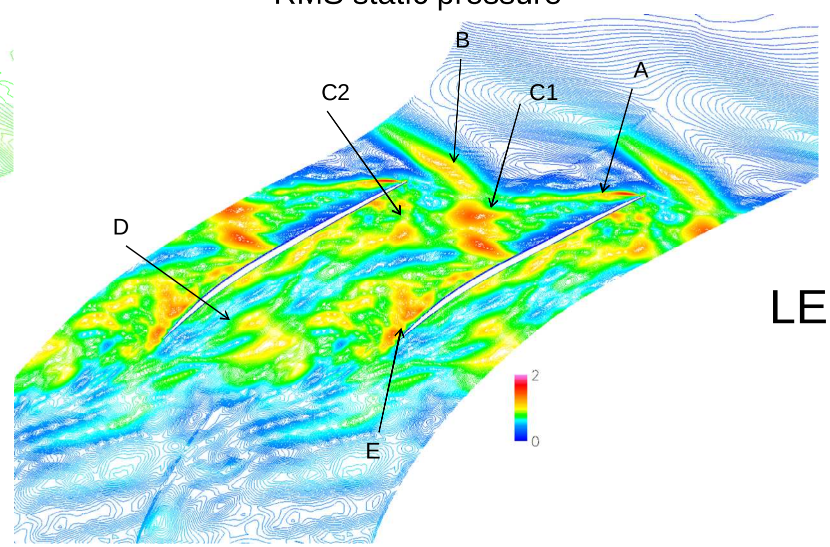


measurement

Static pressure

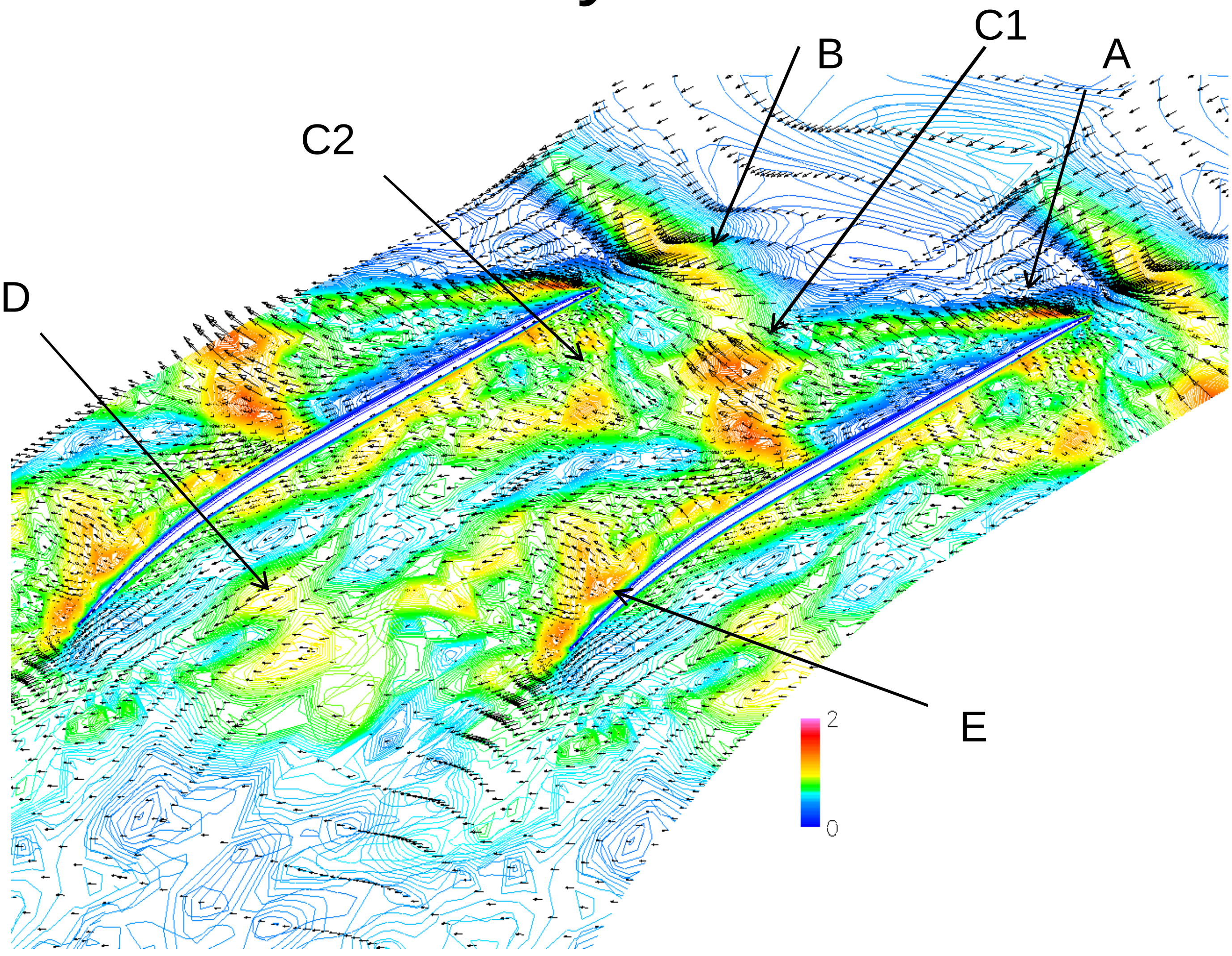


RMS static pressure

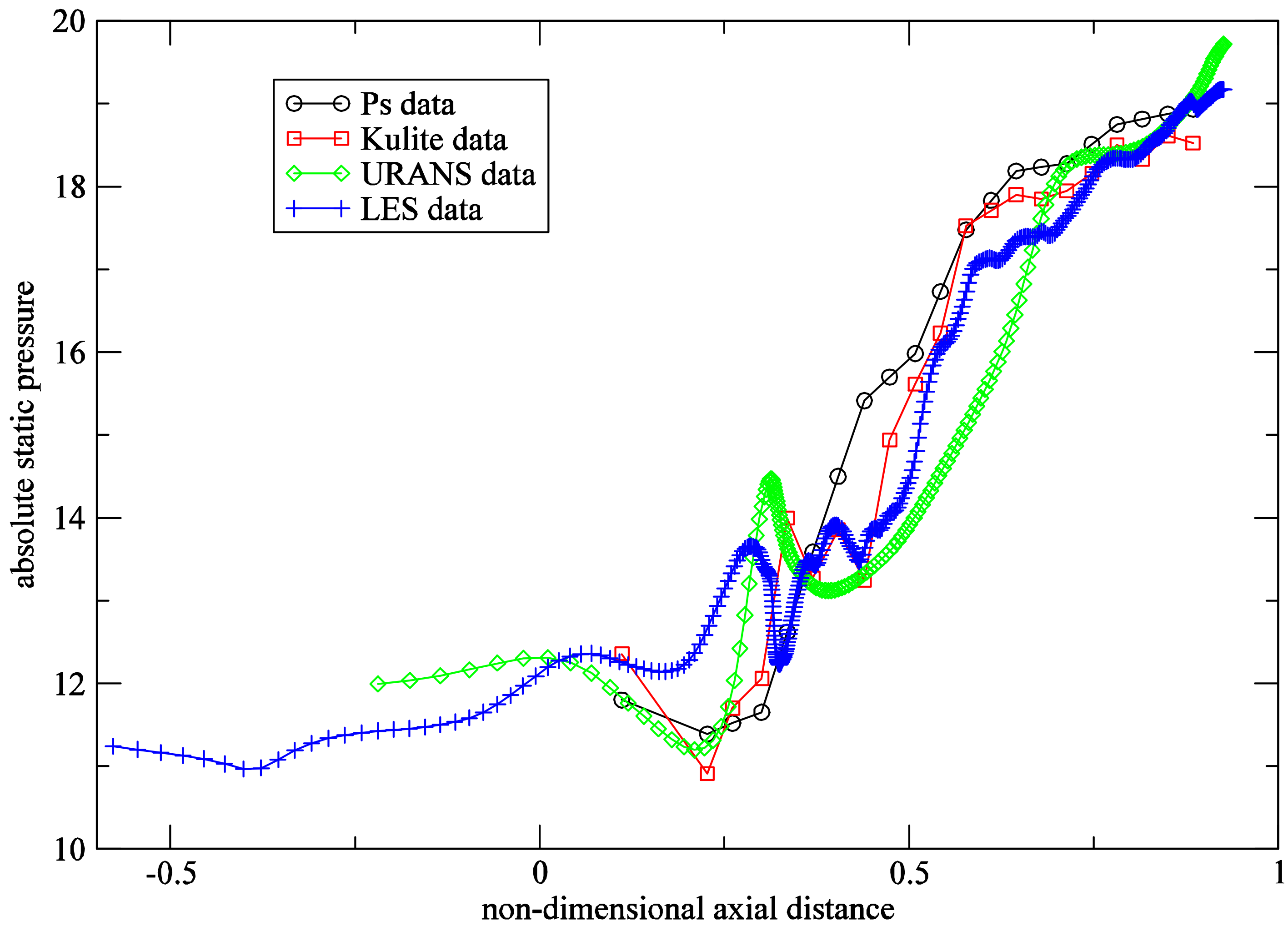


LES

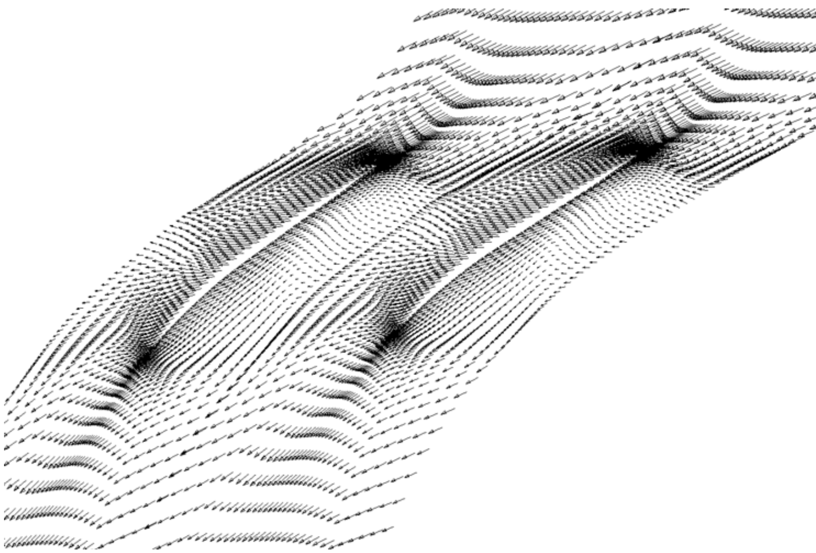
RMS static pressure and averaged velocity vectors



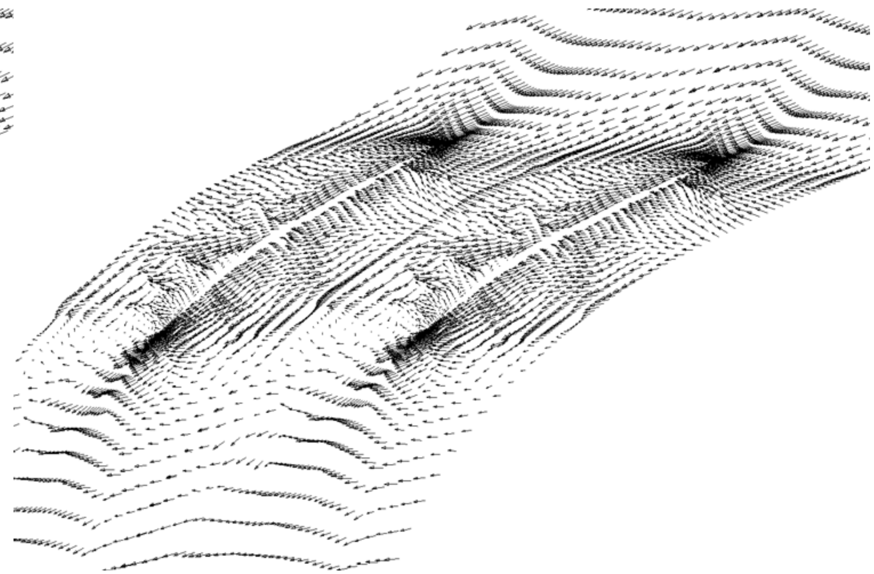
Comparison of pressure rise across rotor



Comparison of instantaneous velocity vectors at rotor tip, near stall

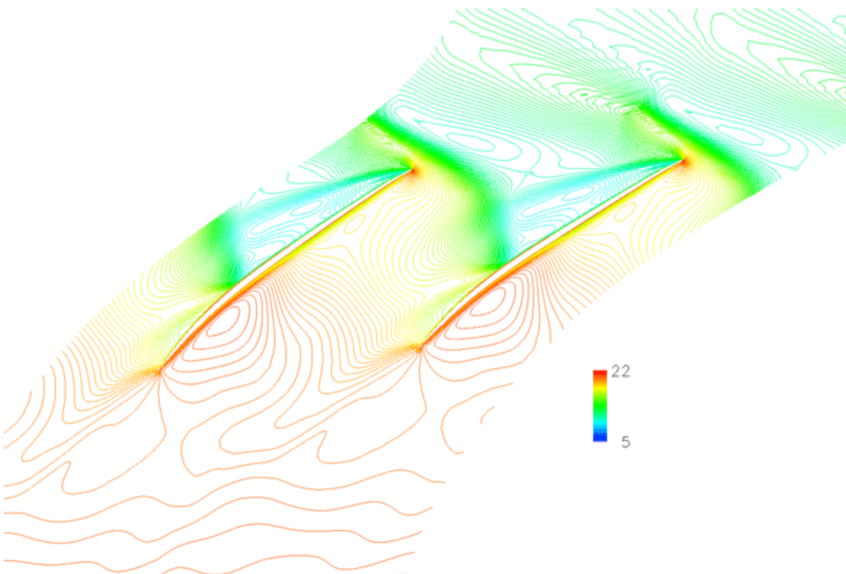


URANS

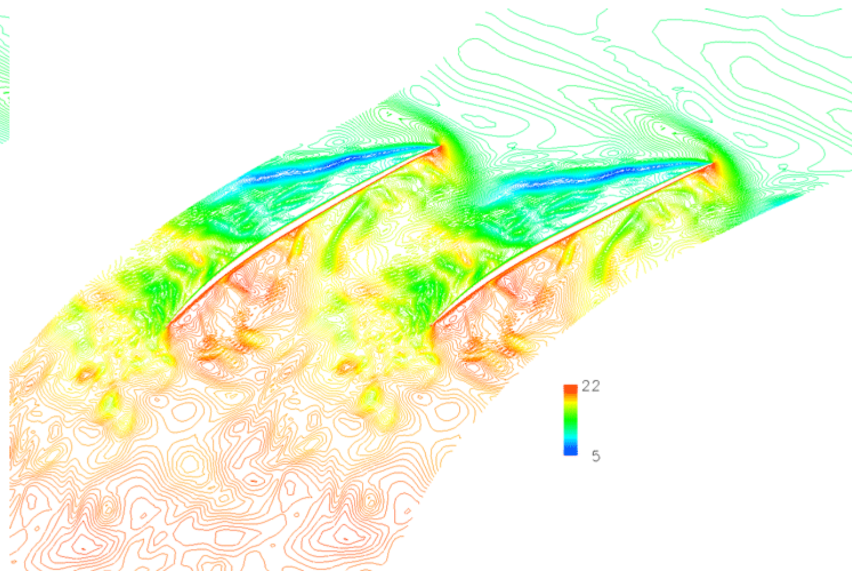


LES

Comparison of instantaneous pressure at rotor tip, near stall



URANS



LES

observations

- Unsteady features of tip flow in a modern transonic fan with composite sweep are examined.
- URANS calculates transient flow features at choke and at PE reasonably well.
- At near stall, LES calculates measured unsteady flow features much better.
- Unsteady flow plays dominant role in stall phenomena (stall line control) in modern transonic fan and better understaning of flow features will lead to better/new design concepts.

Why flow transition and low Reynolds number effects in turbomachinery ?

- 3 – 5 % efficiency loss due to low Reynolds # effects in LP turbine.
- 2 -3 % efficiency loss due to low Reynolds # effects in fan/compressor.
- Possible efficiency gain through flow control (laminar boundary layer etc.)

Prediction/calculation/calibration of transition in turbomachinery

- Transition models in RANS/URANS approach.
- LES/DNS approach.

LES for transition simulation

- Modeling for sub-grid stress term ?
- Near wall treatment ?

Flow transition at low Re.

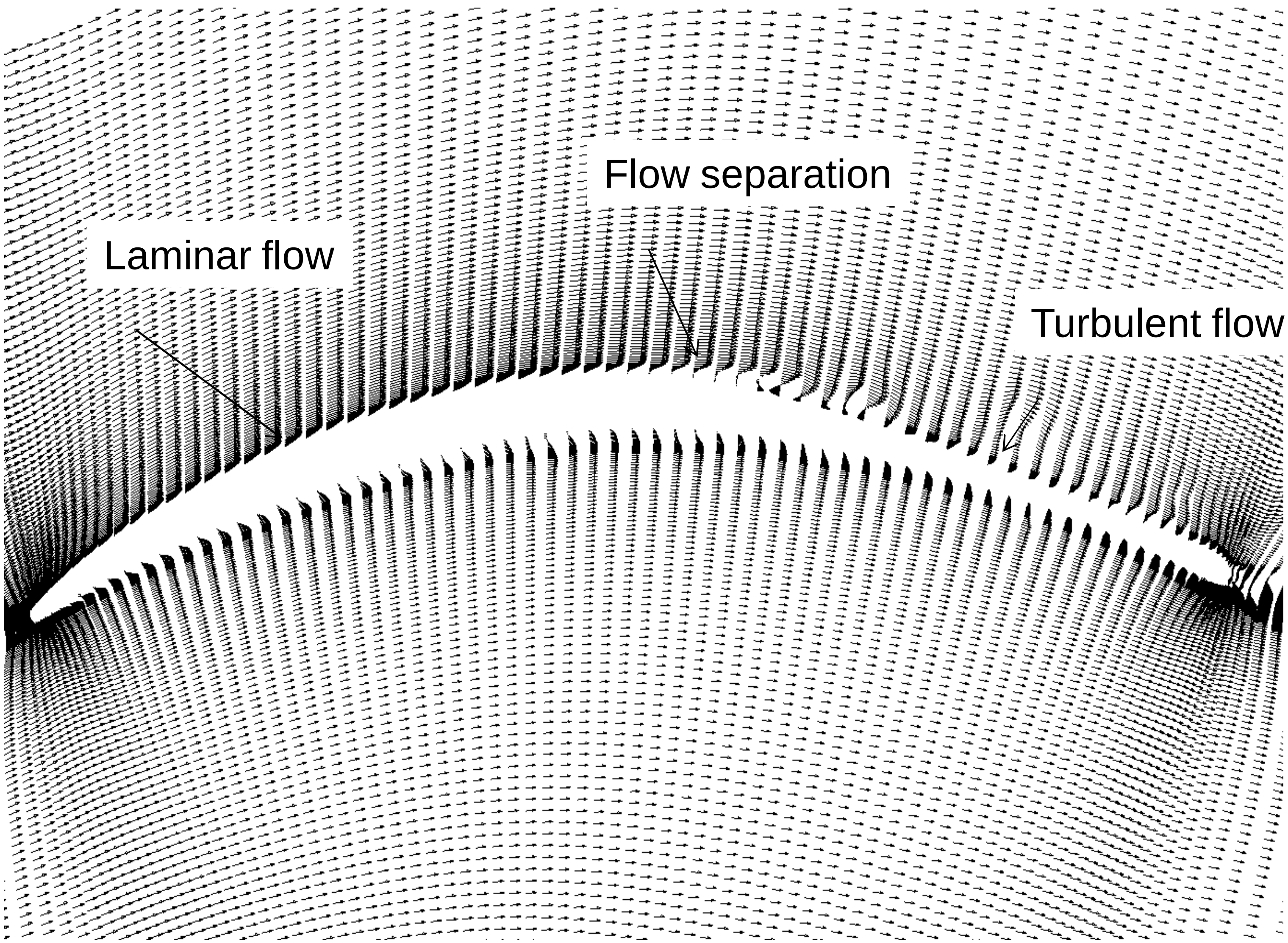
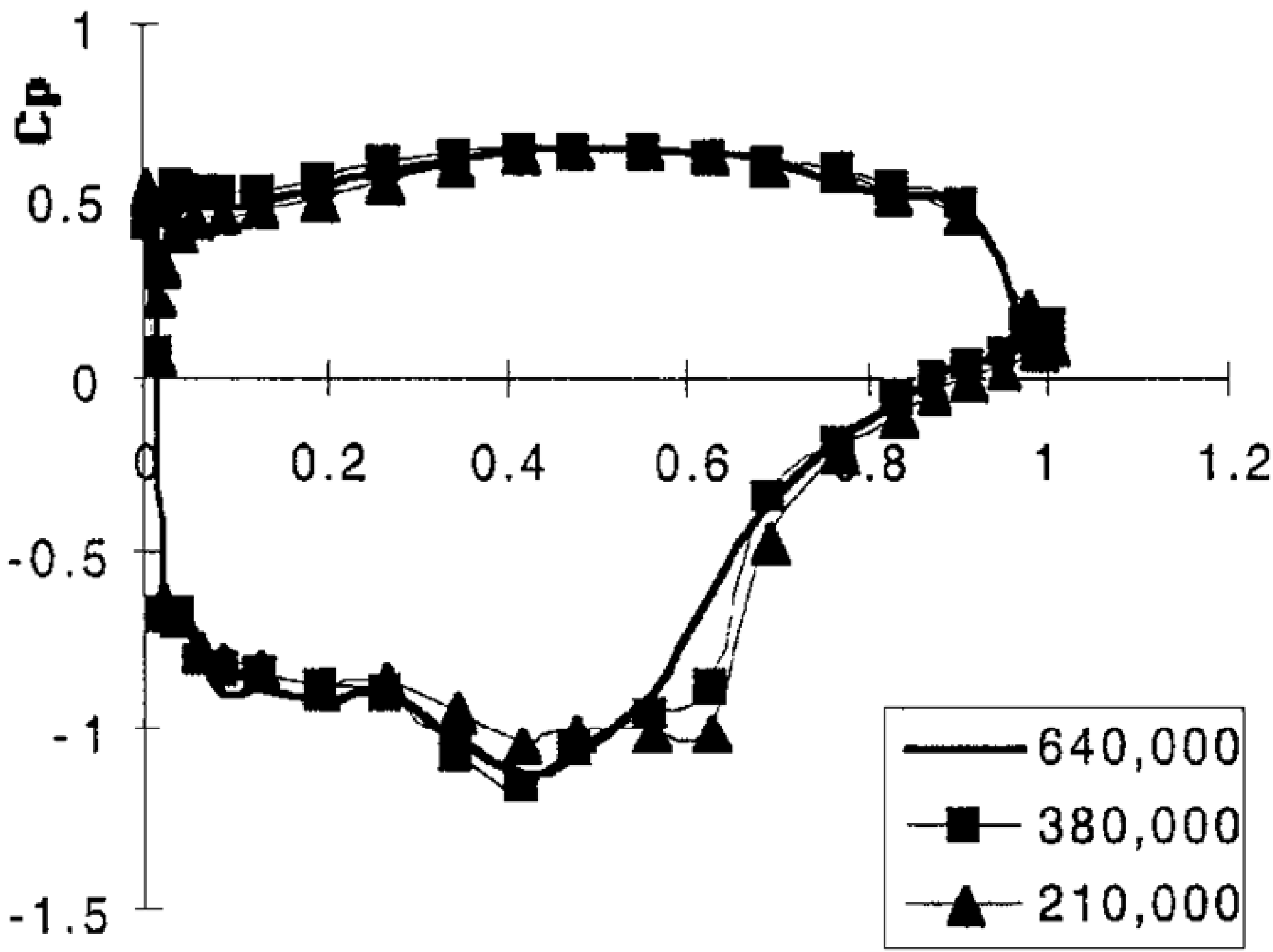


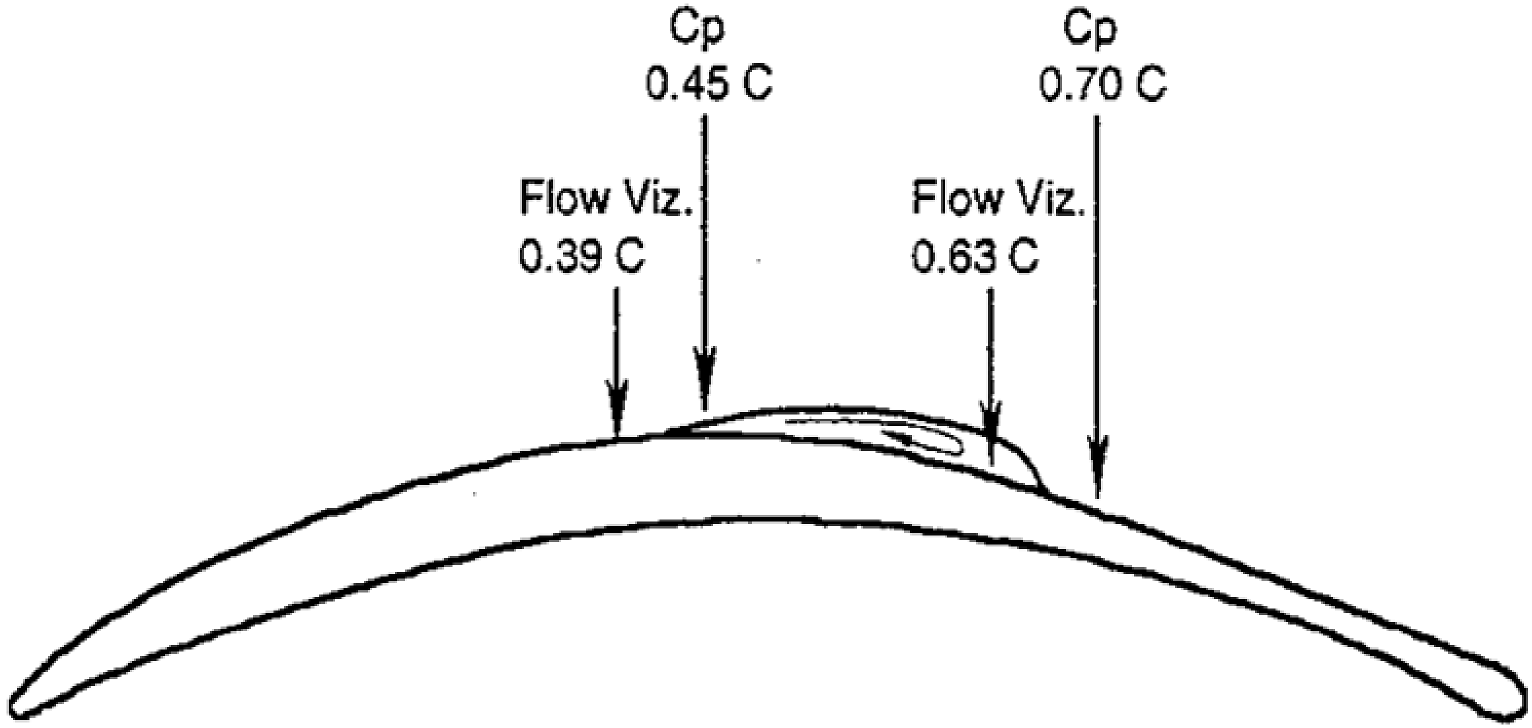
Table 1 Test section specifications

Property	Value
Blade type	Stator 67B CD
Number of blades	10
Blade spacing	152.40 mm
Chord	127.14 mm
Setting angle	16.3 deg $\pm$ 0.1 deg
Span	254.0 mm

Measured changes in blade loading at differe



Flow separation, reattachment, transition at low Re.

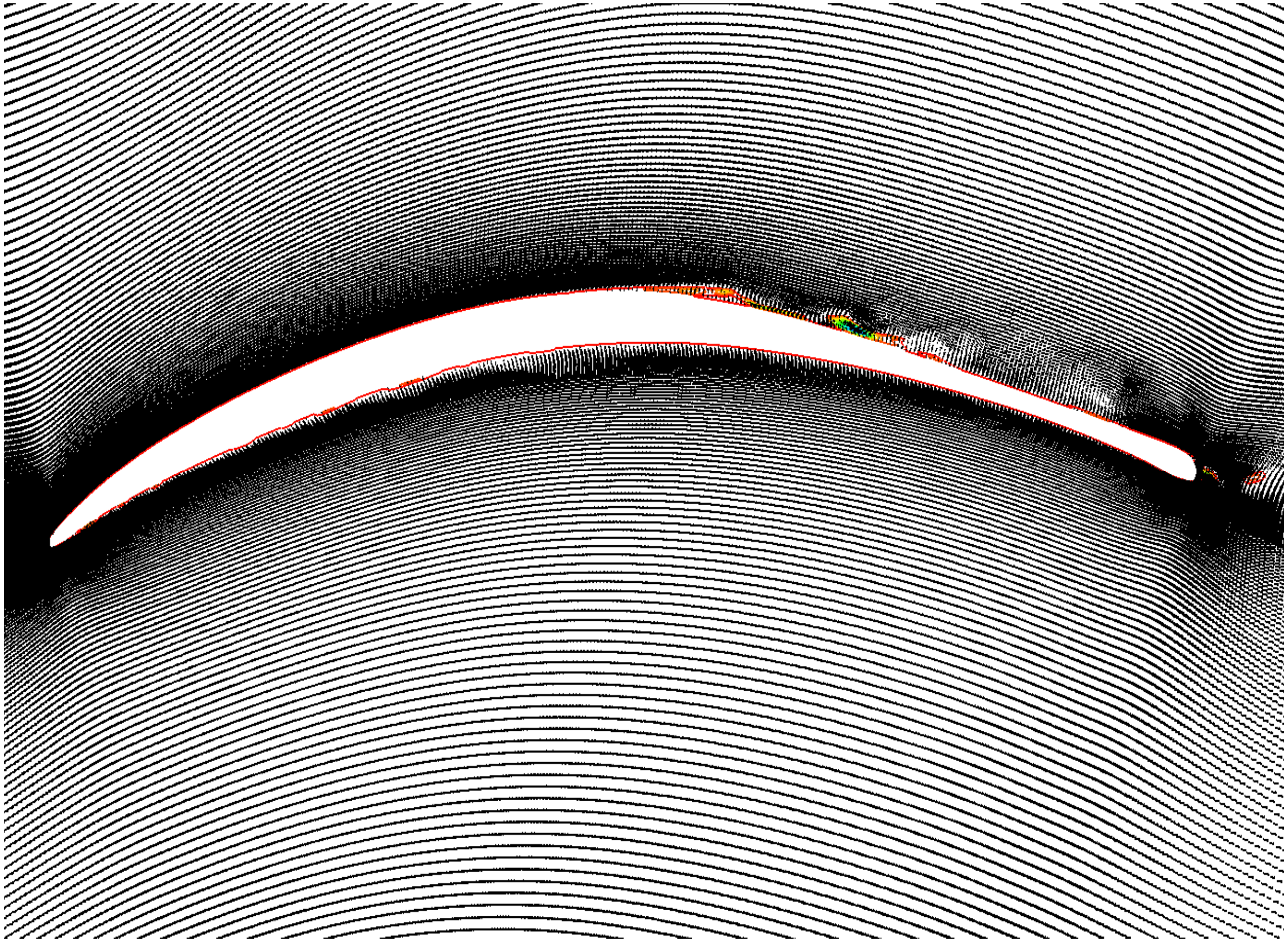


Flow characteristics at Re = 210,000

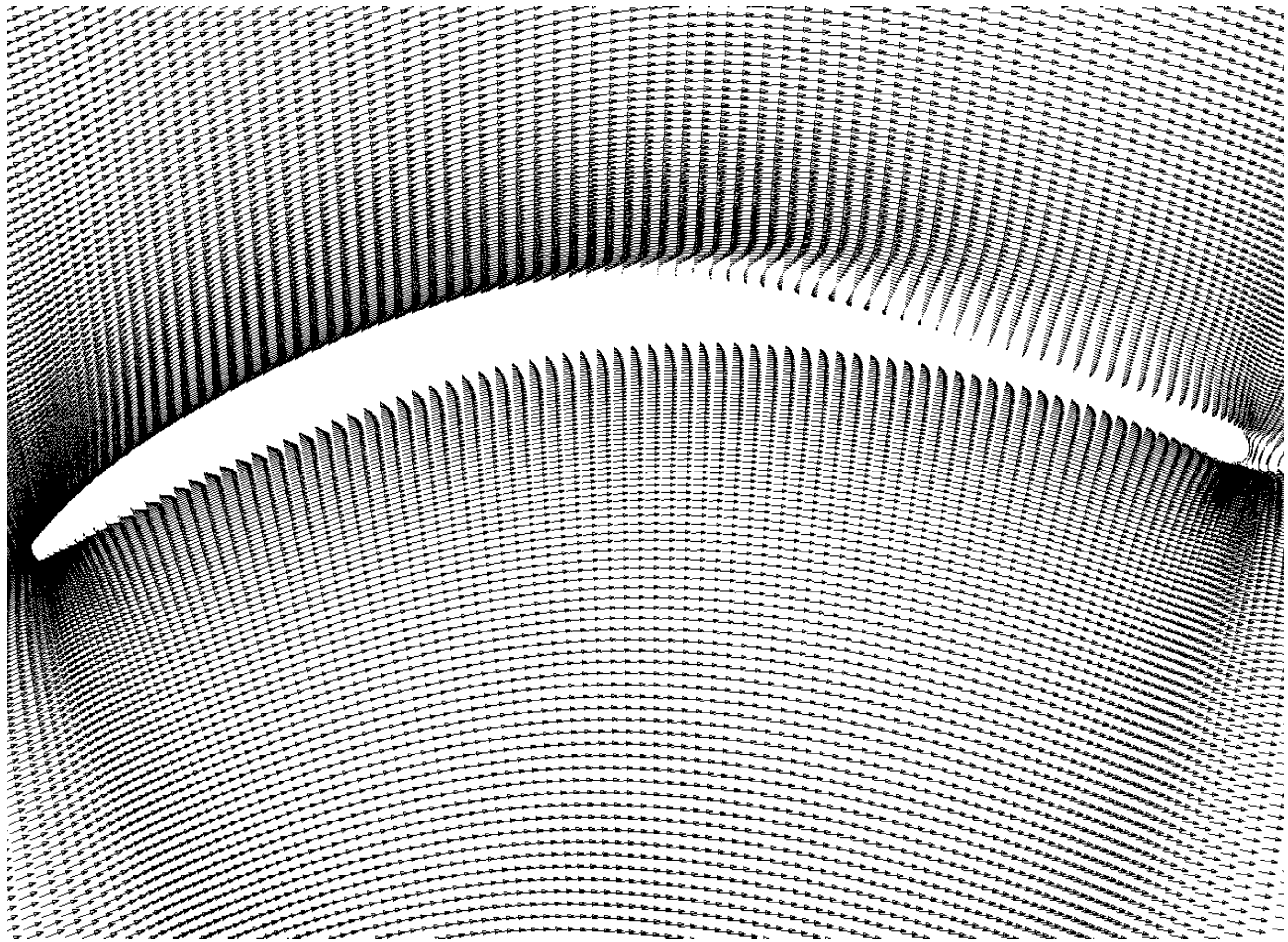
Large Eddy Simulation

- 3^{rd}-order scheme for convection terms.
- 2^{nd}-order central differencing for diffusion terms.
- Sub-iteration at each time
- A single block I-grid, 360x240x720.

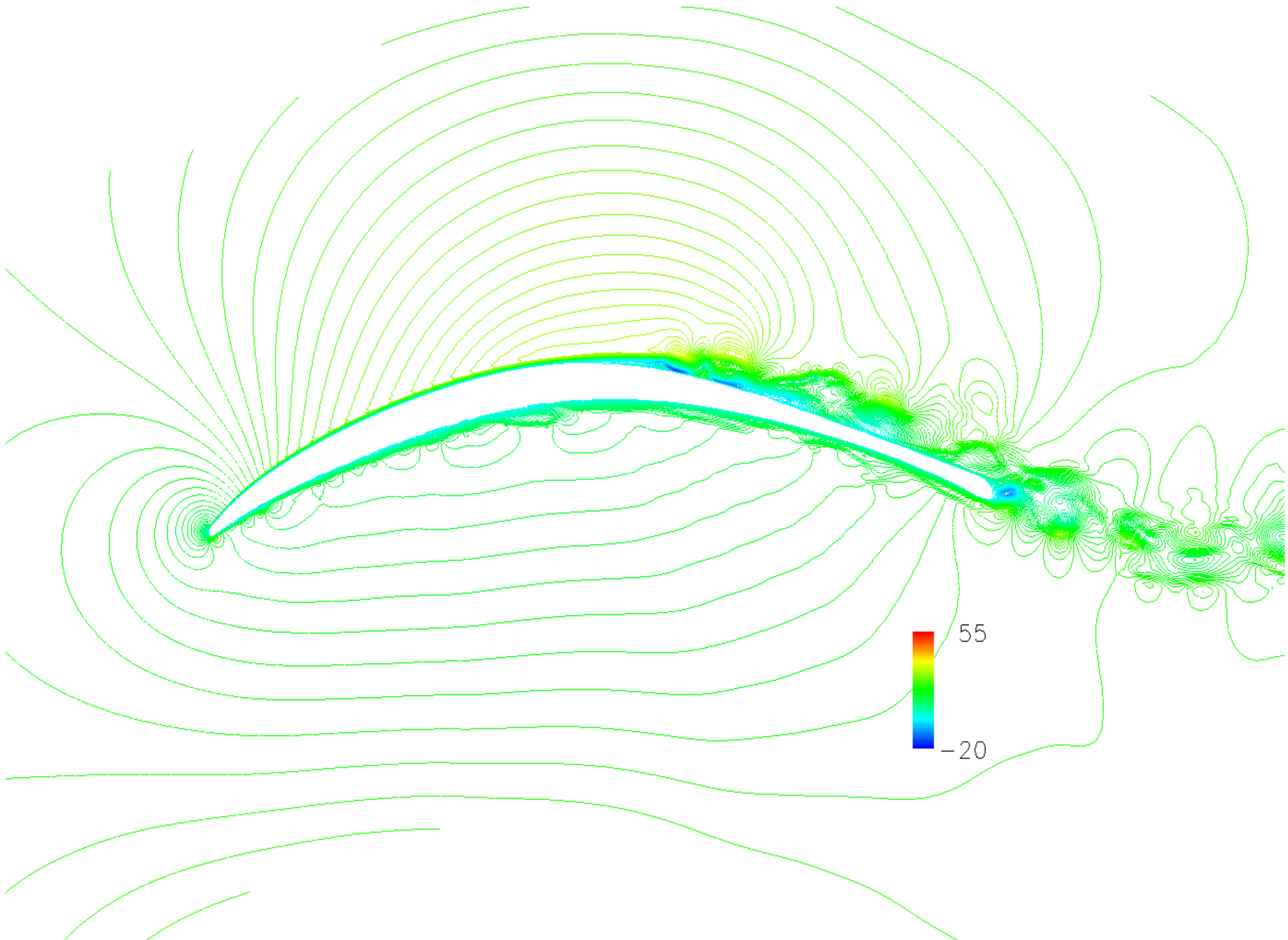
Instantaneous velocity vectors, LES, Re. # 210,000

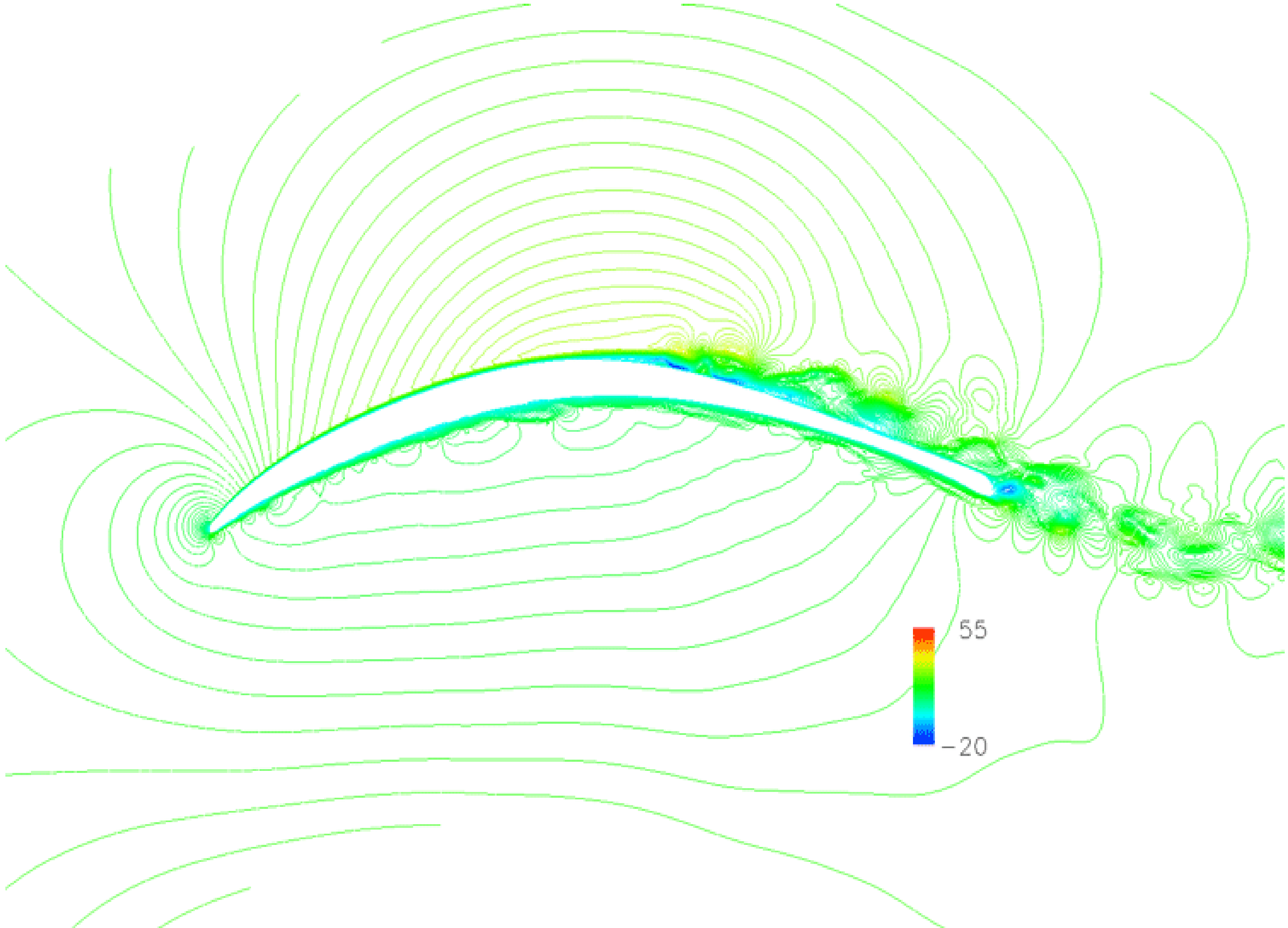


Averaged velocity vectors, LES, Re. # 210,000

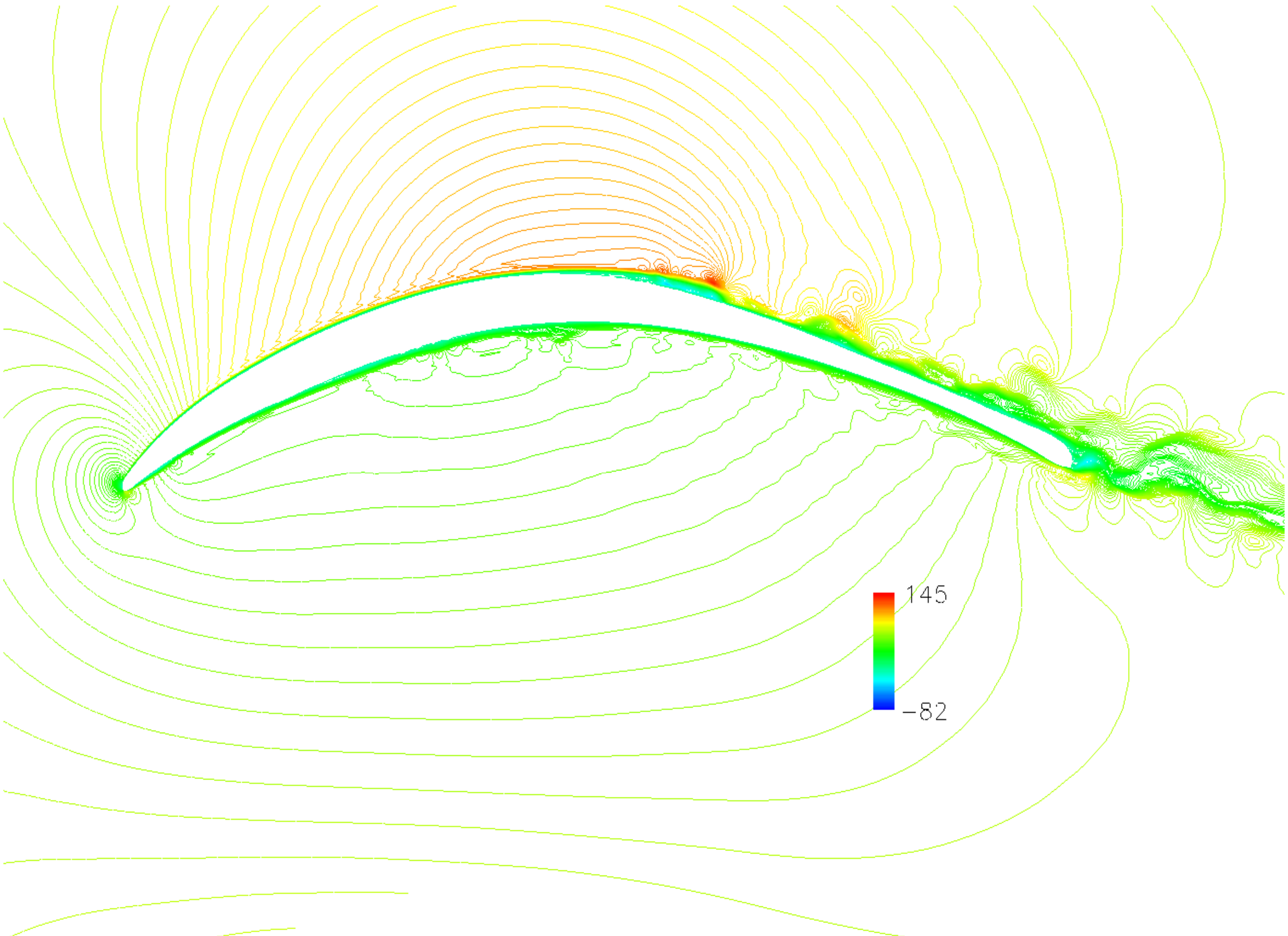


Instantaneous axial velocity contours, LES, Re. # 210,000

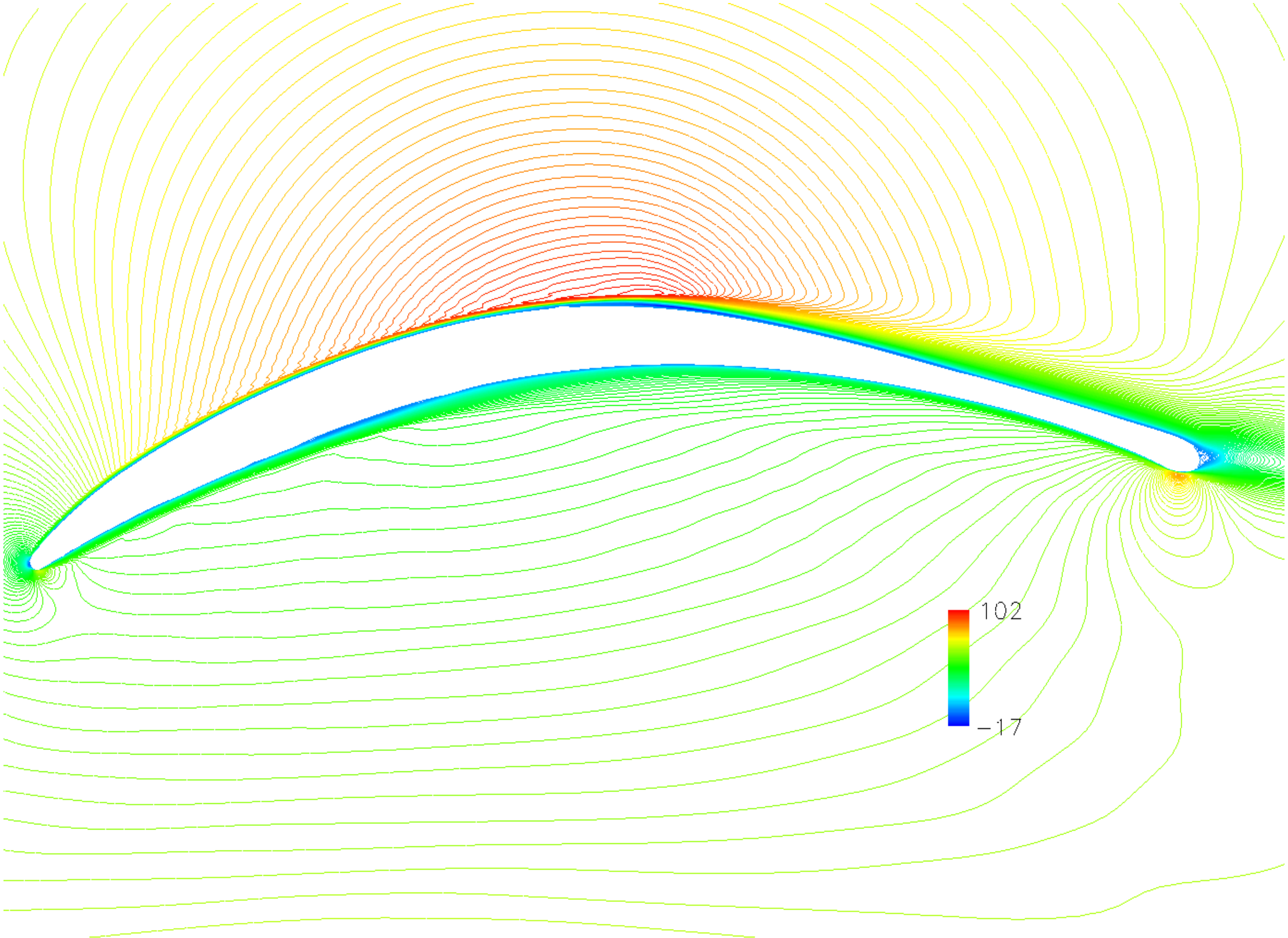



55
−20

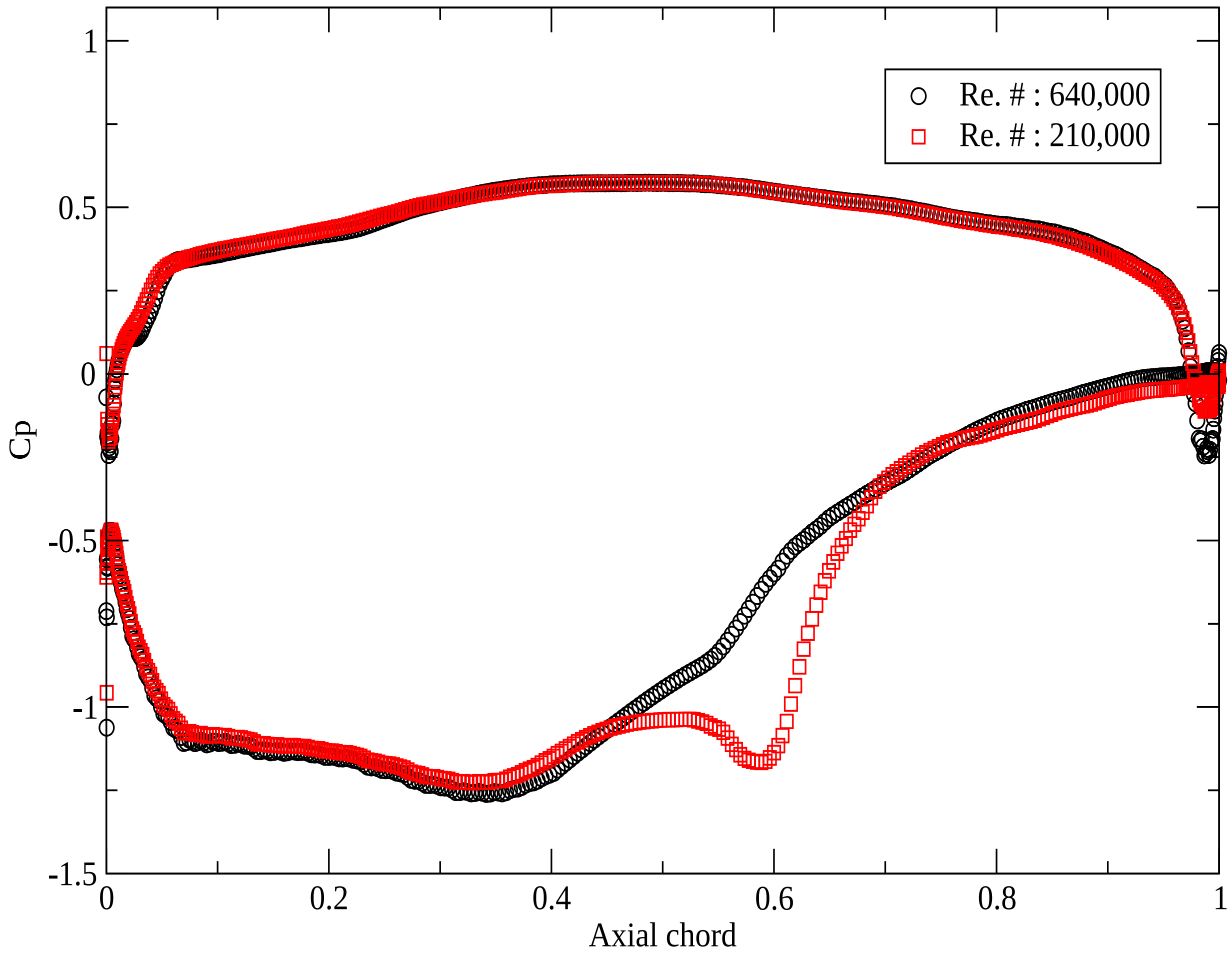
Instantaneous axial velocity contours, LES, Re. # 640,000



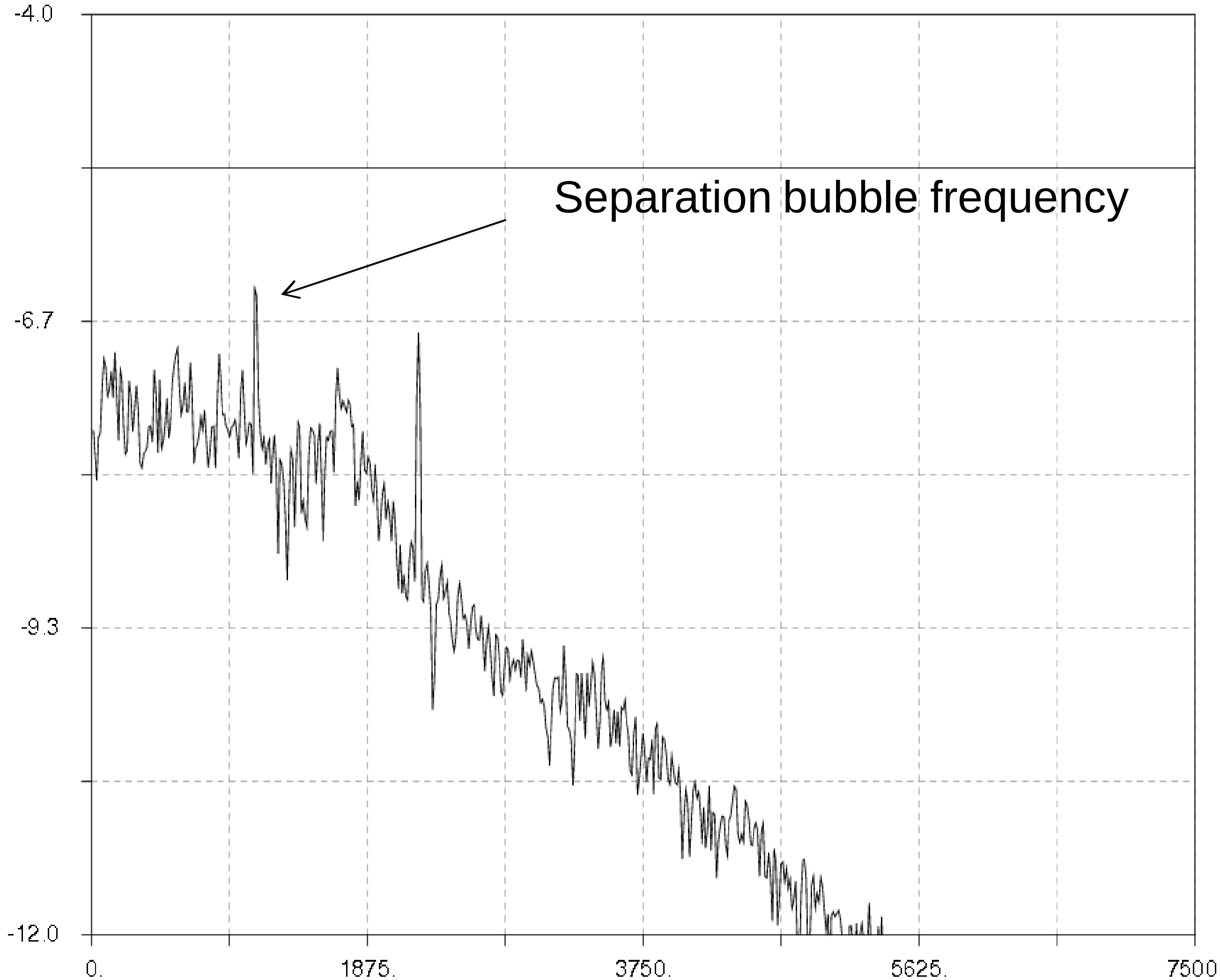
Averaged axial velocity contours, LES, Re. # 640,000



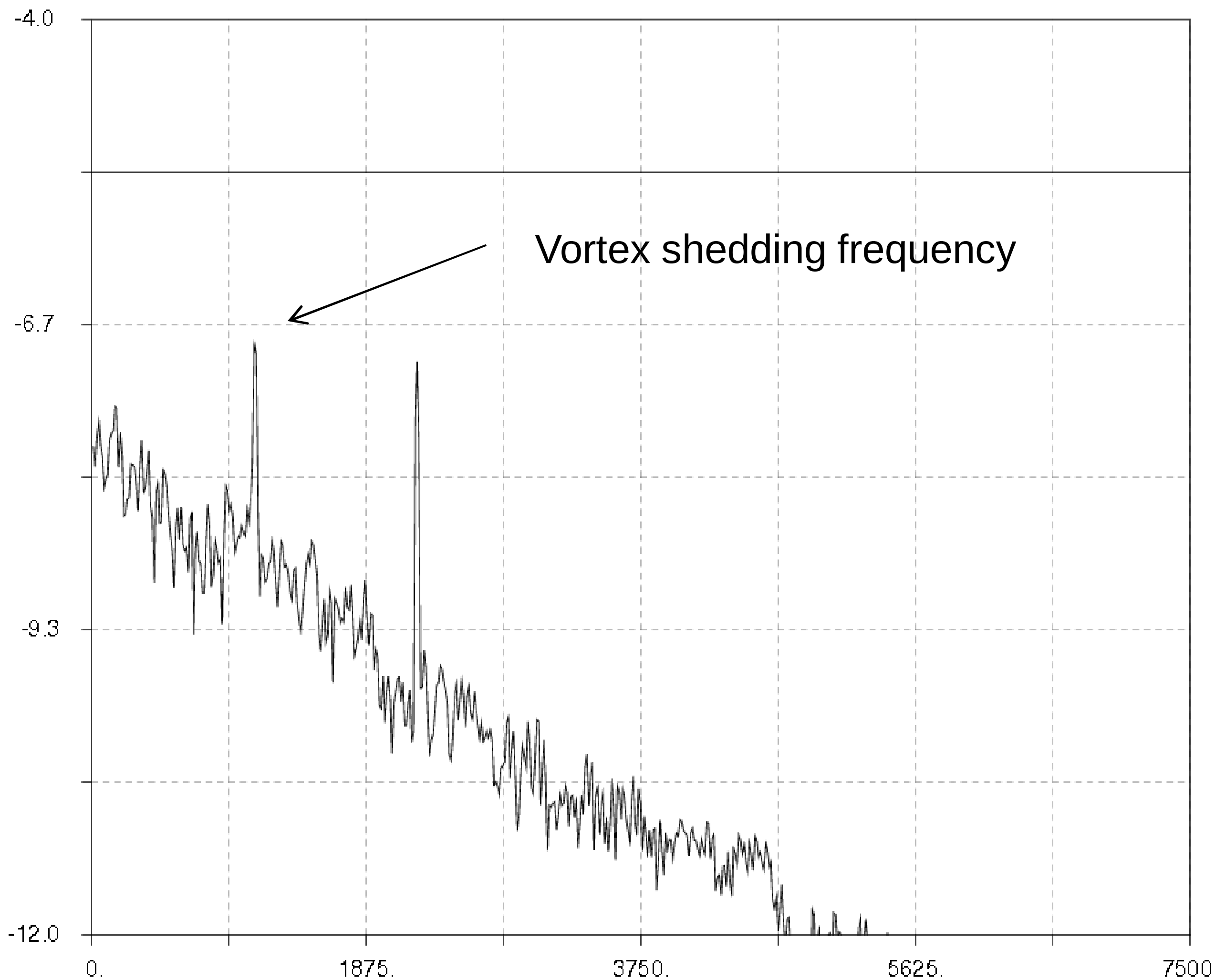
Effects of Re. # on blade loading,



Pressure spectra, center of separation bubble



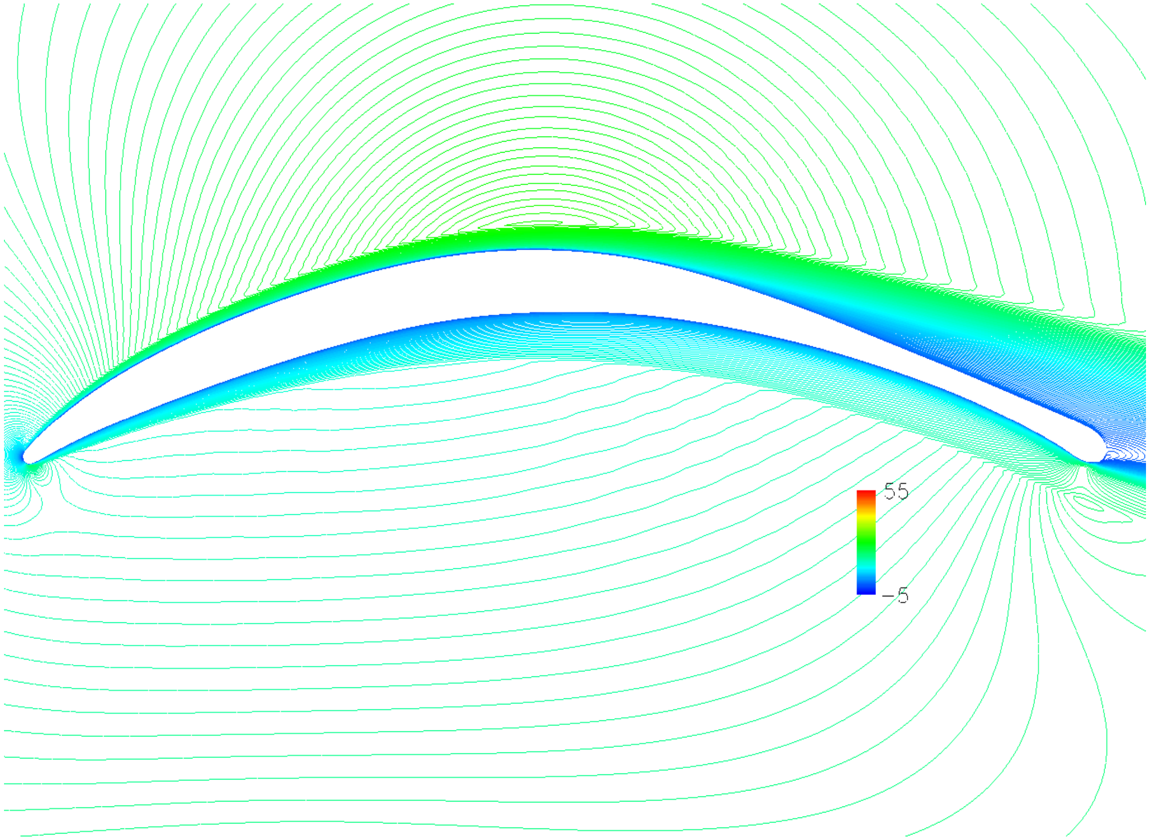
Pressure spectra, trailing edge of blade



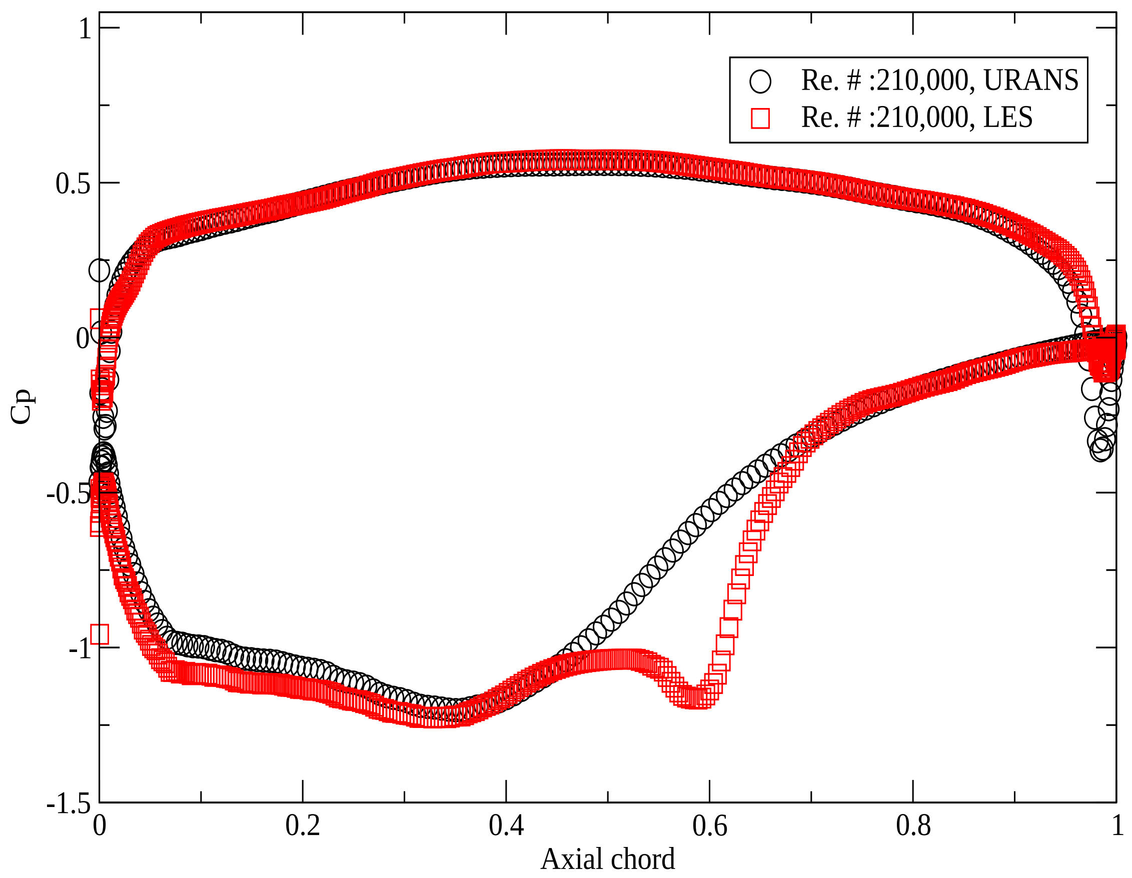
Application of URANS without transition model, Re. # 210,000

- Two-equation turbulence closure.
- 180x120x360 I-grid.

Averaged axial velocity contours, URAN Re. # 210,000



Comparison of blade loading between URANS and LES, Re. # 210,000



Observations

- Flow fields at Re. # of 210,000 and 640,000 are highly transient.
- Laminar separation bubble moves with the same frequency of the TE vortex shedding.
- The investigated type of flow transition (laminar flow separation, reattachment, transition) seems to be calculated reasonably well with the LES based on the current grid.

Current research issues

- Sub grid stress model validation/comparison.
- Near wall treatment validation/comparison.
- Realistic data set of turbomachinery flow highly desirable.