Sensitized-RANS simulations of complex flows in conjunction with ANSA:

towards increasing efficiency

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MASCHINENBAU
We engineer future

June 15, 2023

subject 1

Research Association of Automotive Technology (FAT)

FKFS wind tunnel

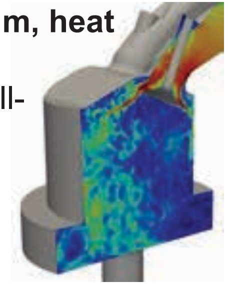

[1]

Numerical simulation

subject 2

German Research Foundation (DFG)

→ **Development of a modeling basis for the computational capturing of the simultaneous turbulent momentum, heat and mass transfer processes** of developing free shear as well as wall-boundary layers.



→ **Dynamic movement of the rim geometry**

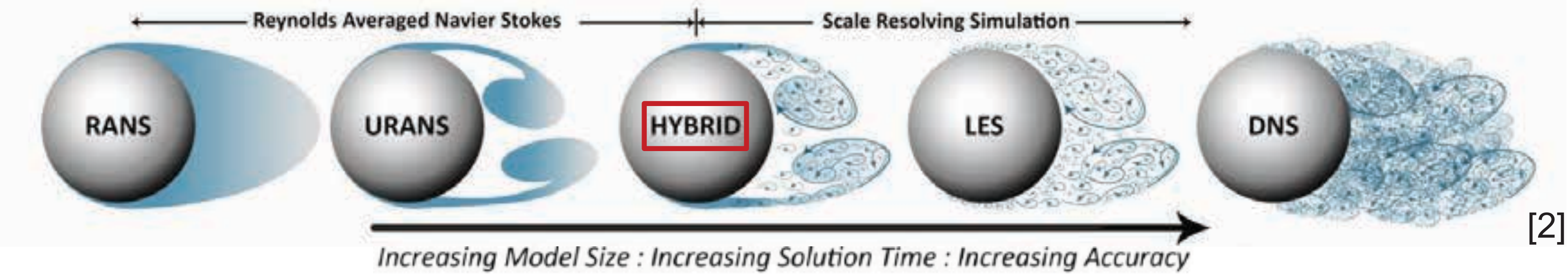
- Transient phenomena due to rim rotation

→ **Hybrid RANS/LES turbulence models**

- Flow fields including turbulent fluctuations

High requirements for the mesh quality → ANSA

On turbulent flow modelling



[2]

Navier-Stokes-Equations (NSE)

$$\frac{\partial \overline{U}_i}{\partial x_i} = 0$$

$$\frac{\partial \overline{U}_i}{\partial t} + \overline{U}_j \frac{\partial \overline{U}_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial \overline{p}}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\nu \frac{\partial \overline{U}_i}{\partial x_j} - \underbrace{\boxed{\overline{u_i u_j}}}_{\text{RST}}\right)$$

ensemble-averaged, incompressible, Newtonian fluids

RANS/URANS →

$k-\omega-\zeta-f$ model
$k-\omega-$SST model
HJRSM model

HYBRID →

$\boxed{\text{ER}-\zeta-f\ \text{model}}$
DDES – SA model
$\boxed{\text{IIS} - \text{RSM model}}$

Computational framework

Eddy-resolving $k-\omega-\zeta-f$ model | $\mathrm{IIS{-}RSM}$ model

$$k-\omega-\zeta-f \text{ model} \xrightarrow{\left(\frac{D\omega}{Dt}\right)_{k-\omega-\zeta-f} + P_{\mathrm{SAS}} = \left(\frac{D\omega}{Dt}\right)_{\mathrm{ER}-\zeta-f}} \mathrm{ER}-\zeta-f \text{ model}$$

- Four equation (k, ω, ζ, f) near-wall model
- $\zeta = \frac{\overline{v^2}}{k}$ representing a measure for the wall-normal turbulent intensity
- Elliptic function f
  - → no damping functions (to account for the near-wall effects) required

- Introduction of an additional source term motivated by the scale-adaptive simulation (SAS) concept of Menter and Egorov (2010; $k-\omega$ SST SAS)
- Source term formulation proposed by Maduta *et al*. (2015) for a scale-supplying equation based on the specific dissipation rate $\omega = \varepsilon / k$

Goal: enable the model to resolve turbulent fluctuations by suppressing modeled turbulent kinetic energy

Computational framework

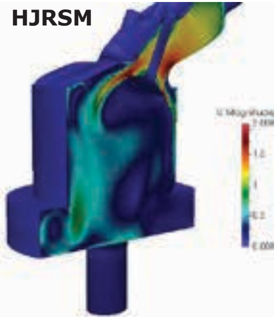
Eddy-resolving $k-\omega-\zeta-f$ model | $\mathrm{IIS{-}RSM}$ model

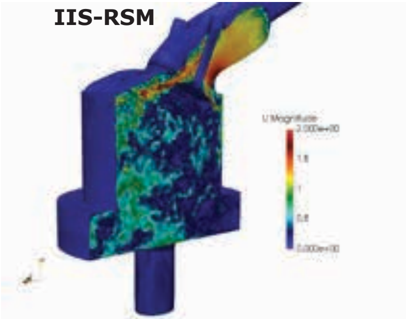
$$k-\omega-\zeta-f\ \text{model} \xrightarrow{\left(\frac{D\omega}{Dt}\right)_{k-\omega-\zeta-f} + P_{\mathrm{SAS}} = \left(\frac{D\omega}{Dt}\right)_{\mathrm{ER}-\zeta-f}} \mathrm{ER}-\zeta-f\ \text{model}$$

$$\left(\frac{D\omega}{Dt}\right)_{\mathrm{ER}-\zeta-f} = C_{\omega 1}\frac{\omega}{k}P_k - C_{\omega 2}\omega^2 + \frac{\partial}{\partial x_i}\left[\left(\nu+\frac{\nu_t}{\sigma}\right)\frac{\partial\omega}{\partial x_i}\right] + \mathrm{CD} + \boxed{P_{\mathrm{SAS}}}$$

$$\rightarrow \underline{\underline{P_{\mathrm{SAS}} = f(\nabla^2 U_i)}}$$

$$\mathrm{HJRSM}\ \text{model} \xrightarrow{\left(\frac{D\omega^h}{Dt}\right)_{\mathrm{HJRSM}} + P_{\mathrm{SAS}} = \left(\frac{D\omega^h}{Dt}\right)_{\mathrm{IIS-RSM}}} \mathrm{IIS{-}RSM}\ \text{model}$$





The model doesn't explicitly include a grid-dependent parameter:
⇒ towards a grid-spacing-free model formulation

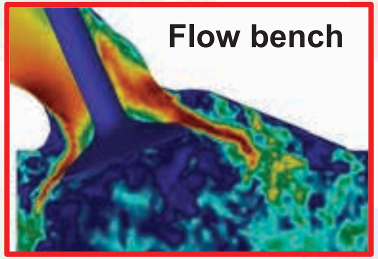
Predictive performances

Tandem cylinder
(different in-between distances)

Physiological flow in
an aortic aneurysm

Flow past a fence – complex
separation at a sharp edge

2D hill



Flow bench

Plungin

Vehicle aerodynamics

ction

3D diffuser
(with plasma-actuated flow control)

Impinging jet (heat transfer)

Car configuration: DrivAer

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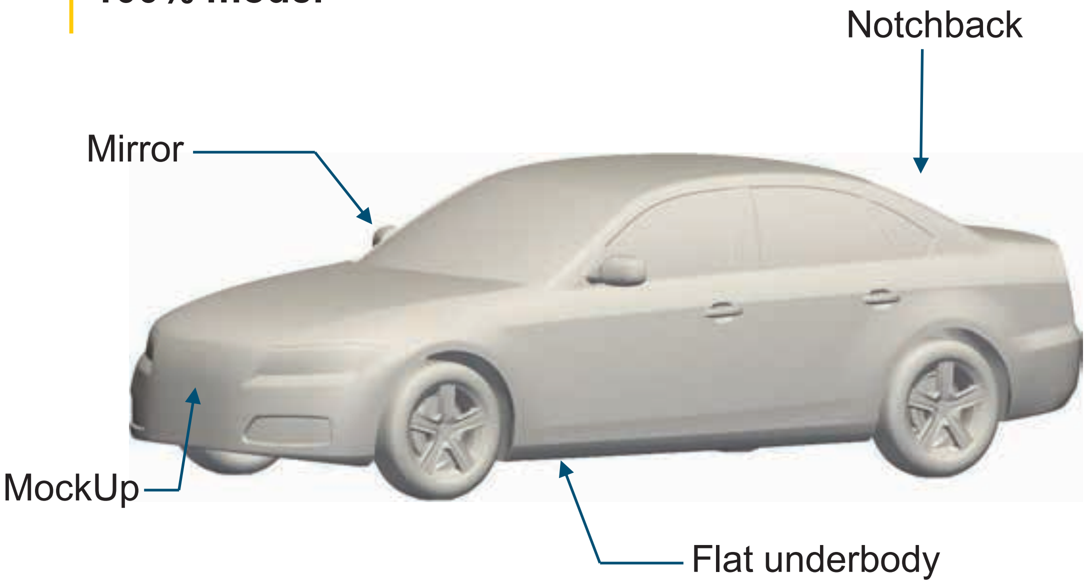
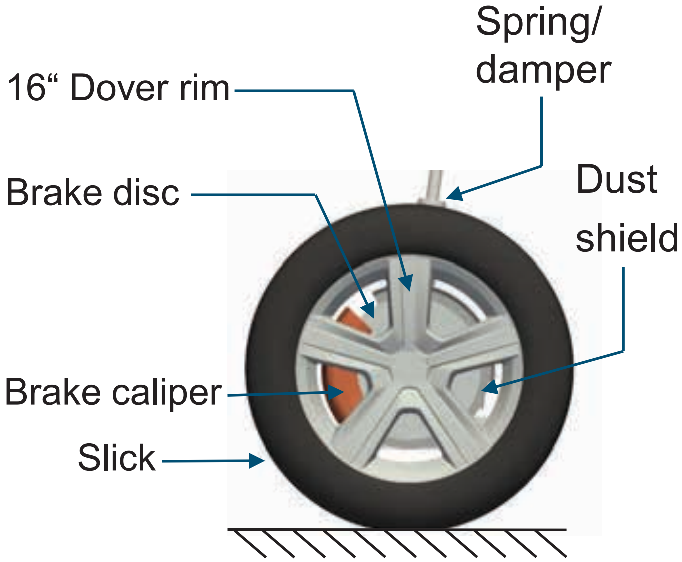
A. Heft (2014)

100% model





$4.61 \times 2.03 \times 1.42\,\mathrm{m}\,(\mathrm{L} \times \mathrm{W} \times \mathrm{H})$

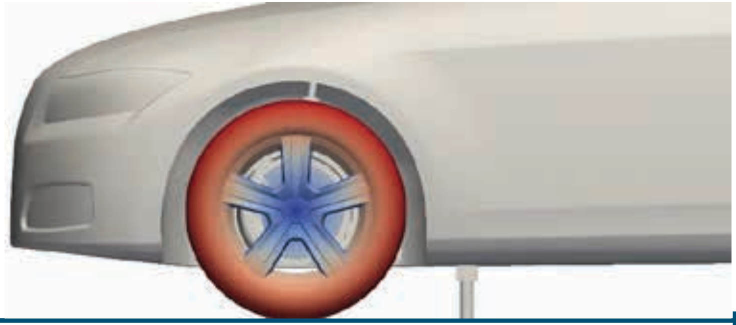
Wheel rotation approach

Tangential velocity

Multiple Reference Frame

Sliding Mesh

- Stationary approximation
- Rim rotation using velocity boundary condition
- Specify rotational axis + angular velocity



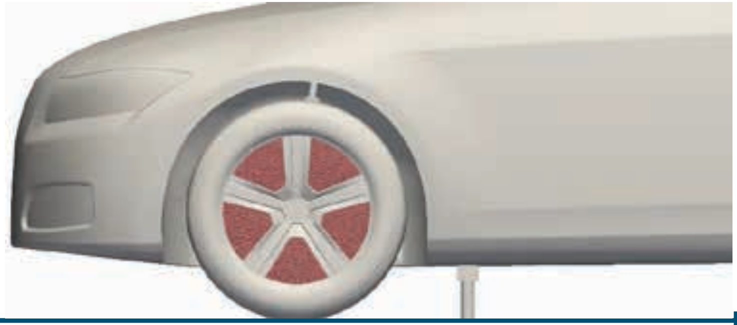
Wheel rotation approach

Tangential velocity

Multiple Reference Frame

Sliding Mesh

- Stationary approximation
- Moving reference coordinate system
- Mesh regions: inertial system and reference system (MRF region)
- Additional apparent forces: Coriolis and centrifugal force



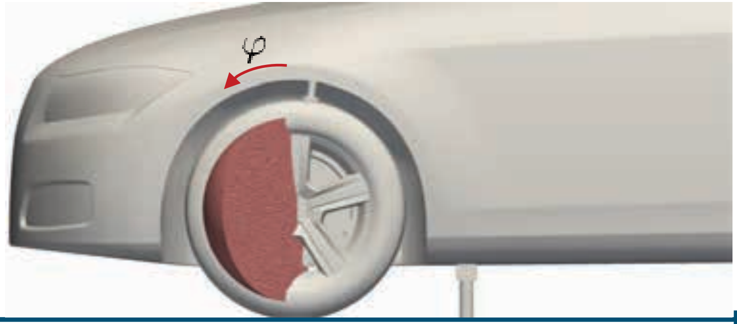
Wheel rotation approach

Tangential velocity

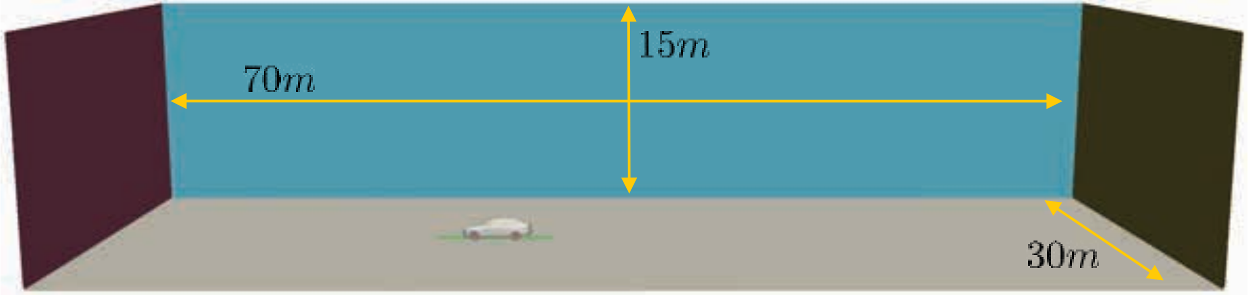
Multiple Reference Frame

Sliding Mesh

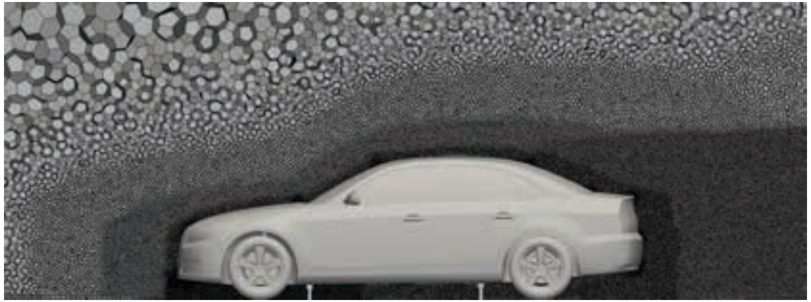
- Unsteady approach
- Dynamic rotation of the rim geometry
- Steady and unsteady mesh regions
- 0.5 degrees rim rotation/time step



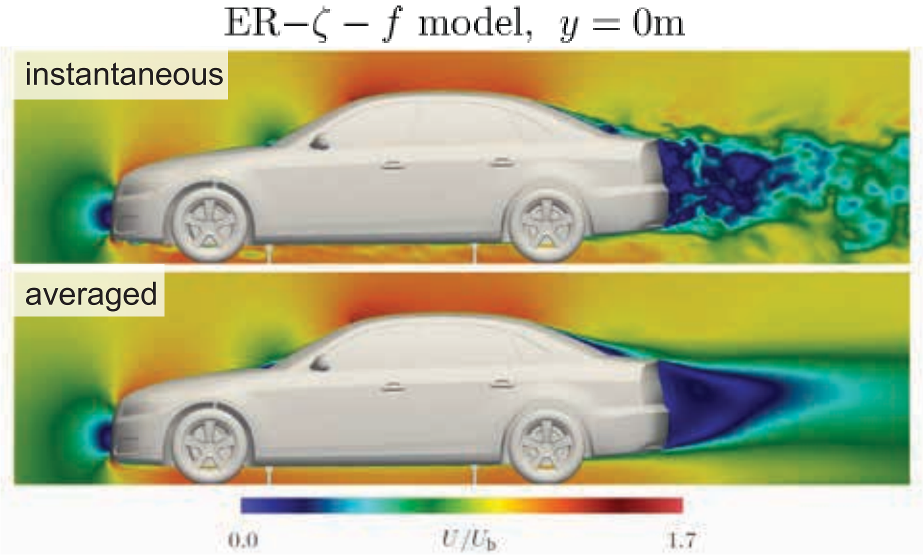
Computational domain & boundary conditions



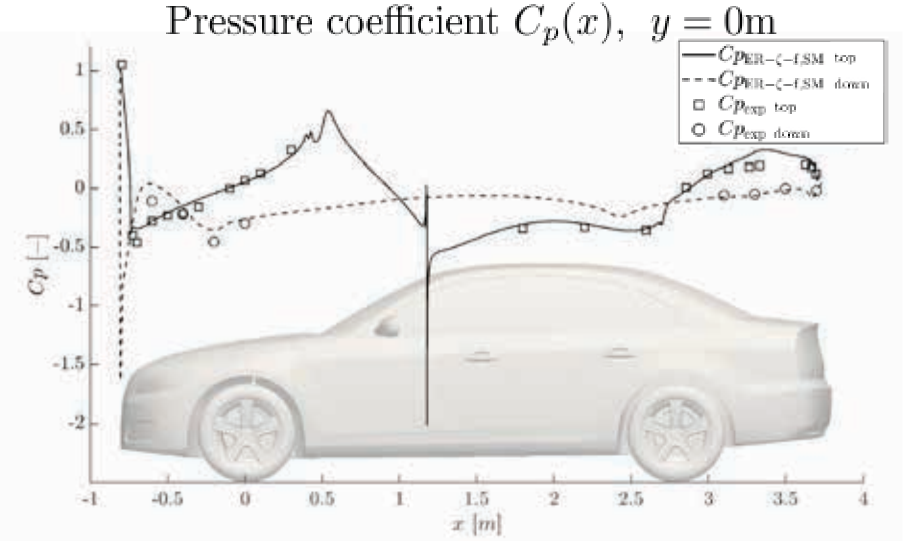
- Inlet velocity: $U_{\mathrm{b}} = 140\ ^{\mathrm{km}}/_{\mathrm{h}}$
- Full moving ground approach
- ~ 46 Mio. volume cells, y+ < 5
- 28 simulations, OpenFOAM
- CPU hours > 15 Mio.



Global flow topology



$\mathrm{ER}{-}\zeta - f$ model, $y = 0\mathrm{m}$

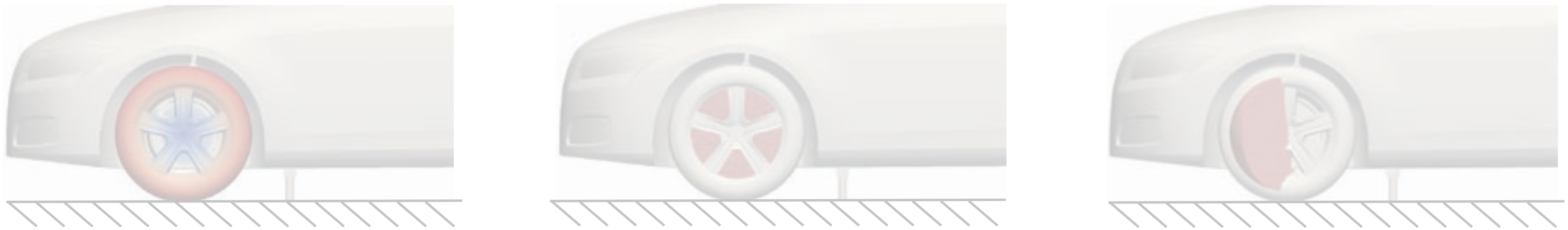


Pressure coefficient $C_p(x)$, $y = 0\mathrm{m}$

$$C_p(x) = \frac{p_x - p_\infty}{\frac{1}{2}\rho_\mathrm{L} U_\mathrm{b}^2}$$

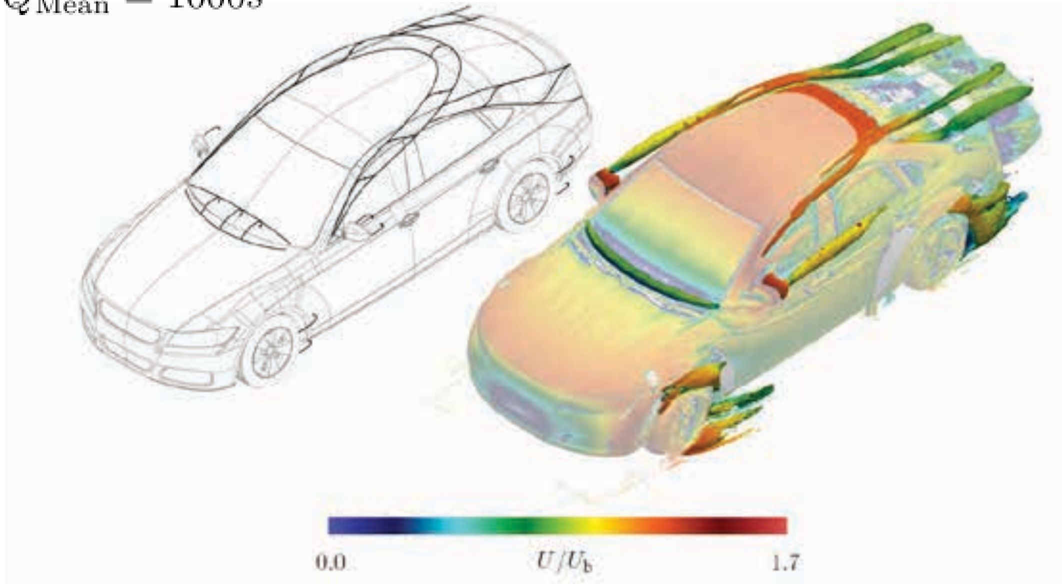
1. What is the impact of the wheel rotation approach?
2. What is the influence of the turbulence model?

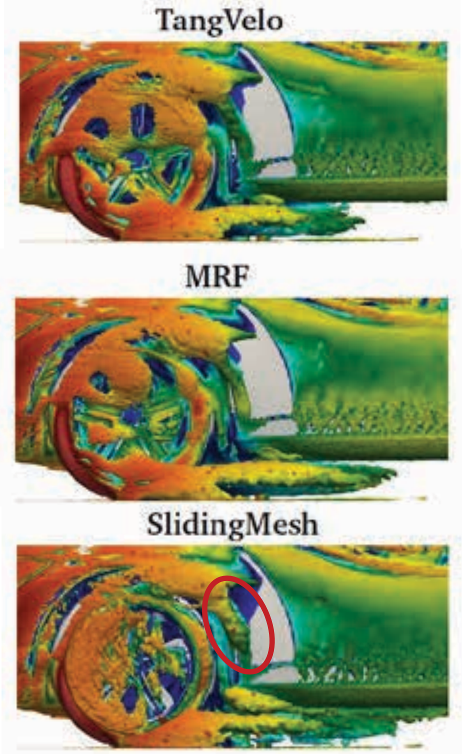
What is the impact of the wheel rotation approach?



Characteristic vortex structures

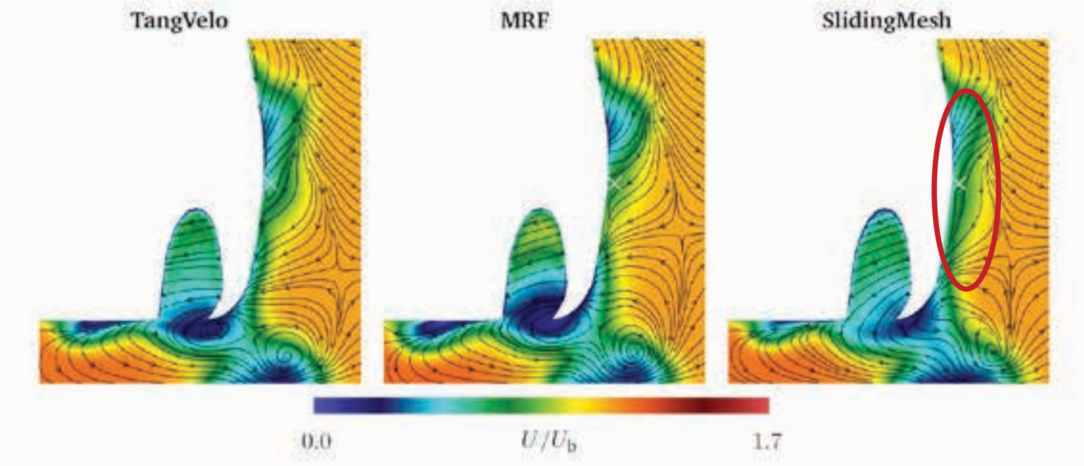
$$Q_{\mathrm{Mean}} = 1000 s^{-1}$$



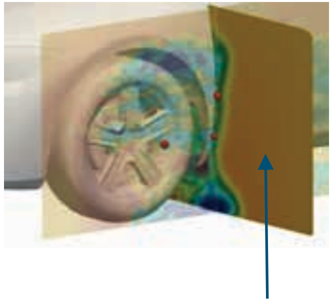


$$Q_{\mathrm{Mean}} = {}^{1}\!/_{2} \left(||\overline{\Omega}_{ij}||^2 - ||\overline{S}_{ij}||^2 \right)$$

Velocity field in the wheel wake



Velocity field in the wheel wake ($\mathrm{ER}-\zeta-f\ \mathrm{model}$)

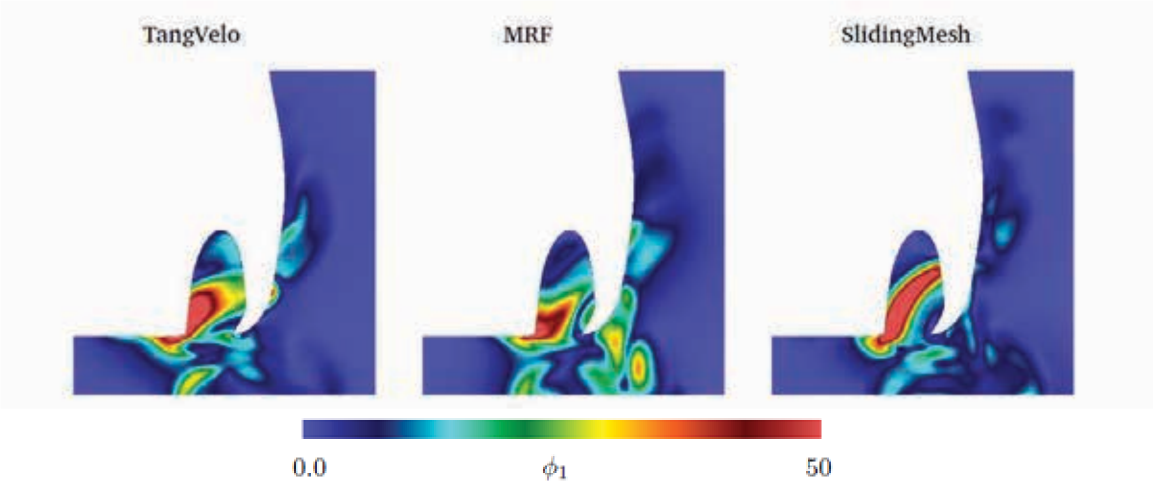

Plane

- Similar structures in the velocity field for all three wheel rotation models
- SlidingMesh velocity profile extends further in the z-direction & moves closer to the sidewall

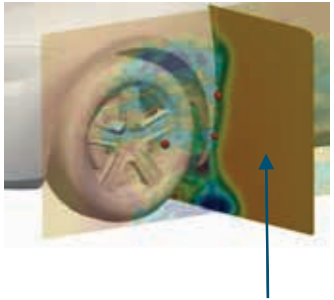
Proper-Orthogonal-Decomposition (POD)

- Vortex structures create a spatial and temporal correlation between locations
- POD: spatial modes and their time dynamic

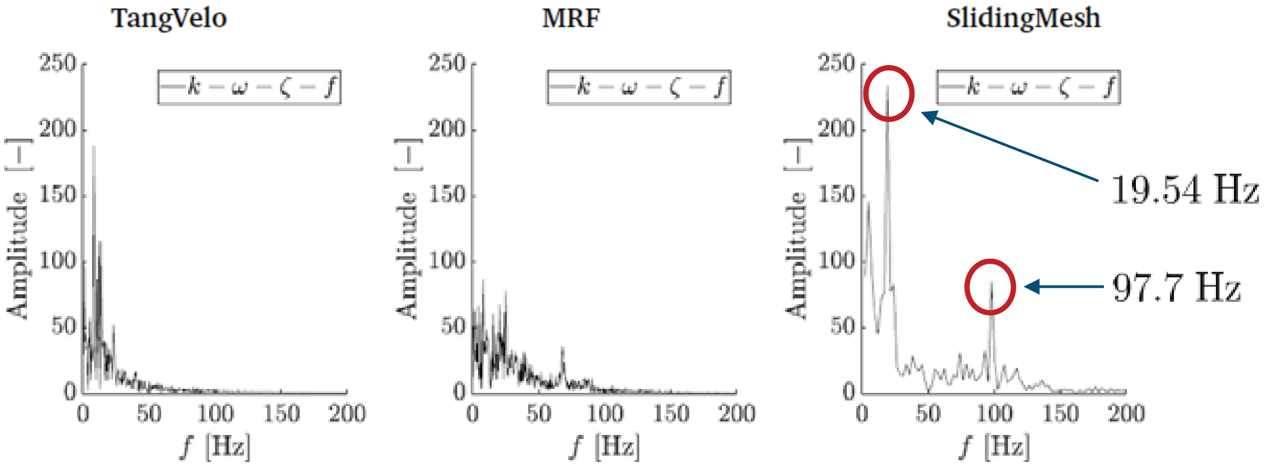
→ isolated view of vortex structures sorted by their turbulent kinetic energy fraction



First POD mode in the wheel wake ($\mathrm{ER}{-}\zeta - f$ model)



Proper-Orthogonal-Decomposition (POD)

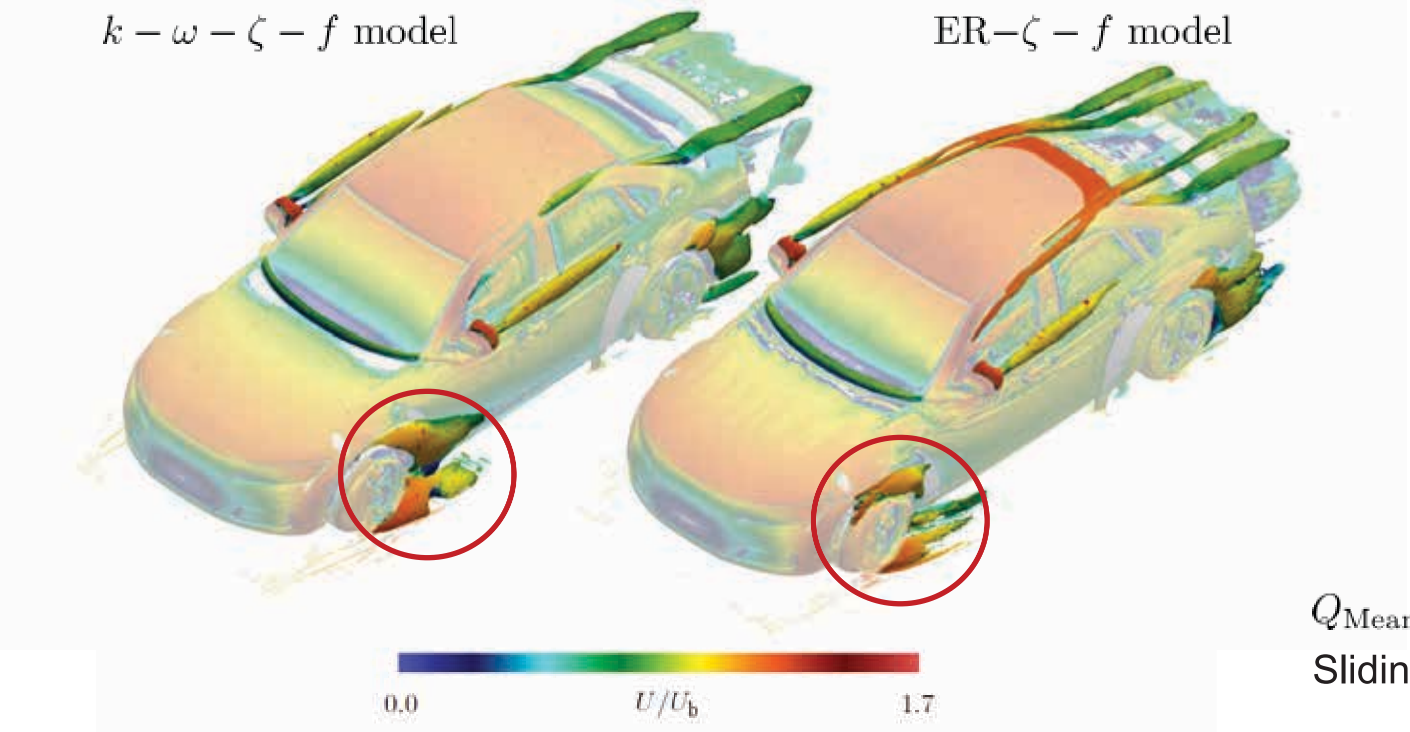


Temporal dynamic of first POD mode in the wheel wake ($\mathrm{ER}-\zeta-f$ model)

- Dominating frequency corresponds to the frequency of one complete wheel revolution ($f = 19$ Hz)
- TangVelo/ MRF frequency spectra differ significantly from SlidingMesh result

What is the influence of the turbulence model?

Characteristic vortex structures



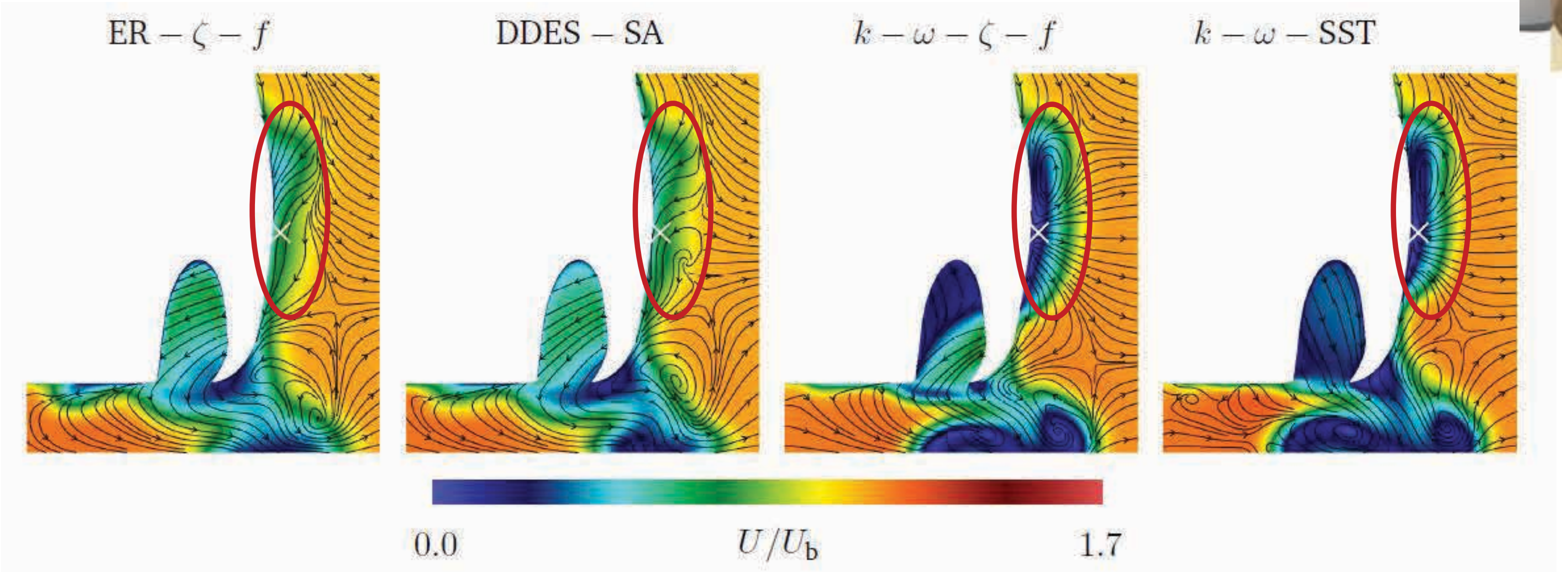
$Q_{\text{Mean}} = 1000s^{-1}$

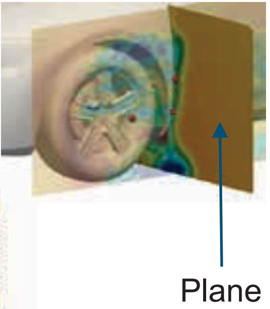
Sliding Mesh

Velocity field in the wheel wake

HYBRID

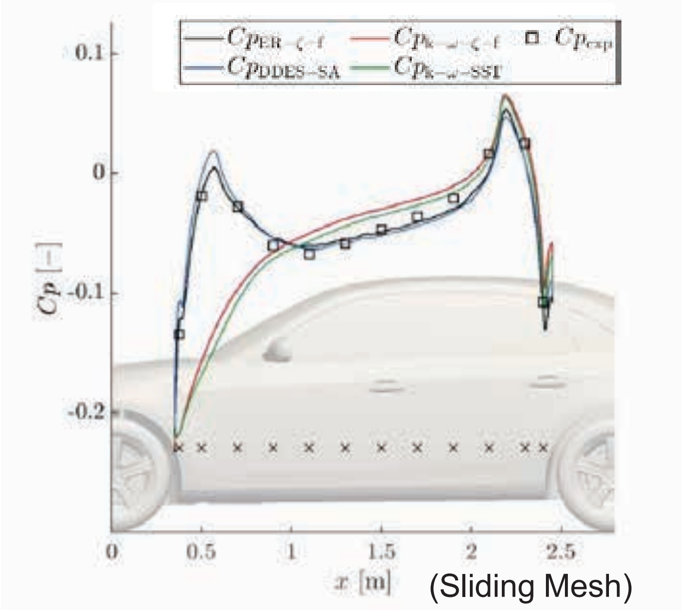
RANS/URANS





Velocity field in the wheel wake at location P2 (Sliding Mesh)

Pressure coefficient along the vehicle side



(Sliding Mesh)

Wheel wake only correctly captured by scale-resolving turbulence models

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subject 1

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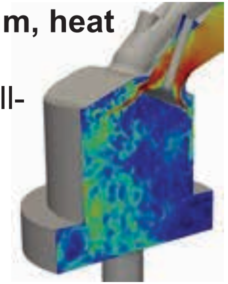
→ **Development of a modeling basis for the computational capturing of the simultaneous turbulent momentum, heat and mass transfer processes** of developing free shear as well as wall-boundary layers.



→ **Dynamic movement of the rim geometry**

- Transient phenomena due to rim rotation

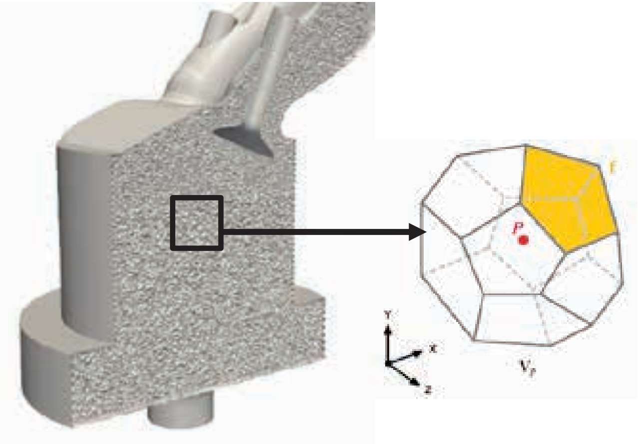
→ **Hybrid RANS/LES turbulence models**

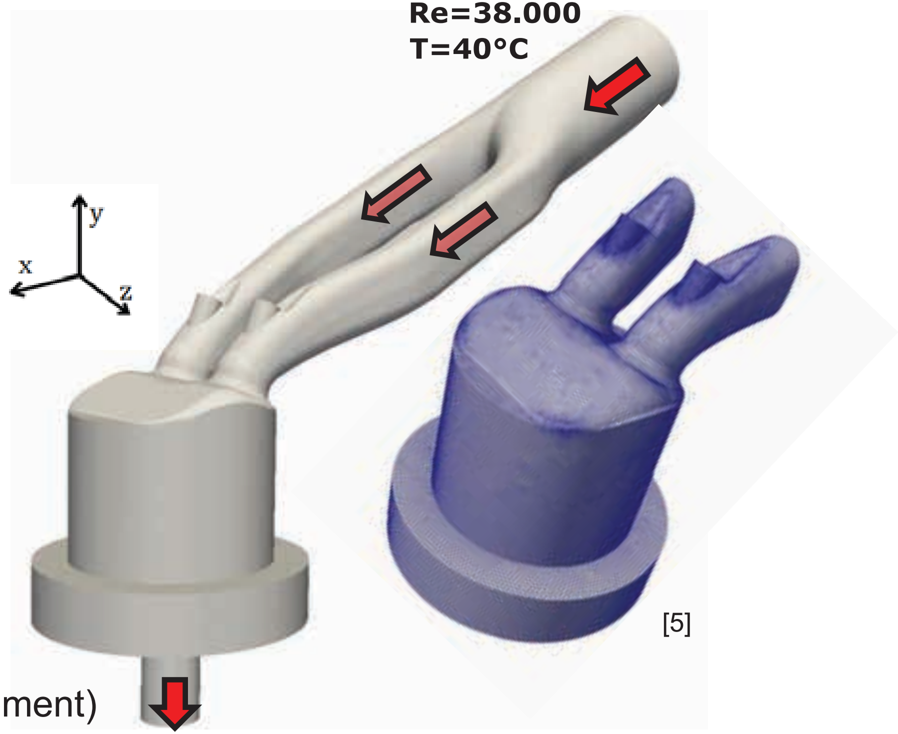
- Flow fields including turbulent fluctuations

High requirements for the mesh quality → ANSA

IC-Engine Intake Flow, Flowbench

- **Geometry** → CA = 270° bTDC
- **Meshing software** → ANSA pre-processor





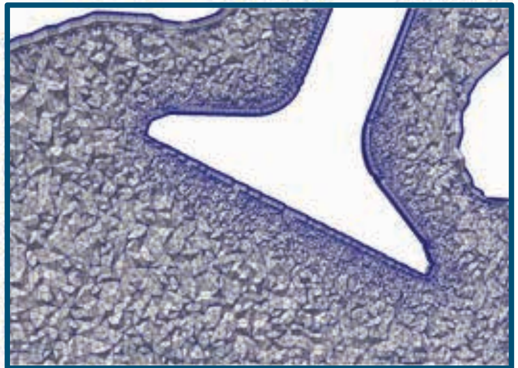
Re=38.000
T=40°C

[5]

- **Simulation software** → OpenFOAM
  - Eddy-resolving RANS-RSM model (own development)

Mesh study

Flowbench - CAD



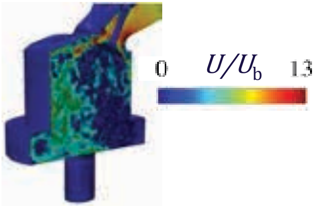
IISRSM - 2.3m cells

IISRSM - 4m cells

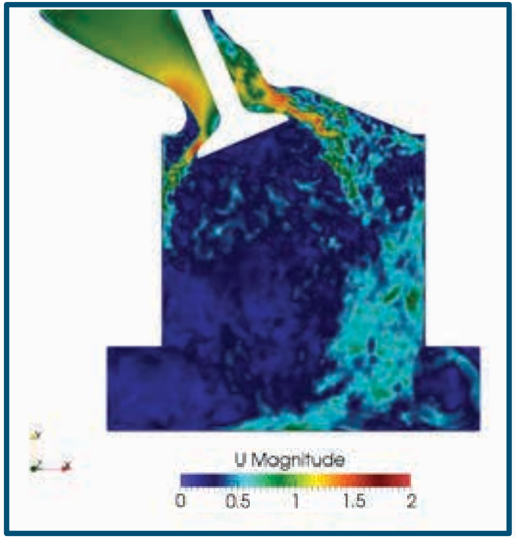
LES – 8m cells

- **Mesh study** in the range of 2.3 to 8 million cells.
- **Surface mesh study** (prismatic and hexahedral cells)
- **Boundary layer study** (resolution for near-wall modeling)
- Comparison between different mesh generation softwares

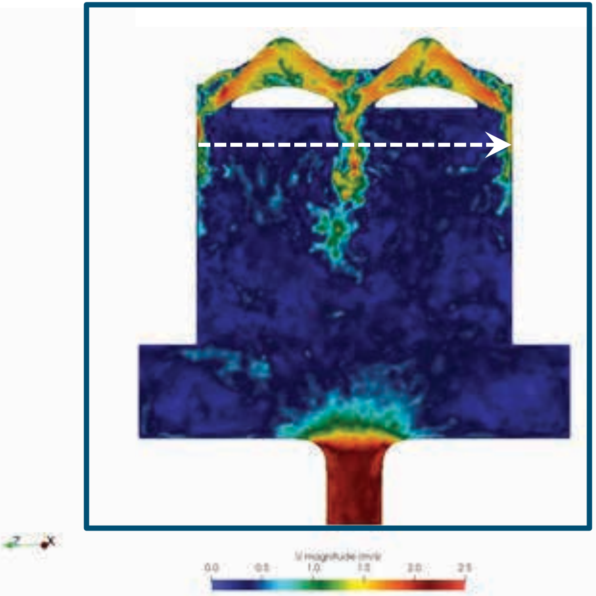
Instantaneous velocity field

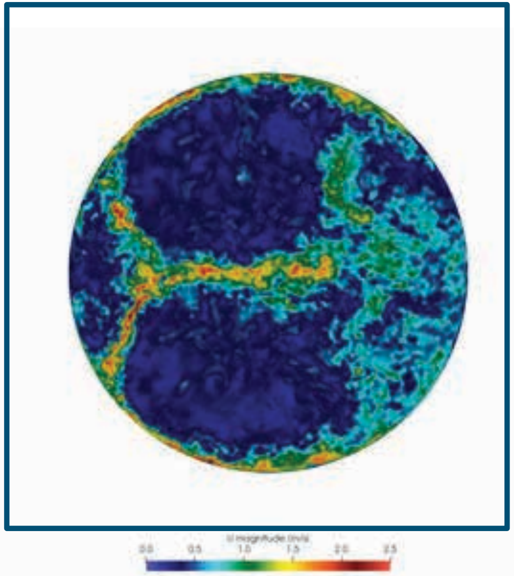


Tumble plane

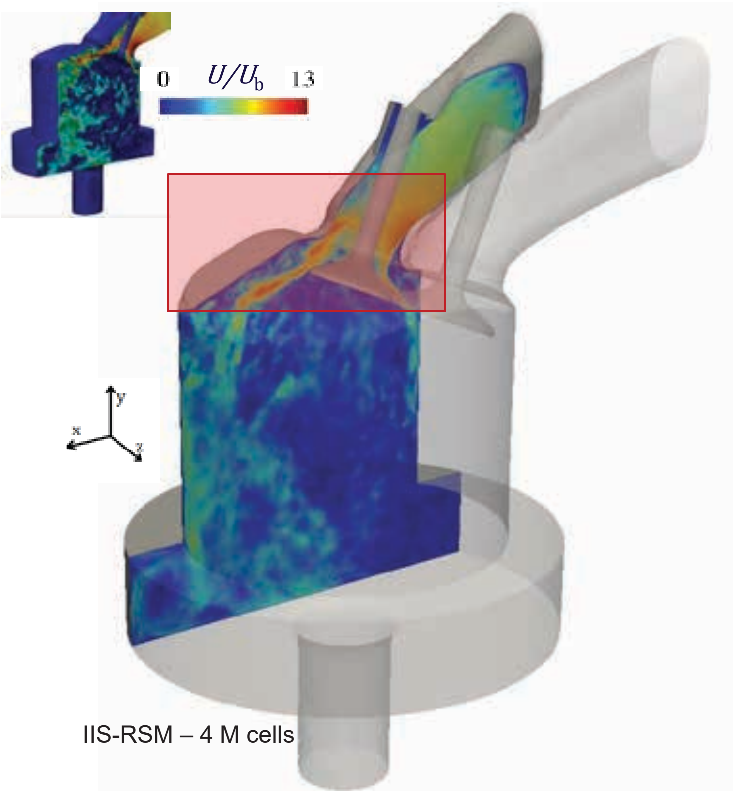


Jet collision plane

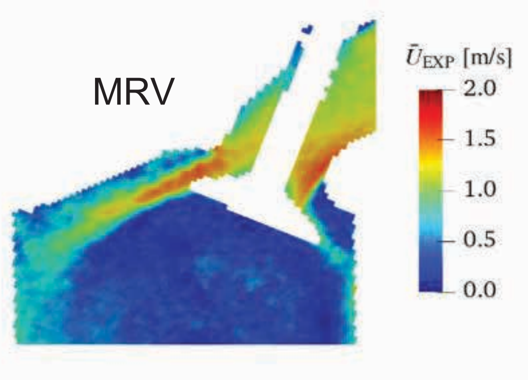


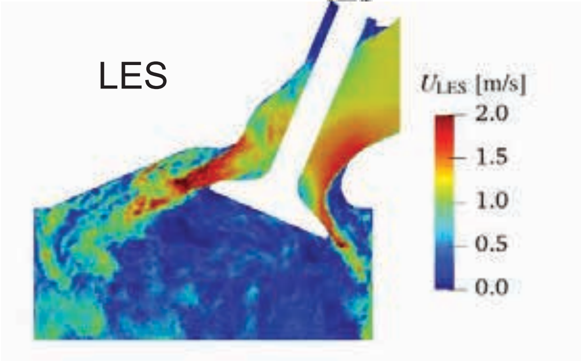


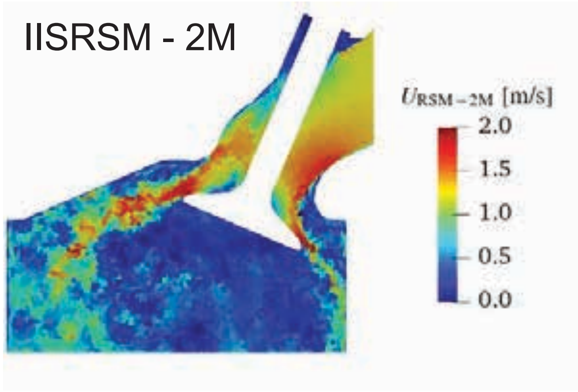
Instantaneous velocity field

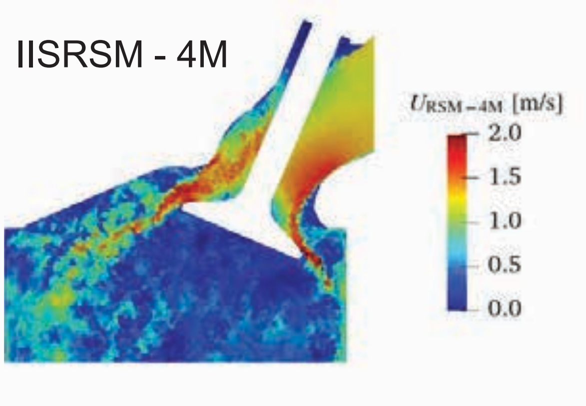


IIS-RSM – 4 M cells

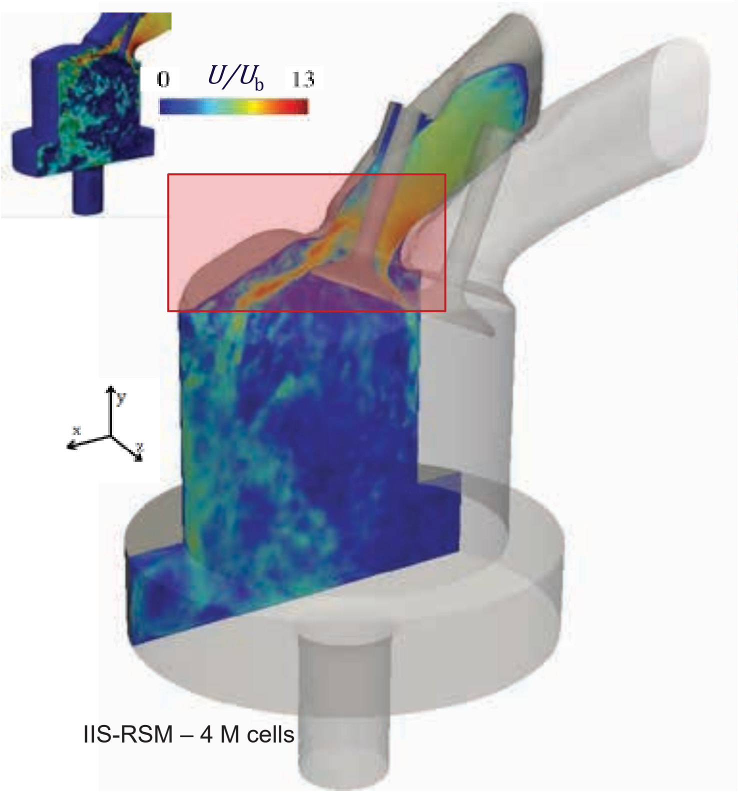




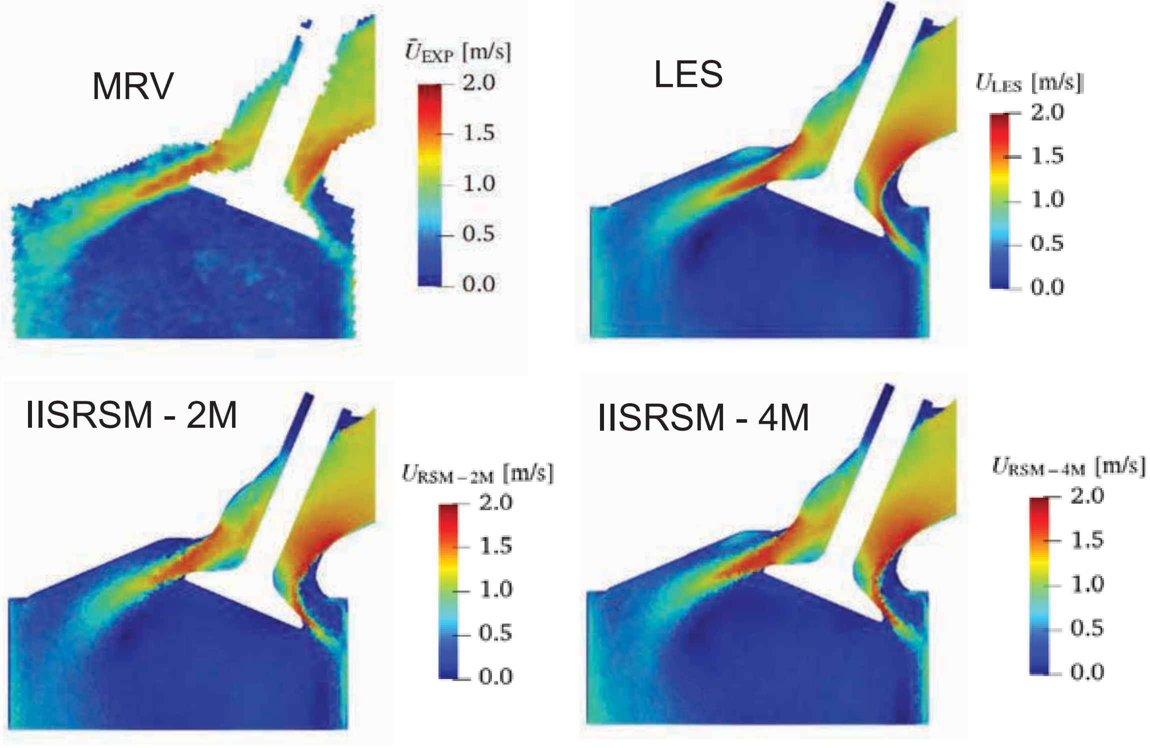




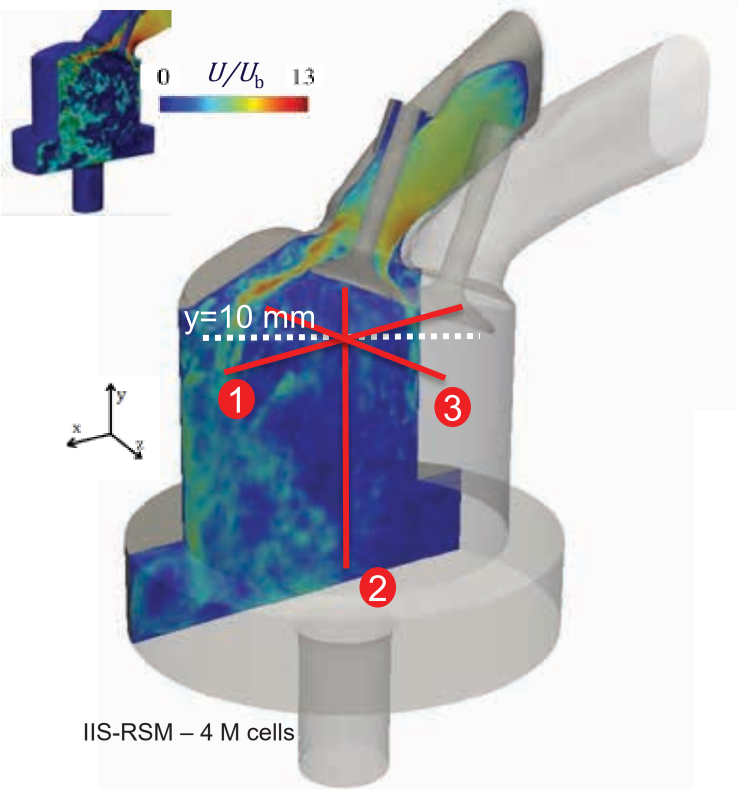
Time-averaged velocity field



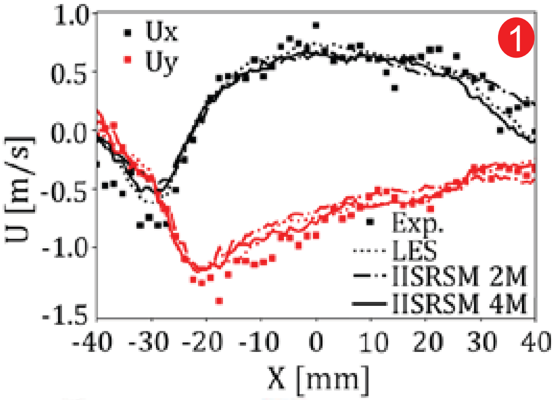
IIS-RSM – 4 M cells

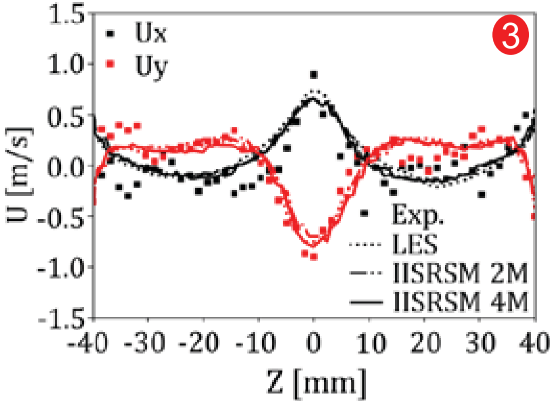


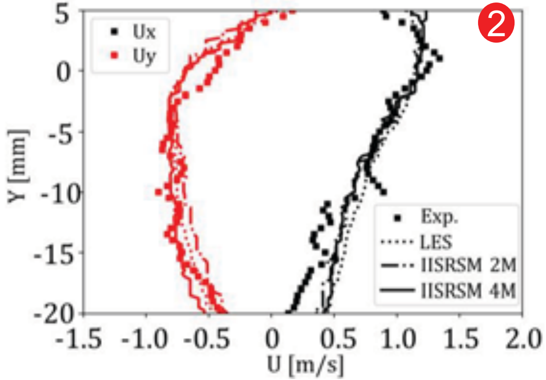
Time-averaged velocity field profiles



IIS-RSM – 4 M cells







Summary

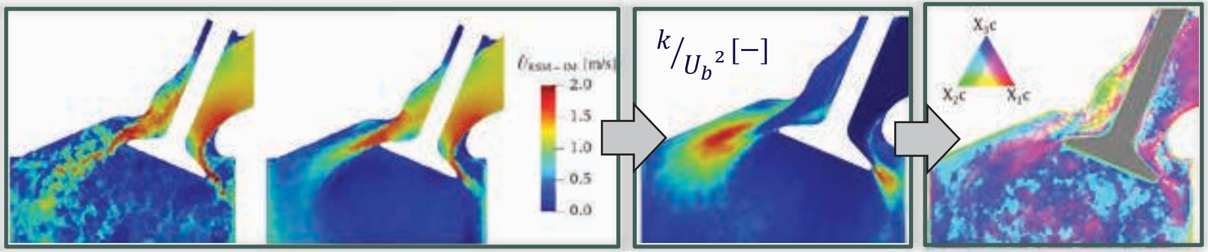
Influence of the wheel rotation approach

- Additional vortex structure + influence on local flow conditions
- Time dynamics of the velocity field + first POD mode
- Qualitative agreement of stationary & dynamic models

Influence of the turbulence model

- Wheel wake only correctly captured by scale-resolving turbulence models

Comparative evaluation of mean velocity and turbulent quantities → anisotropy characterization



References

[1] – Johannes Burgbacher. 68. Arbeitskreissitzungsitzung FAT AK6, Handout (2022)

[2] – John Hart. „Comparison of Turbulence Modeling Approaches to the Simulation of a Dimpled Sphere“. In: *Procedia Engineering* 147 (2016). S. 68–73.

[3] – https://mdolab-mach-aero.readthedocs-hosted.com/en/latest/_images/overset_guide_4.jpg

[4] – Oliver T. Schmidt. “Guide to Spectral Proper Orthogonal Decomposition”. In: *American Institute of Aeronautics and Astronautics* (2020)

[5] - Freudenhammer, D., Baum, E., Peterson, B., Böhm, B. & Grundmann, S., “Towards time-resolved magnetic resonance velocimetry for IC-engine intake flows mag.” EXiF 55, 2015


THANK U

BACKUP

Computational framework

Eddy-resolving $k-\omega-\zeta-f$ model

$$\begin{tikzcd} k-\omega-\zeta-f \text{ model} \arrow[r, "\left(\frac{D\omega}{Dt}\right)_{k-\omega-\zeta-f} + P_{\mathrm{SAS}} = \left(\frac{D\omega}{Dt}\right)_{\mathrm{ER}-\zeta-f}"] & \mathrm{ER}-\zeta-f \text{ model} \end{tikzcd}$$

$$\left(\frac{D\omega}{Dt}\right)_{\mathrm{ER}-\zeta-f} = C_{\omega 1}\frac{\omega}{k}P_k - C_{\omega 2}\omega^2 + \frac{\partial}{\partial x_i}\left[\left(\nu + \frac{\nu_t}{\sigma}\right)\frac{\partial \omega}{\partial x_i}\right] + \mathrm{CD} + \boxed{P_{\mathrm{SAS}}}$$

P_{SAS} formulated directly in terms of the second derivative of the velocity field instead of von Karman length scale (following Maduta *et al*., 2015)

$$P_{\mathrm{SAS}} = C_{\mathrm{SAS}} \max\left(\boxed{\sqrt{\frac{\partial^2 \overline{U}_i}{\partial x_j \partial x_j}\frac{\partial^2 \overline{U}_i}{\partial x_k \partial x_k}}}\sqrt{k} - C_{T_2}T_2, 0\right)$$

The model doesn't explicitly include a grid-dependent parameter:
⇒ towards a grid-spacing-free model formulation

Turbulence model: Eddy-resolving URANS-RSM → IIS-RSM**

$$\frac{\partial}{\partial t}(\overline{U_i}) + \overline{U_j}\frac{\partial(\overline{U_i})}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\nu\left(\frac{\partial \overline{U_i}}{\partial x_j}\right) - \overline{u_i'u_j'}\right]$$

$$\frac{D\overline{u_i'u_j'}}{Dt} = P_{ij} + \Phi_{ij} - \varepsilon_{ij}^h + (0.5D_{ij}^{\nu} + D_{ij}^{p'} + D_{ij}^{u'})$$

- Sensitized RANS momentum equation → instantaneous velocity field
- Transport equation for sub-scale stress tensor

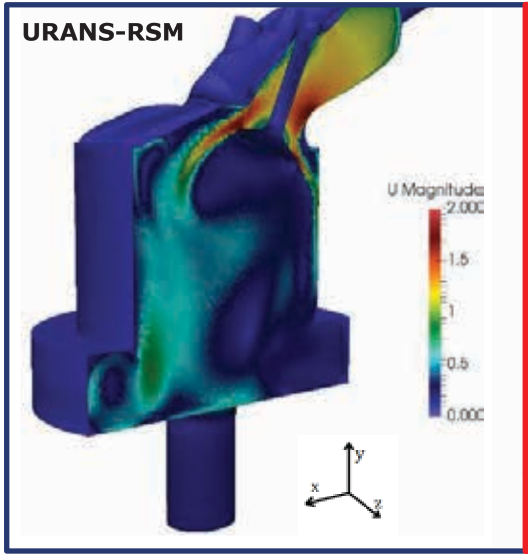
$$\epsilon_{ij}^h = f_s \overline{u_i u_j}\frac{\epsilon_h}{k} + (1 - f_s)\frac{2}{3}\epsilon_h \delta_{ij}$$

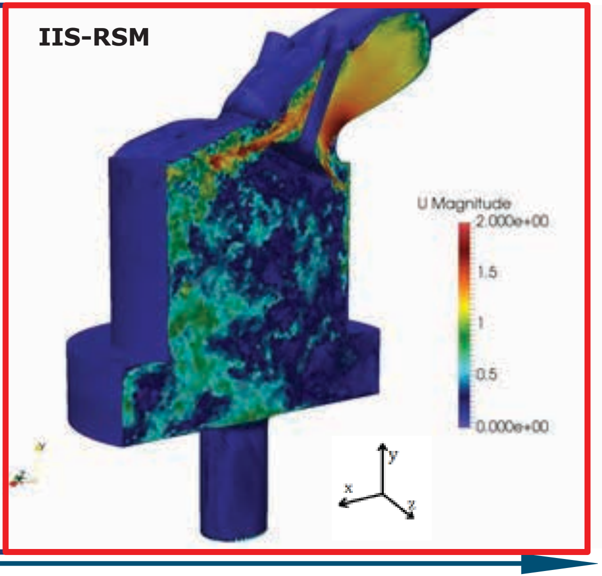
- Model extension toward an eddy-resolving version (SAS*-related)

$$\left(\frac{D\omega^h}{Dt}\right)_{IIS-RSM} = \left(\frac{D\omega^h}{Dt}\right)_{RSM} \boxed{+P_{IIS-RSM}}$$

$$\epsilon_h = \omega_h k$$

$$\boxed{P_{IIS-RSM} = f(\nabla^2 U_i)}$$


URANS-RSM


IIS-RSM

*Jakirlic & Maduta, "Extending the bounds of 'steady' RANS closures: Toward an instability-sensitive Reynolds stress model." IJ HFF 51, 2015
*Menter & Egorov, "The scale-adaptive simulation method for unsteady turbulent flow predictions: theory and model description." FTaC 85(1), 2010
** More details about the model is given in "back-up transparencies"

Computational framework

Eddy-resolving $k - \omega - \zeta - f$ model

- Ensemble-averaged continuity and momentum equations for incompressible Newtonian fluids

$$\frac{\partial \overline{U}_i}{\partial x_i} = 0 \qquad \frac{\partial \overline{U}_i}{\partial t} + \overline{U}_j \frac{\partial \overline{U}_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial \overline{p}}{\partial x_i} + \frac{\partial}{\partial x_j}(\nu \frac{\partial \overline{U}_i}{\partial x_j} - \underbrace{\boxed{\overline{u_i u_j}}}_{\text{RST}}))$$

- Boussinesq eddy-viscosity hypothesis for Reynolds stress tensor modeling

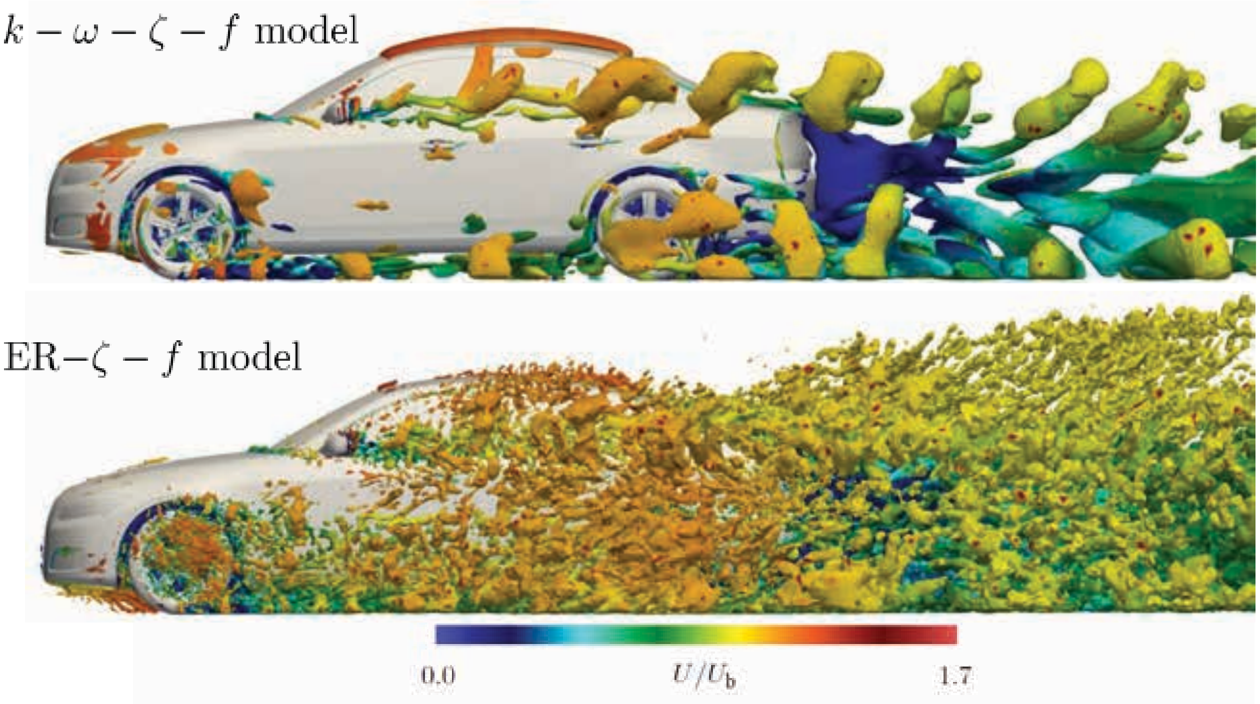
$$\overline{u_i u_j} = -2\boxed{\nu_\mathrm{t}}\overline{S}_{ij} + \tfrac{2}{3}k\delta_{ij} \qquad \overline{S}_{ij} = \tfrac{1}{2}\left(\frac{\partial \overline{U}_i}{\partial x_j}\frac{\partial \overline{U}_j}{\partial x_i}\right)$$

$$\nu_\mathrm{t} = C_\mu^\zeta \zeta k T$$

$$\longrightarrow \boxed{k - \omega - \zeta - f \text{ model}} \longrightarrow \boxed{\text{ER}{-}\zeta - f \text{ model}}$$

Characteristic vortex structure

Sliding Mesh



$$\text{FlowType} = -0.1$$

$$\text{FlowType} = \frac{|S|-|\Omega|}{|S|+|\Omega|}$$