International Conference on Flow Physics and its Simulation
- In memory of Prof. Jaw Yen Yang,
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Numerical Study of Transition-Related Turbomachinery Flows

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Outline

- Modelling transitional flow
- Hybrid RANS(transition model)/LES method
- Hybrid RANS/LES for noise prediction

Motivations

- The determination of (turbomachinery flow) transitional region is very important for blade design optimization:
  - A mixture of laminar, transitional & turbulent flow on blade surface (Re_c <1E6).
- Studies on turbomachinery flow transition have revealed multiple transition modes that arise:
  - Separation-induced transition: much larger turbulent spot formation rate than in attached flows;
  - Bypass transition: dominated by freestream

Motivations

- The determination of transitional region is very important for blade design optimization:
  - Laminar, transitional & turbulent flows on blade surface ($Re_c<10^6$).
- Studies on turbomachinery flow transition have revealed multiple transition modes that arise:
  - Separation-induced transition: much larger turbulent spot formation rate than in attached flows;
  - Bypass transition: dominated by freestream disturbances
    - Disturbances penetrate into laminar boundary layer by pressure diffusion (non-local effects) (Jacobs & Durbin 2001).
  - Natural transition: T-S & crossflow instabilities.
- Approaches to simulate transition flows:
  - DNS, LES & PSE (Parabolized stability equation) ;
  - Empirical methods: correlation with experiment data;
  - Model predictions: e^N & RANS for engineering application.

Categories of RANS transition models

- Low-Re turbulence models;
  - Damping functions for modelling the viscous sublayer (Wilcox 1992);
  - Solutions exhibit arbitrary dependence on initial conditions (Lumley et al. 2005).
- Intermittency models (γ + turbulence model: $\mu_{eff} = \gamma \mu_t$);
  - More accurate predictions;
  - Calculating γ need a separate transition-onset (*tr*) prediction criteria:

$$Re_{\theta,tr} = F(Tu_{\infty}, \nabla P)$$

  - Non-local formulations (e.g. θ) are cost-ineffective with modern CFD.
- Models based on local variables:
  - Lardeau et al (2008), Walters & Leylek (2004): $k = k_L + k_T$, $k_L \rightarrow k_T$;
    - Non-turbulent fluctuation exits before transition (Mayle 1997);
  - Menter et al (2002, 2005, 2006): solving the transport Eq. of $Re_{\theta,tr}$
    - Be incorporated into a commercial software package.

Transition model

- Former local-variable-based models: not validated for supersonic & crossflow-induced transition (Menter 2005)
  - No consideration of instability mechanisms.
- Suitable for all-speed aerodynamic flow as well as turbomachinery flow transition prediction:
  - Considering in μ_{eff} the effects of different instability modes & interaction between turbulent spots and surrounding laminar flows;
  - Non-local processes indirectly represented by an elliptic Eq.;
  - Formulated with local variables;
- Publications:
  - Wang & Fu. Development of an intermittency equation for the modeling of the supersonic/hypersonic boundary layer flow transition. Flow Turbu & Combust 2011.
  - Wang et al. A modular RANS approach for modelling laminar-turbulent transition in turbomachinery flows. Int J Heat Fluid Flow 2012.
- Incorporated into ELAN3D (TUB), TAU (DLR) and EDGE (FOI).

Modelling Separation-Induced Transition Flow

- *k-ω-γ* model (Wang , Fu, et al. 2012)

$$\frac{\partial(\rho\gamma)}{\partial t}+\frac{\partial(\rho u_j\gamma)}{\partial x_j}=\frac{\partial}{\partial x_j}\left\{(\mu+\mu_{eff})\frac{\partial\gamma}{\partial x_j}\right\}+P_\gamma-\varepsilon_\gamma$$

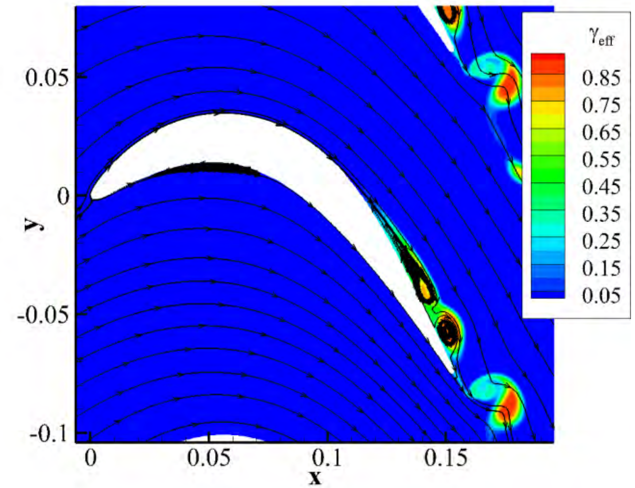
$$\frac{\partial(\rho\omega)}{\partial t}+\frac{\partial(\rho u_j\omega)}{\partial x_j}=\frac{\partial}{\partial x_j}\left\{(\mu+\frac{\mu_{eff}}{\sigma_\omega})\frac{\partial\omega}{\partial x_j}\right\}+P_\omega-D_\omega+Cd_\omega$$

$$\frac{\partial(\rho k)}{\partial t}+\frac{\partial(\rho u_j k)}{\partial x_j}=\frac{\partial}{\partial x_j}\left\{(\mu+\frac{\mu_{eff}}{\sigma_k})\frac{\partial k}{\partial x_j}\right\}+P_k-\varepsilon$$

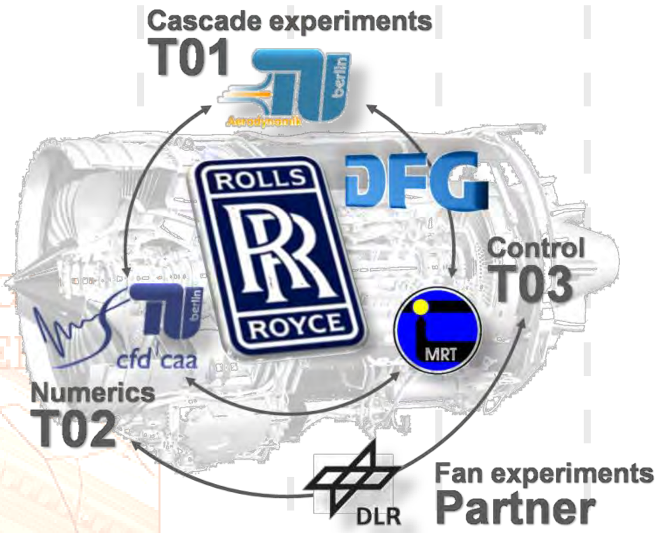
$$\mu_{eff}=(1-\gamma_{eff})\mu_{nt}+\gamma_{eff}\mu_t \qquad \mu_{nt}=C_\mu\bar{\rho}k\tau_{nt}$$

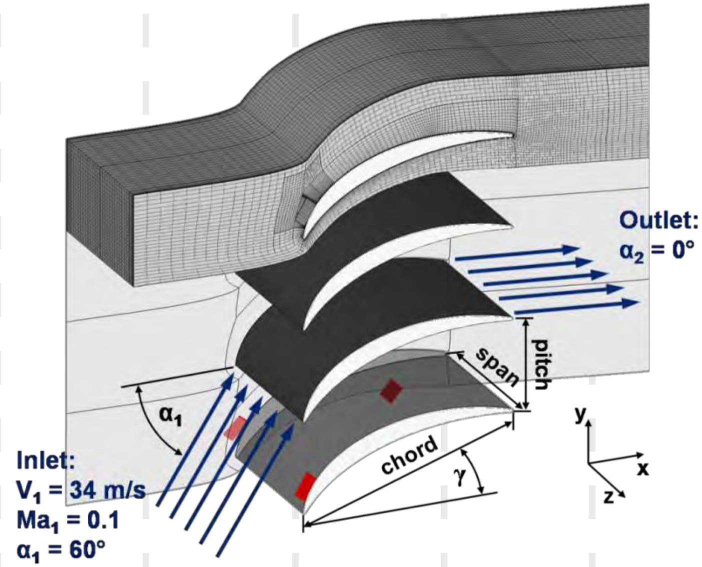
$$P_\gamma=C_4\rho F_{onset}\left[-\ln(1-\gamma)\right]^{0.5}\left(1+C_5\frac{k^{0.5}}{(2E_u)^{0.5}}\right)\frac{d^*}{\nu}\left|\nabla E_u\right|$$

$$\zeta_{eff}=\min\left[d^{*2}\Omega/(2E_u)^{0.5},C_1 l_T\right]$$



Active Flow Control (AFC) on a Highly Loaded Stator Cascade (EU TATMo project)





Transfer project:

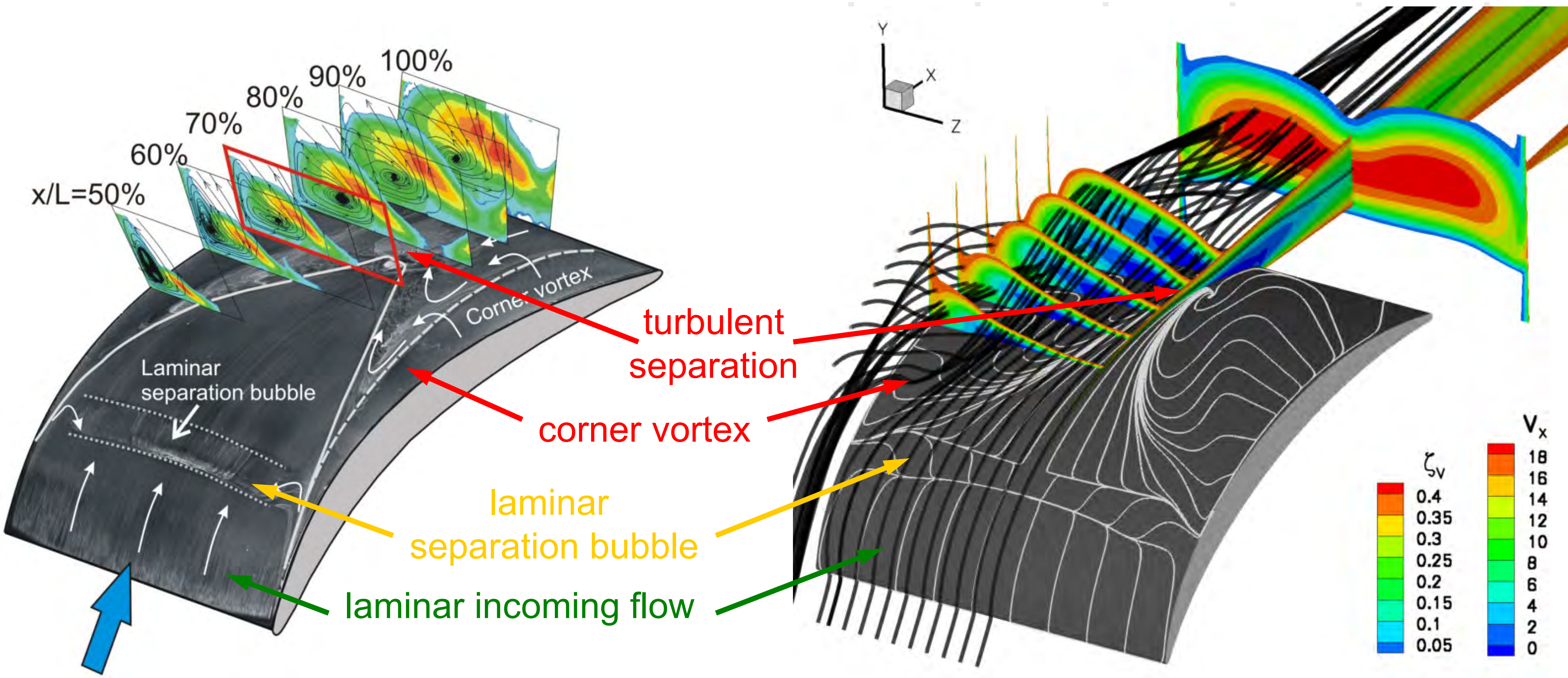
- Transfer of knowledge to industrial application
- Investigation of AFC on turbomachinery application
- T2: Numerical feasibility

Compressor cascade:

- Increase of pressure rise per stage
- Suppression of flow separation by AFC at casing and blade suction side
- Increase in compressor performance

EU TATMo (Turbulence and Transition Modelling for Special Turbomachinery Applications) project, 2006-2011.

Base flow



experiment

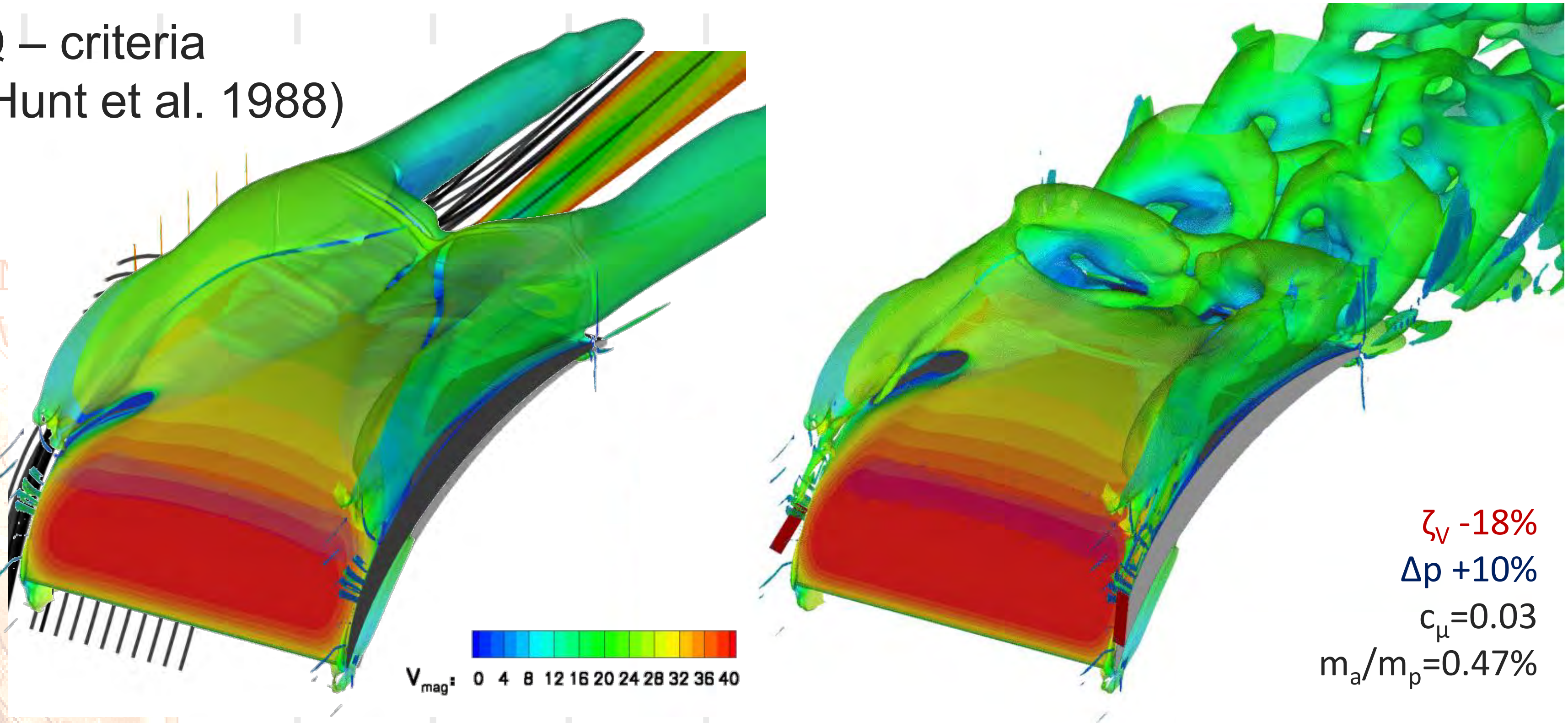
$Ma_1=0.1$

$Re_l=840000$

calculation

Visualization of combined actuation

Q – criteria
(Hunt et al. 1988)



base flow - steady

pulsed jets - combined AFC

RANS-LES 混合方法

- Turbulent Flow Simulation:

100%Modelling | 70% Resolved | 80-90% Resolved | 100% Resolved

RANS | hybrid RANS-LES (Detached-Eddy Simulation, DES) | LES | DNS

1990年 | | 2070年 | 2080年

Increasing cost and accuracy

- HRLM: Keep accuracy (LES) vs. Save cost (RANS).
- DES is replacing RANS becoming the main tool for the simulation of practical turbulent flows
  - Realized rational switching between RANS and LES;
  - P. Spalart (Boeing Aircraft Company, USA), M. Strelets, M. Shur, A. Travin (NTS, Russia).
  - Transition model has been implemented in RANS.

DES Type Hybrid Method

- Based on the SST turbulence model
  - Modify dissipation-rate term of TKE equation

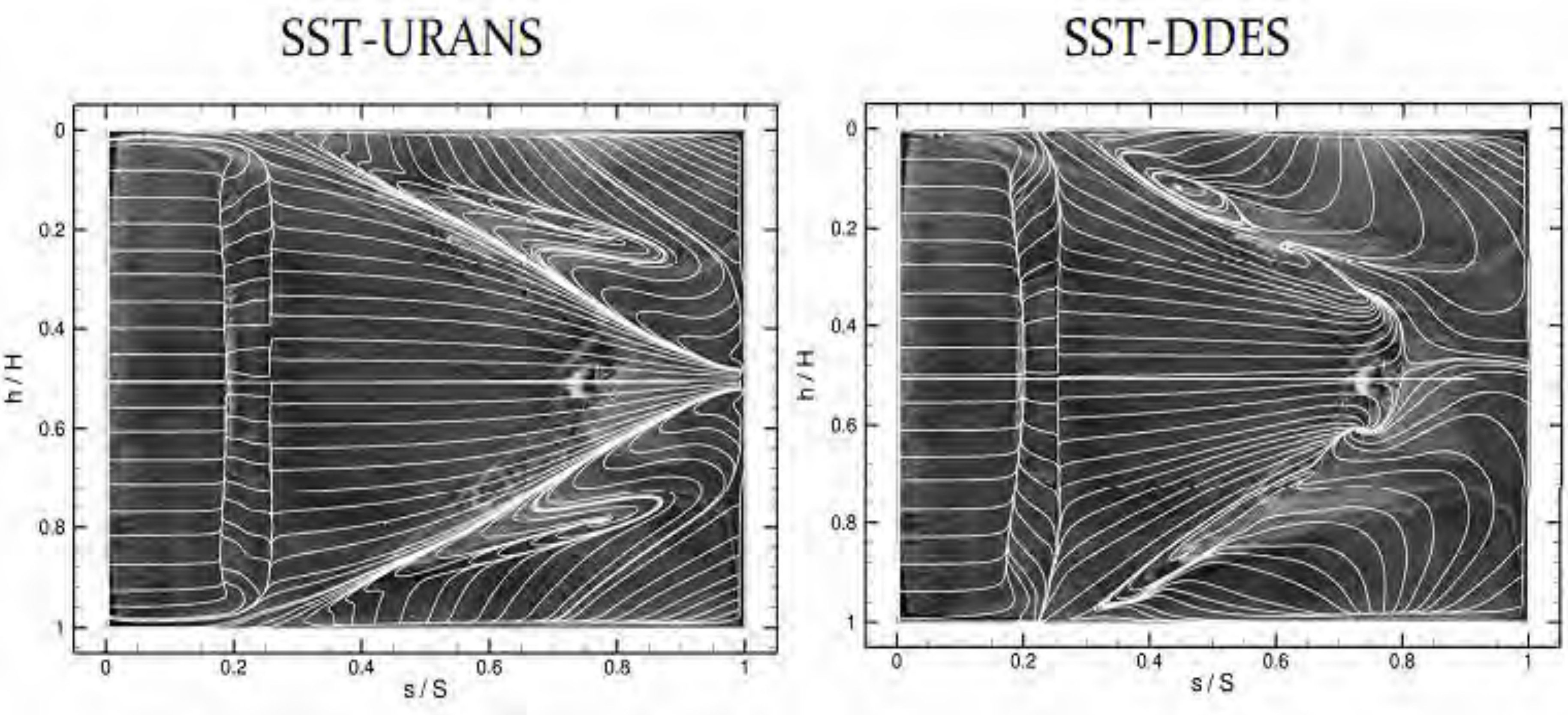
$$\frac{\partial(\rho k)}{\partial t}+\frac{\partial(\rho u_j k)}{\partial x_j}=\tau_{ij}S_{ij}+\frac{\partial}{\partial x_j}\left((\mu+\sigma_k\mu_t)\frac{\partial k}{\partial x_j}\right)-\frac{\rho k^{\frac{3}{2}}}{l_{Hybrid}}$$

- DES: $l_{DES}=\min(l_{RANS},l_{LES})$, where $l_{RANS}=\frac{\sqrt{k}}{\beta^*\omega}$; $l_{LES}=C_{DES}\Delta$

$$LES\_region: l_{RANS}>l_{LES}; RANS\_region: l_{RANS}<l_{LES}$$

- DDES: $\frac{\rho k^{3/2}}{l_{\mathrm{DES}}}\Longrightarrow\beta^*\rho k\omega F_{DDES}$, where $F_{DDES}=\max\left[(1-F_{SST})\cdot\frac{l_{RANS}}{l_{LES}},\ 1\right]$
  - Function F_{SST}: preserve RANS mode or delay LES
- IDDES: $l_{IDDES}=\tilde{f}_d(1+f_e)l_{RANS}+(1-\tilde{f}_d)l_{LES}$ — Spalart et al., 2006
  - combines DDES and the wall-modeled LES (WMLES)

Active Flow Control on a Highly Loaded Stator Cascade (TATMO project)



Flow

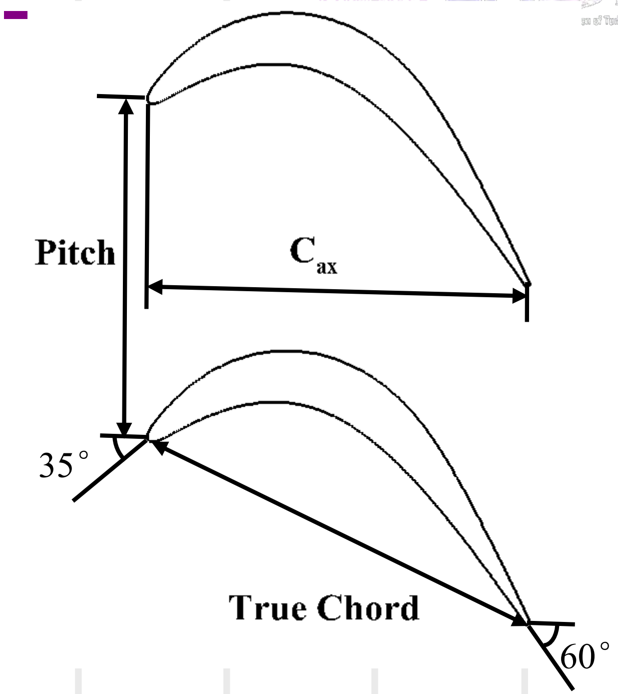
Flow

N.B. SST turbulence model with Fu-Wang transition model

Simulation of Transition at Low-Pressure Turbine

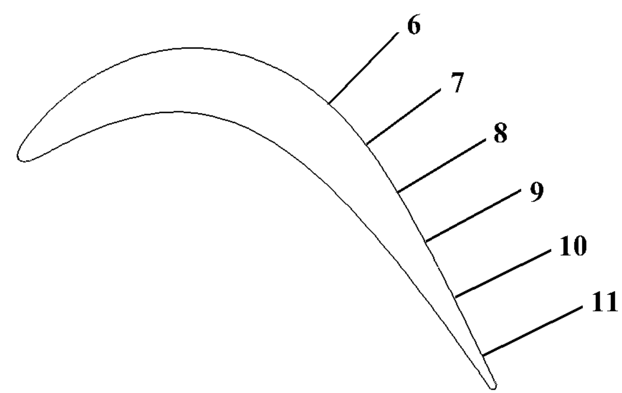
- **Low-pressure turbine cascade Pak-B**

Axial Chord, C_{ax}	Pitch	Suction surface length, L_s	Inlet flow angle	Exit flow angle
153.6	136.0	228.6	35°	60°



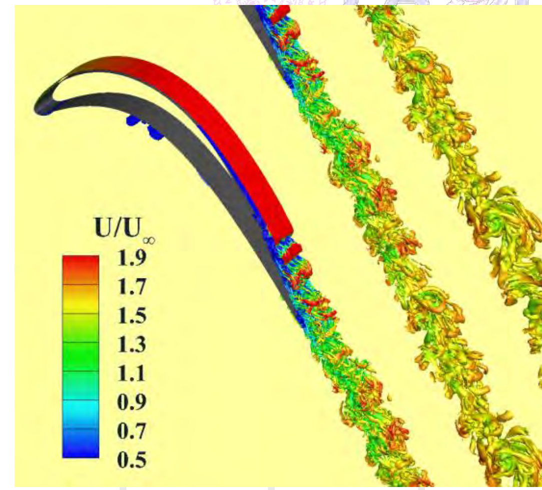
- **Measurement locations**

Station	6	7	8	9	10	11
s/L_s	0.528	0.611	0.694	0.777	0.861	0.944



DNS of Transition at Low-Pressure Turbine

- **Inviscid transition mode in shear layer**
- **Dominated by K-H type instability mode**



λ_2 contour

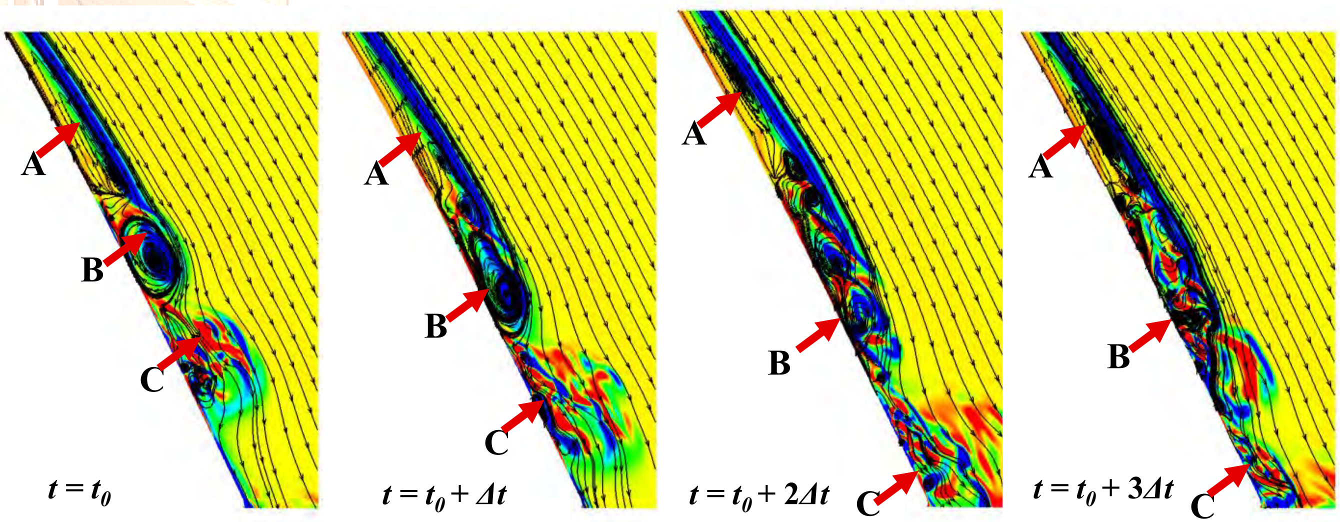
二维剪切层 → 准二维分离泡 A → 分离泡A 再附，与近壁面结构相互作用

↓

准二维分离泡 B →剪切层中形成 λ 涡→发卡涡包

↓

发卡涡包向下游脱落→ 尾迹

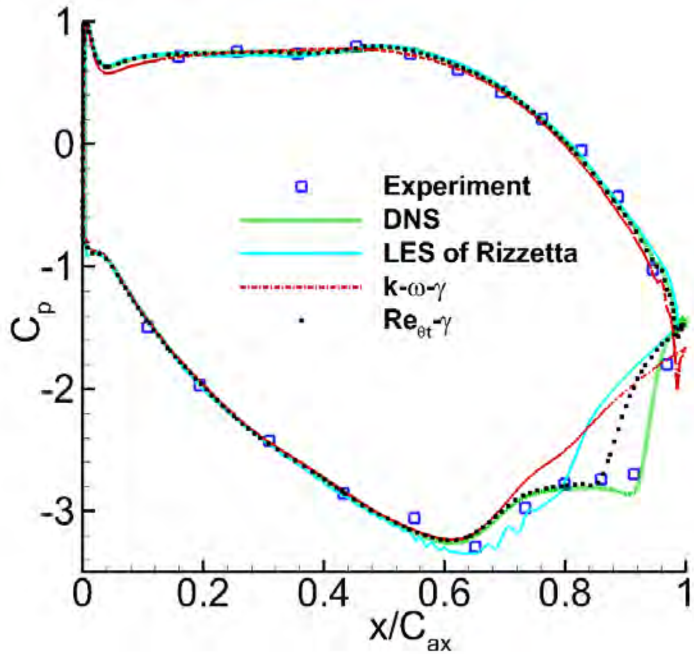


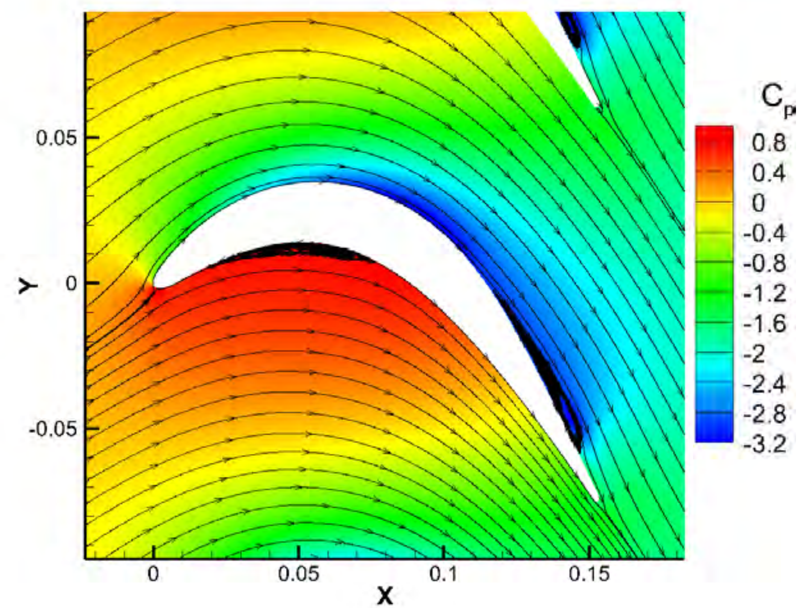
瞬时流线和涡量云图

Comparison of Transition at Low-Pressure Turbine with Different Methods

- 流场统计量

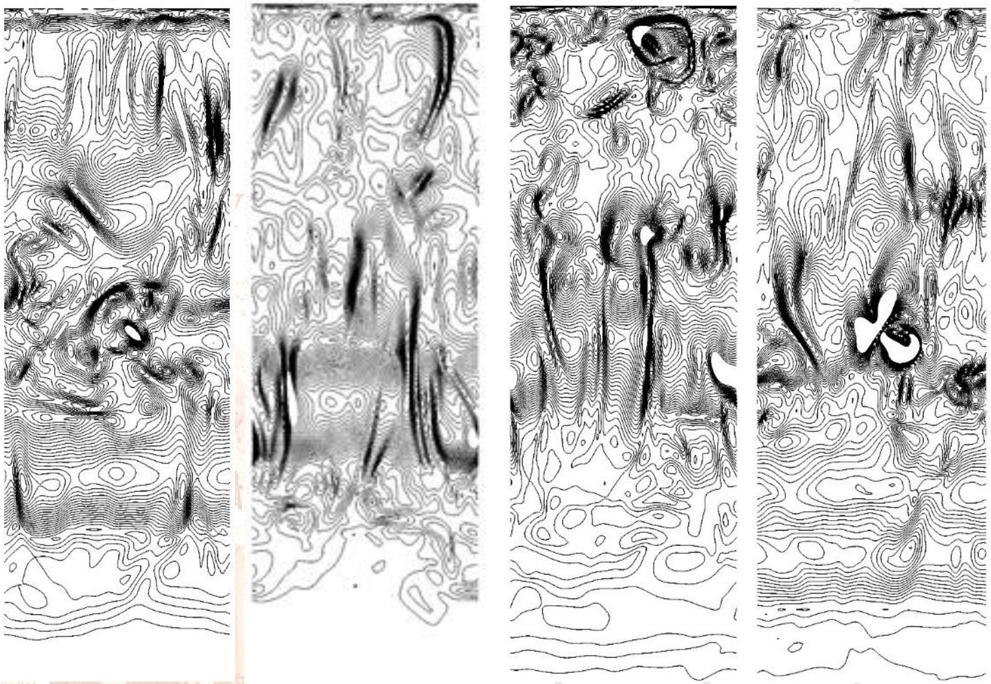
  - Re=100000



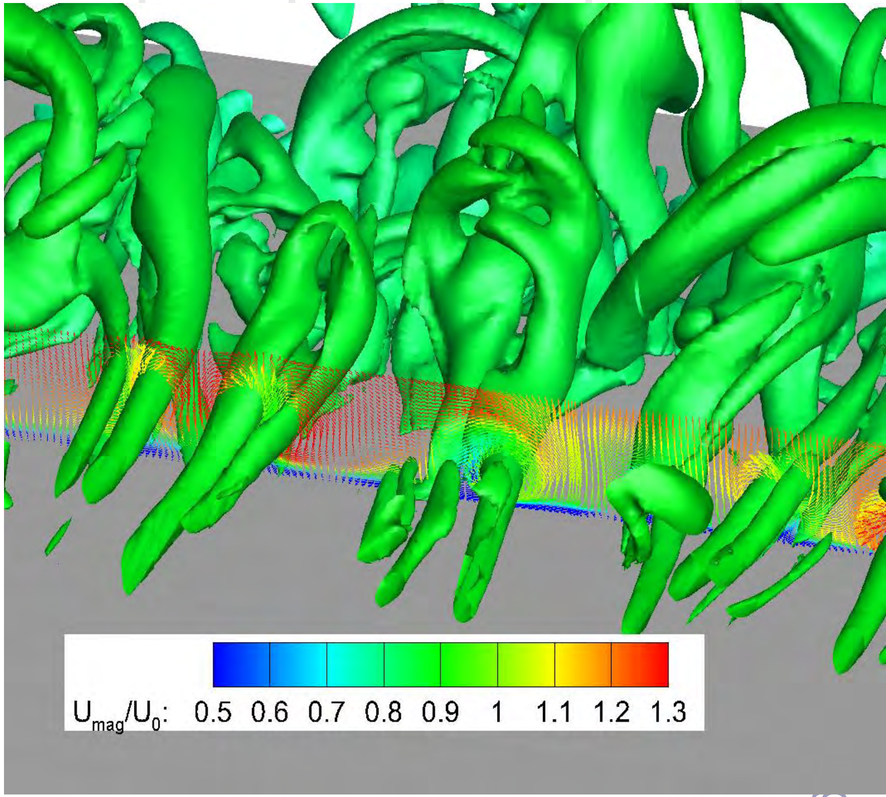


DNS agrees well with experiment.

Viscous transition mode near wall



y+ ≈ 50 处的瞬时速度云图



s ≈ 0.85 L_s 处的瞬时速度云图

1、近壁处出现高速条带和低速条带，它们与流向涡对应；
2、流向涡结构和是粘性失稳产生的，它表明壁面附近仍由粘性失稳占主导

An Advanced CFD & CAA Tool

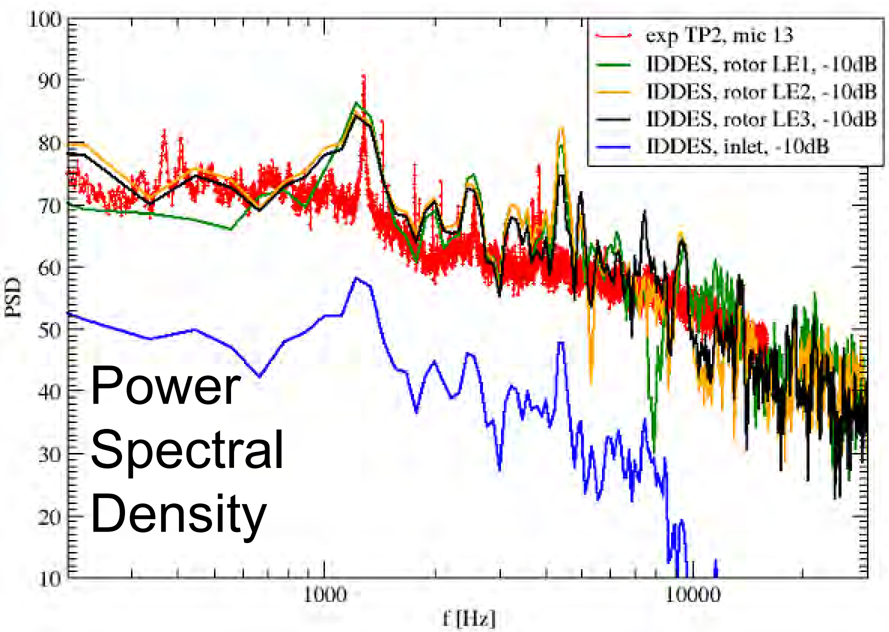
- Near-field simulation → ElaN3D
  - Pressure-based, compressible finite-volume-program
  - Cell-centered variable storage on block-structured meshes
  - 2nd order accurate in both time and space, implicit time discretisation
  - *DESs based on different RANS models.*
- Far-field extrapolation → C3Noise
- Integrates Ffowcs-Williams & Hawking equation (FW-H)
- 2nd order accurate in time and space
- DES provides access to noise prediction at minimal computational cost .

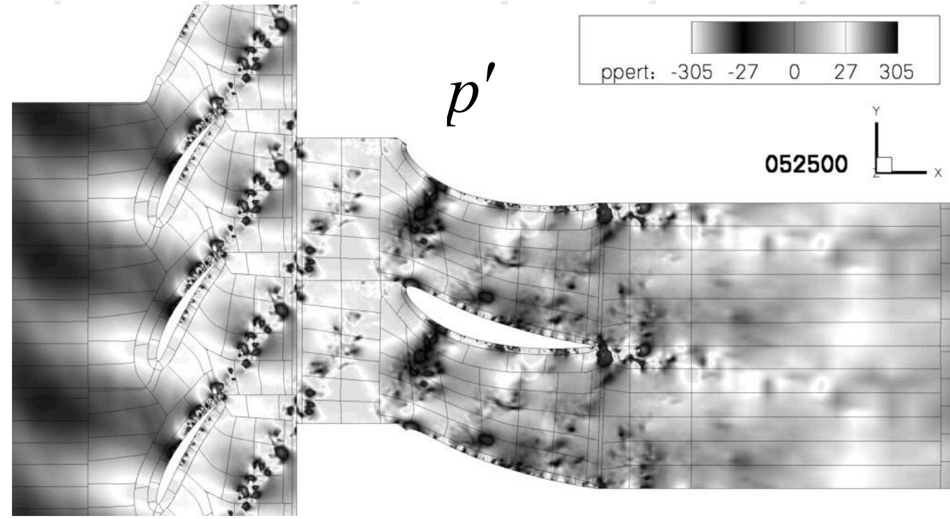
DES of Rotor-Stator-Cascade Broadband Noise

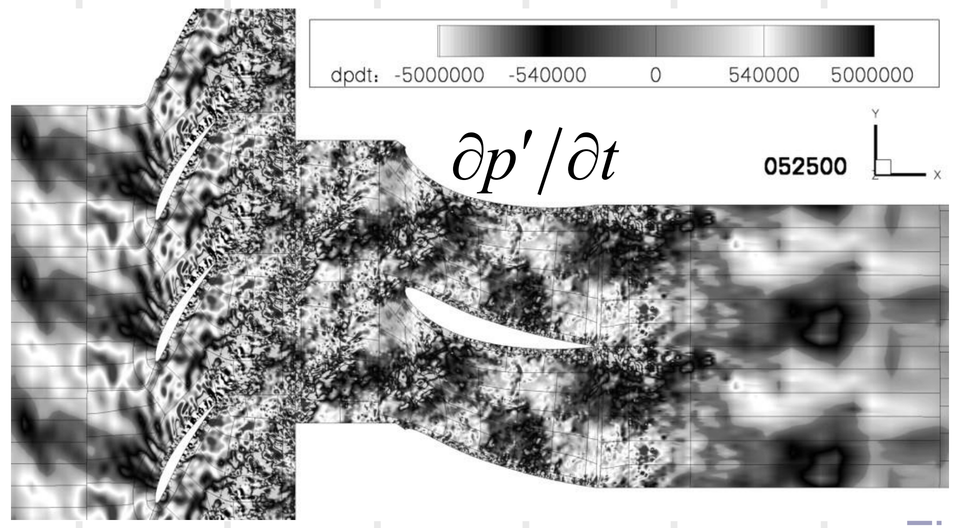
DLR Berlin Fan Rig:

- 24 rotor blades & 30 stator vanes;
- rotational tip Mach number 0.22.

First & successful attempt

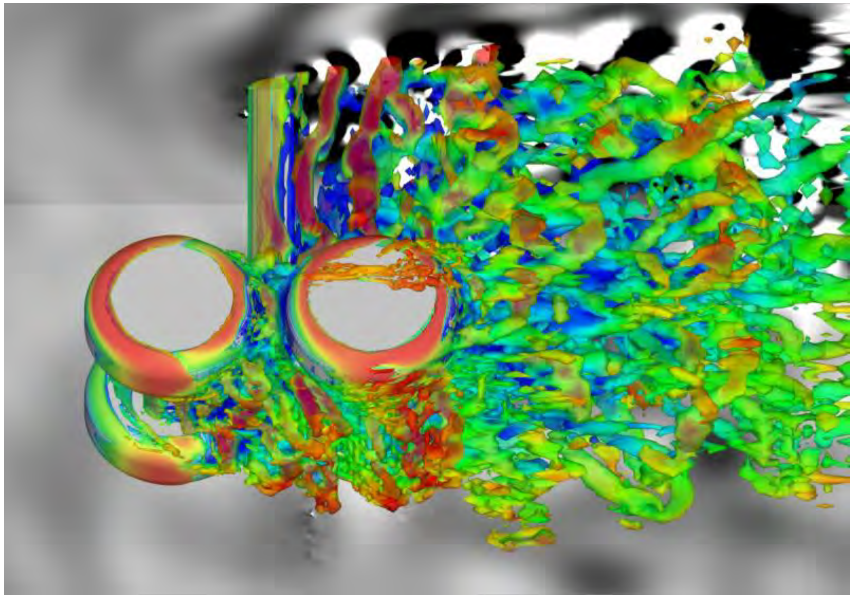






Noise prediction of a Rudimentary Landing Gear (RLG) using Detached-Eddy Simulation

- The landing-gear area is one of the major generators of airframe noise during taking off and landing.



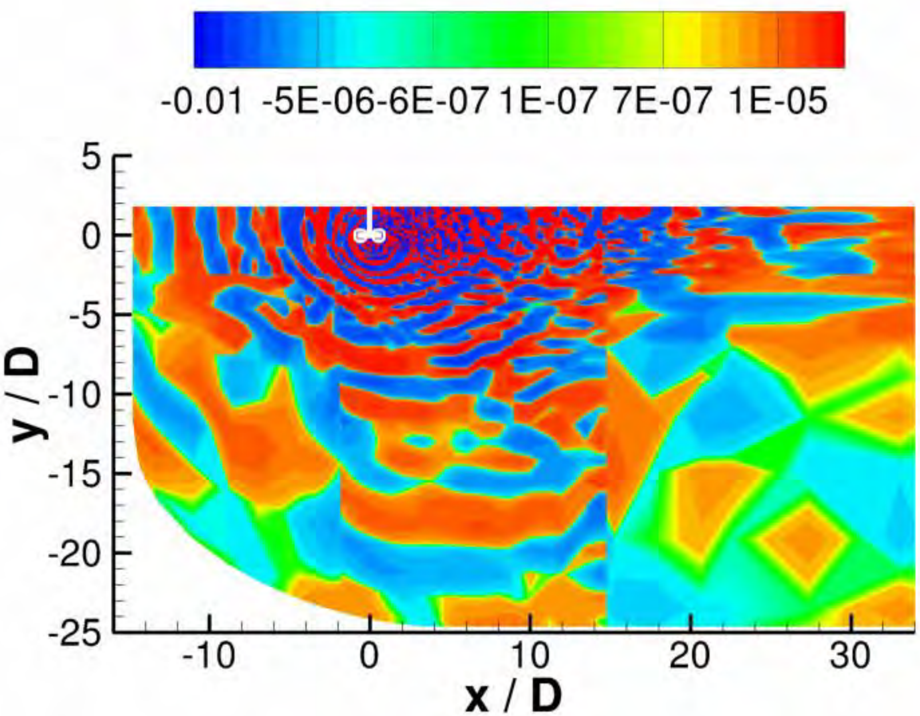
- First noise prediction of RLG using DES (Spalart & NTS, 2011).
- Goal: Independent verification of Spalart’s results.

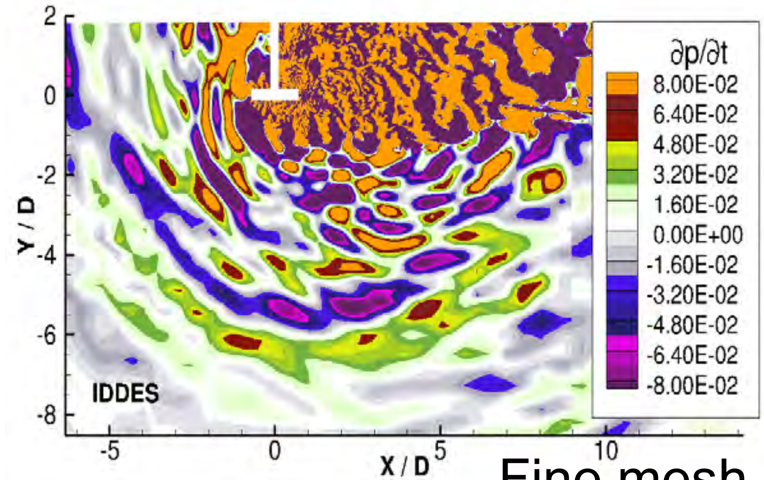
Wang L, Mockett C, Knacke T and Thiele F. Noise prediction of a rudimentary landing gear using Detached-Eddy Simulation. In: 4th Symposium on Hybrid RANS-LES Methods, Beijing, China, 2011.

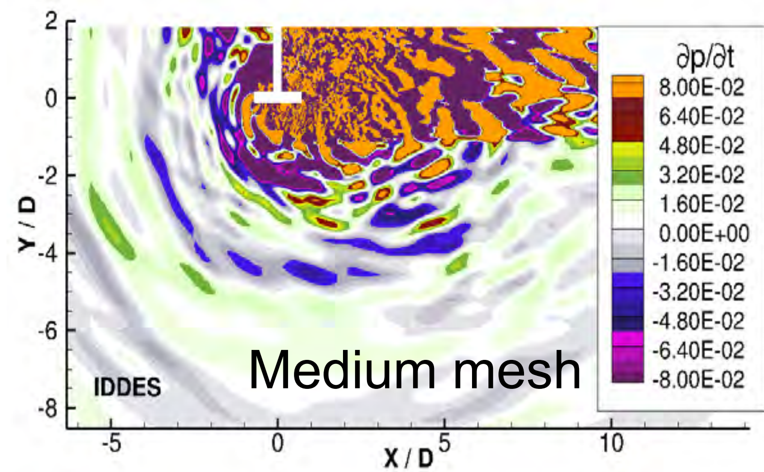
Pressure time-derivative in symmetry plane

Ma =0.115

- **Non-reflecting BC works;**
- **weak effect of hanging nodes.**







Summary

- Fu-Wang transition model is suitable for all-speed aerodynamic flow as well as turbomachinery flow transition prediction.
- DES with Fu-Wang transition model can well resolve both the boundary layer and the free shear flows.
- The present CFD & CAA tool has the capabilities to simulate broadband noise in turbomachines.

谢　谢

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