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DIMAXER TECH

Wall-modeled LES of the TUDa Compressor Stage Using a Fourth-order FR Method

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Numerical Method

Governing equations:

unsteady compressible Navier-Stokes equations

$$\frac{\partial U}{\partial t} + \nabla \cdot \left(\vec{F}_c + \vec{F}_d\right) = S$$

$$U = \begin{bmatrix} \rho \\ \rho u \\ \rho v \\ \rho w \\ \rho E \end{bmatrix} \quad \vec{F}_{c,i} = \begin{bmatrix} \rho v_i \\ \rho v_i u + P\delta_{i0} \\ \rho v_i v + P\delta_{i1} \\ \rho v_i w + P\delta_{i2} \\ \rho v_i H \end{bmatrix} \quad \vec{F}_d = \begin{bmatrix} 0 \\ \tau_{i0} \\ \tau_{i1} \\ \tau_{i2} \\ v_j \tau_{ij} + q_i \end{bmatrix}$$

$$\tau_{ij} = \mu\left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i} - \frac{2}{3}\frac{\partial v_k}{\partial x_k}\delta_{ij}\right) \qquad q_j = -\kappa \frac{\partial T}{\partial x_j}$$

Arbitrary Lagrangian-Eulerian:

$$\vec{F}_{c,i} = \begin{bmatrix} \rho\left(v_i - v_{g,i}\right) \\ \rho\left(v_i - v_{g,i}\right)u + P\delta_{i0} \\ \rho\left(v_i - v_{g,i}\right)v + P\delta_{i1} \\ \rho\left(v_i - v_{g,i}\right)w + P\delta_{i2} \\ \rho\left(v_i - v_{g,i}\right)E + Pv_i \end{bmatrix}$$

Turbulence model:

Wall-Adapting Local Eddy-viscosity (WALE) model

$$\bar{\tau}_{ij}^{SM} = \frac{1}{3}\tau_{kk}\delta_{ij} - 2\nu_{sgs}\bar{S}_{ij}$$

$$\nu_T = (C_w\Delta)^2 \frac{\left(S_{ij}^d S_{ij}^d\right)^{3/2}}{\left(\widetilde{S}_{ij}\widetilde{S}_{ij}\right)^{5/2} + \left(S_{ij}^d S_{ij}^d\right)^{5/4}}$$

$$S_{ij}^d = \frac{1}{2}\left(\widetilde{g}_{ij}^2 + \widetilde{g}_{ji}^2\right) - \frac{1}{3}\delta_{ij}\widetilde{g}_{kk}^2 \qquad \bar{S}_{ij} = \frac{1}{2}\left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i}\right)$$

$$\widetilde{g}_{ij} = \partial\widetilde{u}_i/\partial x_j \qquad \widetilde{g}_{ij}^2 = \widetilde{g}_{ik}\widetilde{g}_{kj} \qquad \Delta = (\Delta x \Delta y \Delta z)^{\frac{1}{3}}$$

Wall model:

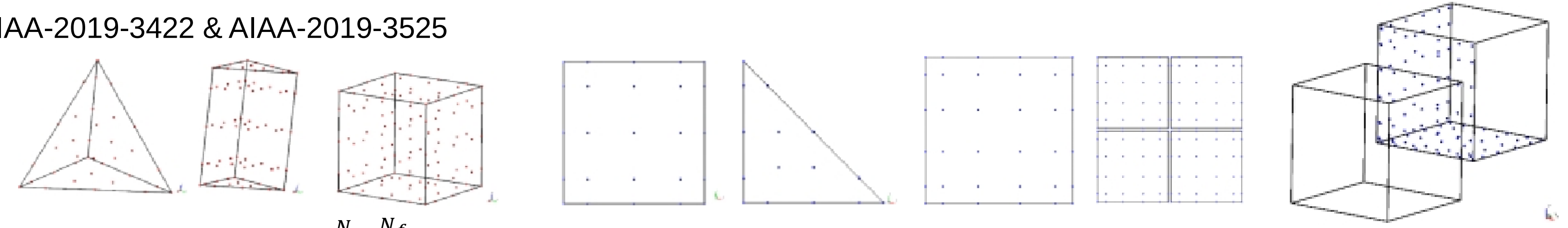
Wall-stress model

$$\frac{U_{\mathrm{wm}}(y)}{u_\tau} = \frac{1}{\kappa}\ln\left(\frac{y u_\tau}{\nu}\right) + B\,.$$

Dimaxer: a STE-KEP-FR Solver

Space-Time Expansion of Kinetic Energy Preserving Flux Reconstruction method

AIAA-2019-3422 & AIAA-2019-3525



$$\frac{\partial \hat{U}_{i,j}}{\partial t} + \left(\nabla^{\xi} \cdot \vec{\boldsymbol{F}}^{\xi}(\boldsymbol{U}_i)\right)_{i,j} + \sum_{s=1}^{N_s}\sum_{f=1}^{N_f} \alpha_{j,s,f}\left(\tilde{\boldsymbol{F}}^{\xi}|_n - \bar{\boldsymbol{F}}^{\xi}|_n\right)_{j,s,f} = 0$$

$$\frac{\partial U_{i,j}}{\partial t} = \mathbb{R}^{Div}_{i,j}(\boldsymbol{U}_i) + \sum_{s=1}^{N_s}\sum_{f=1}^{N_f} \mathbb{R}^{Cor}_{i,j,s,f}\left(\boldsymbol{U}_i, U^{adj}_{i,s,f}\right)$$

$$\mathbb{R}^{Div}_{i,j} = -\frac{1}{|\boldsymbol{J}|_{i,j}}\left(\nabla^{\xi} \cdot \vec{F}^{\xi}(\boldsymbol{U}_i)\right)_{i,j}$$

$$\mathbb{R}^{Cor}_{i,j,s,f} = -\frac{1}{|\boldsymbol{J}|_{i,j}}\, \alpha_{j,s,f}\left(\tilde{\boldsymbol{F}}^{\xi}|_n - \bar{\boldsymbol{F}}^{\xi}|_n\right)_{j,s,f}$$

$$U^{n+1}_{i,j} - U^{n}_{i,j} = \int_{t^n}^{t^{n+1}} \mathbb{R}^{Div}_{i,j}(\boldsymbol{U}_i) + \sum_{s=1}^{N_s}\sum_{f=1}^{N_f} \mathbb{R}^{Cor}_{i,j,s,f}\left(\boldsymbol{U}_i, U^{adj}_{i,s,f}\right)\, dt$$

Space-time polynomial: $\frac{dv_{i,j}}{dt} = \mathbb{R}^{Div}_{i,j}\left(v(\vec{x}_i, t)\right)$

$$\int_{t^n}^{t^{n+1}} \mathbb{R}^{Div}_{i,j}(\boldsymbol{v}_i)\, dt = v_{i,j}(t^{n+1}) - U^{n}_{i,j}$$

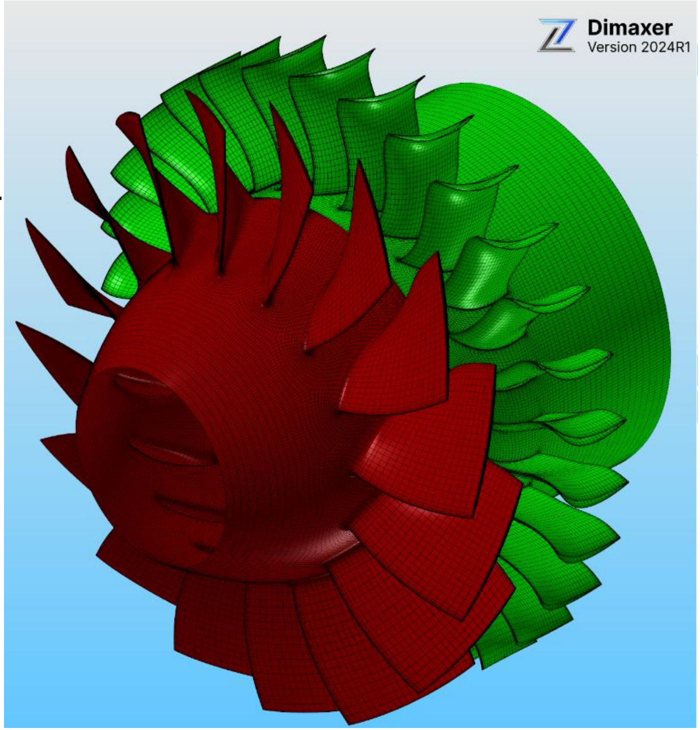
$$U^{n+1}_{i,j} = v_{i,j}(t^{n+1}) + \int_{t^n}^{t^{n+1}} \sum_{s=1}^{N_s}\sum_{f=1}^{N_f} \mathbb{R}^{Cor}_{i,j,s,f}\left(\boldsymbol{v}_i(t^{n+1}), v^{adj}_{i,s,f}(t^{n+1})\right) dt$$

$$U^{n+1}_{i,j} = v_{i,j}(t^{n+1}) + \sum_{s=1}^{N_s}\sum_{f=1}^{N_f}\sum_{qp}^{N^t_{qp}} \Delta t \cdot w^t_{qp}\, \mathbb{R}^{Cor}_{i,j,s,f}\left(\boldsymbol{v}_i(t_{qp}), v^{adj}_{i,s,f}(t_{qp})\right)$$

Computational setup

Computational domain and mesh generation

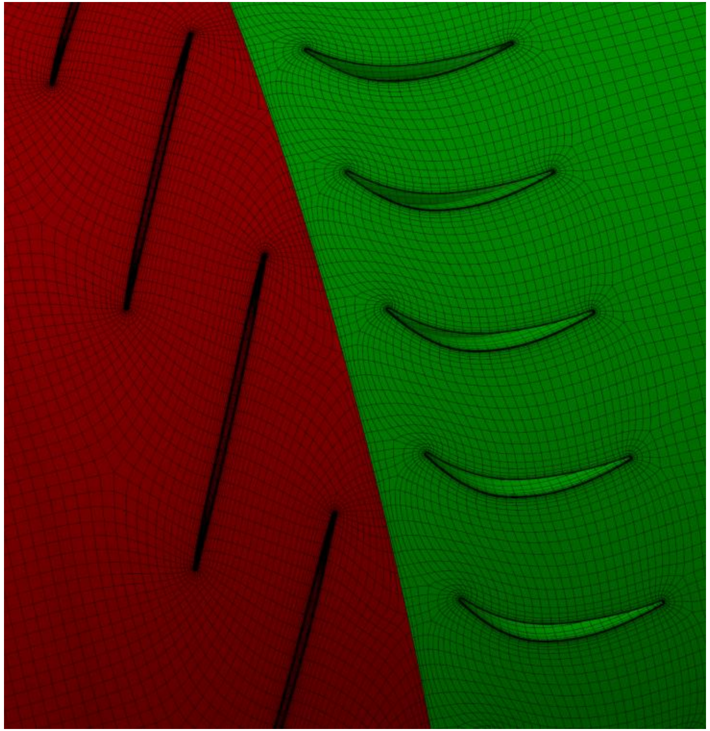
- Full-wheel simulation of the rotor and the stator
  - 1.0 axial chord upstream the rotor leading edge
  - 1.5 axial chord downstream the stator
  - Fillets of the rotor are considered, but not the stator
- Unstructured multi-block O4H mesh
  - Rotor
    - Tip gap radial grid points: 5
    - Total radial grid points: 33
    - Boundary layer grid points: 9
    - Grid growth rate in the boundary layer block: 1.5
    - Grid points around the blade: 76
    - Equivalent y+ is about 30 per degree of freedom, x+ and z+ are less than 50 times y+



Computational setup

Computational domain and mesh generation

- Unstructured multi-block O4H mesh
  - Rotor
    - Total elements: 827,392
    - Total degrees of freedoms: 52,953,088
  - Stator
    - Total radial grid points: 33
    - Boundary layer grid points: 9
    - Grid growth rate in the boundary layer block: 1.5
    - Grid points around the blade: 76
    - Equivalent y+ is about 30 per degree of freedom, x+ and z+ are less than 50 times y+
    - Total elements: 1,083,904
    - Total degrees of freedoms: 69,369,856



Computational setup

Boundary conditions

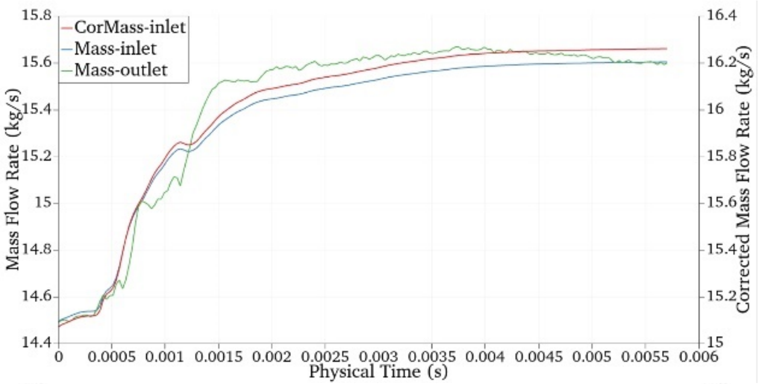
- Peak-efficiency condition (16.00 ± 0.02 kg/s) at 100% design speed (20,000 RPM) is simulated
- Simulation time: 0.006s
- Total pressure inlet:
  - Uniform (laminar inlet), 1-D non-reflect
  - Total pressure: 98,594 Pa
  - Total temperature: 288.15 K
  - Flow direction: Axial
- Pressure outlet:
  - Uniform, 1-D non-reflect
  - Pressure: 123,000 Pa (adjusted to make the mass flow rate meet the experimental value)
- Wall: No-slip adiabatic

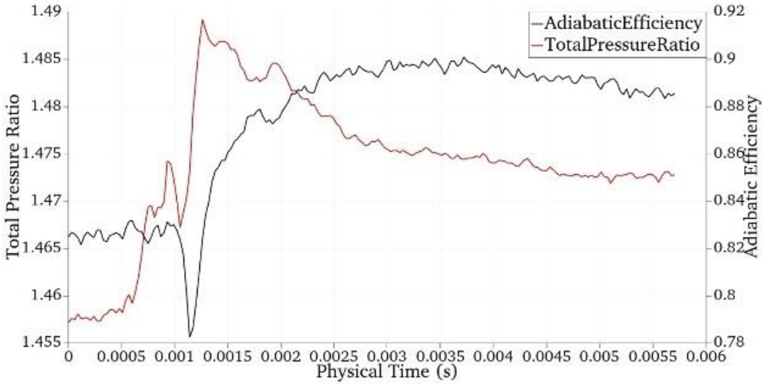
Computational setup

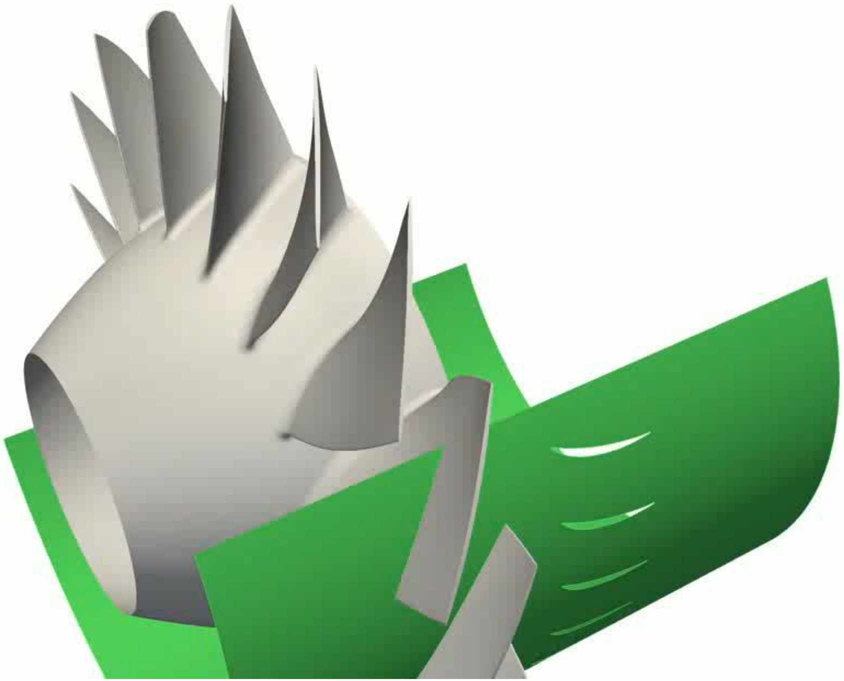
Solver methods

- Governing equations: Unsteady compressible Navier–Stokes equations
- Turbulence model: Wall-modeled LES
- Property of material: Ideal gas
- Spatial discretization method: STE-KEP-FR
- Advection Scheme: HLLC
- Temporal discretization scheme: Runge-Kutta
- Spatial and temporal accuracy: 4^{th}
- Time step: Local time step
- Moving mesh method: Arbitrary Lagrangian-Eulerian
- Rotor-stator interface: Dynamic overset
- Computing resource: 8 Nvidia RTX 4090 GPUs, 1 revolution takes 1 week

Results

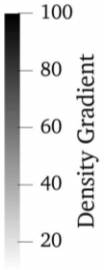

CorMass-inlet
Mass-inlet
Mass-outlet
Mass Flow Rate (kg/s)
Corrected Mass Flow Rate (kg/s)
Physical Time (s)
15.8
15.6
15.4
15.2
15
14.8
14.6
14.4
16.4
16.2
16
15.8
15.6
15.4
15.2
15
0 0.0005 0.001 0.0015 0.002 0.0025 0.003 0.0035 0.004 0.0045 0.005 0.0055 0.006


AdiabaticEfficiency
TotalPressureRatio
Total Pressure Ratio
Adiabatic Efficiency
Physical Time (s)
1.49
1.485
1.48
1.475
1.47
1.465
1.46
1.455
0.92
0.9
0.88
0.86
0.84
0.82
0.8
0.78
0 0.0005 0.001 0.0015 0.002 0.0025 0.003 0.0035 0.004 0.0045 0.005 0.0055 0.006



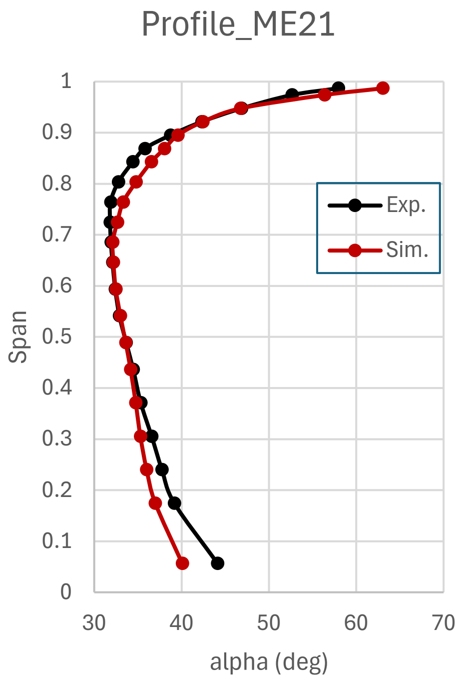
Results

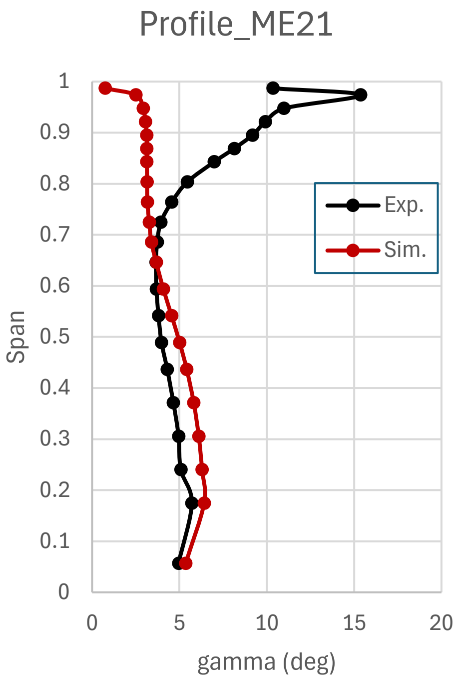
Cylindrical slice where R = 0.16m

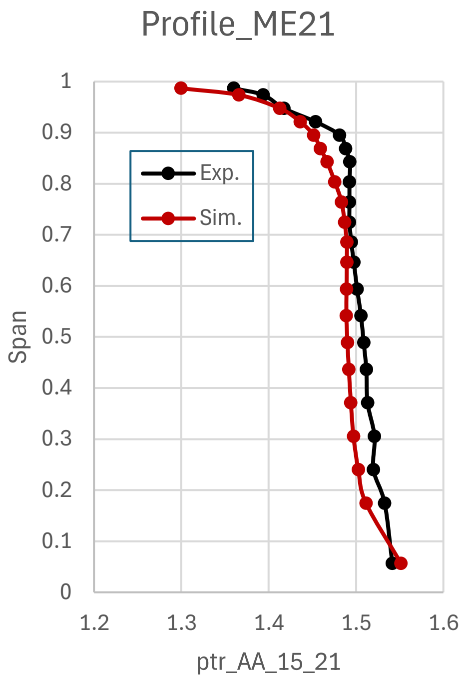


Results

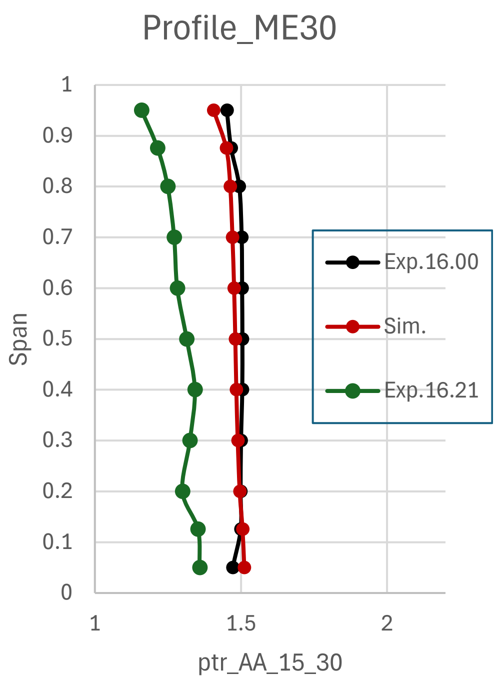
In the Sim., data is calculated using mass-flow averaged method

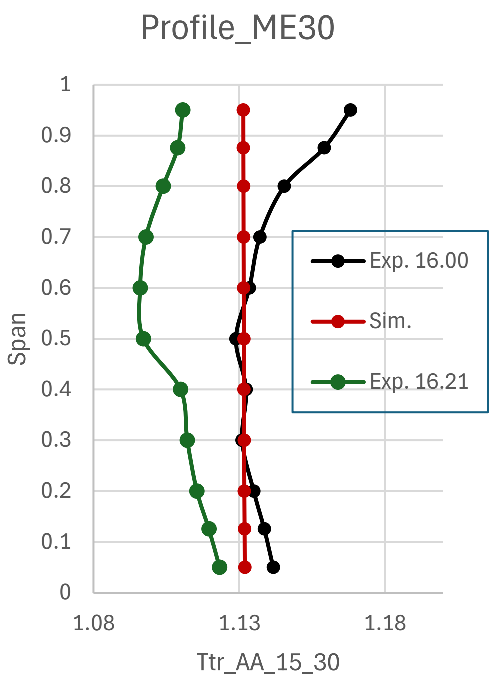






Results





- The rotor rotates one and a half revolutions from a uniform initial field to a statistical steady state.
- Compared to the experiment, clearance leakage flow has not been fully resolved.
- Under the same mass flow rate, the calculated pressure ratio is lower, which may be due to the shorter inlet and less obvious blockage effect.

Thank you