ON THE DEVELOPMENT OF NUMERICAL TECHNUQUE OF ROTOR AERACOUSTICS AND AERODIMAMICS CHARACTERISTICS IN FORWARD FLIGHT

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OUTLINE

MOTIVATION

Robust computational techniques for rotor **aerodynamics** and **acoustic** characteristics evaluation are required

"**Robust**" – compromise between acceptable accuracy and available resources

MATHEMATICAL MODEL AND NUMERICAL METHOD

Mathematical model and numerical method

$$\frac{\partial \mathbf{Q}}{\partial t}+\frac{\partial \mathbf{F}(\mathbf{Q})}{\partial x}+\frac{\partial \mathbf{G}(\mathbf{Q})}{\partial y}+\frac{\partial \mathbf{H}(\mathbf{Q})}{\partial z}=\frac{1}{Re}\left(\frac{\partial \mathbf{F}_\nu(\mathbf{Q})}{\partial x}+\frac{\partial \mathbf{G}_\nu(\mathbf{Q})}{\partial y}+\frac{\partial \mathbf{H}_\nu(\mathbf{Q})}{\partial z}\right)$$

NOISEtte

Q – vector of full or linearized conservative variables

F, G, H – vectors of full or linearized conservative fluxes

F_v, G_v, H_v – vectors of dissipative fluxes, Re – Reynolds number

Family of Euler-based models

- EE – full Euler equations
- NSE – full Navier-Stokes equations

Near field

Turbulence models

- RANS, URANS (SA, K-Epsilon, K-Omega, SST Menter)
- DES, DDES, IDDES

Far field

Far field acoustics – FW/H («1A» Farassat formulation)

Mathematical model and numerical method

Higher-accuracy schemes on **unstructured meshes**:
Quasi-1D EBR (Edge-Based Reconstruction) scheme

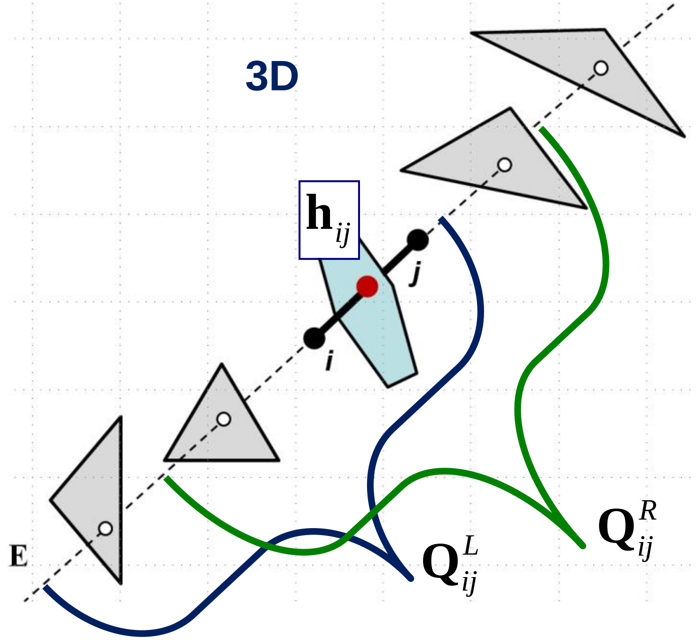
The basic idea is **quasi-1D reconstruction**

1) FV approximation of NS convective terms

2) Godunov-type numerical fluxes as the function of **reconstructed** gas dynamic variables

3) edge-based direction “pierces” the mesh and finds the points of intersection of it with faces from both sides of the endpoints of the parent edge *ij*

4) values in 1D-stencil points are calculated by the linear interpolations on intersecting faces



Mathematical model and numerical method

Navier-Stockes equations in rotating frame reference

NOISEtte

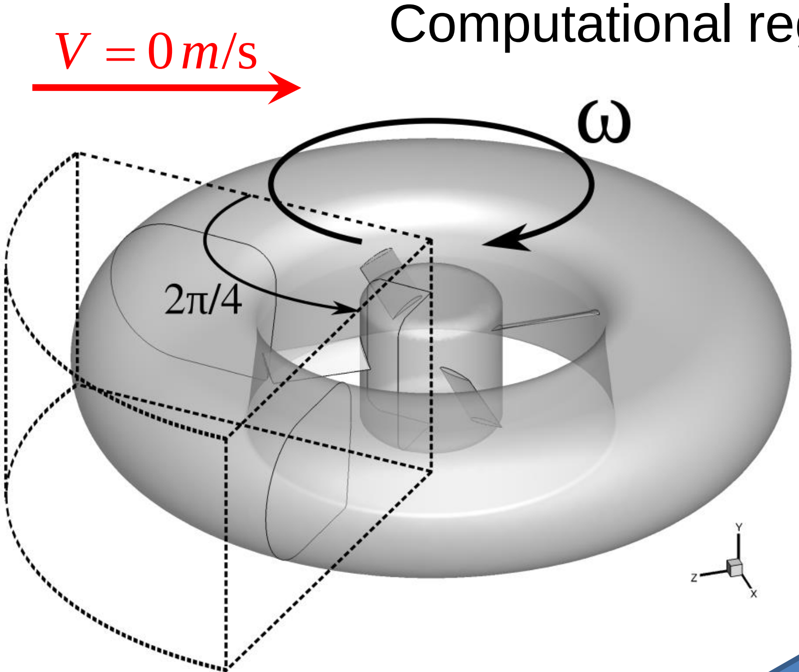
$$\mathbf{V} = \boldsymbol{\omega} \times \mathbf{r}$$

$$\begin{cases} \dfrac{\partial \rho}{\partial t} + \operatorname{div} \rho (\mathbf{u} - \mathbf{V}) = 0 \\ \dfrac{\partial \rho \mathbf{u}}{\partial t} + \operatorname{Div} \rho (\mathbf{u} - \mathbf{V}) \otimes \mathbf{u} + \nabla p = \operatorname{Div} \mathbf{S} - \rho (\boldsymbol{\omega} \times \mathbf{u}) \\ \dfrac{\partial E}{\partial t} + \operatorname{div} (\mathbf{u} - \mathbf{V}) E + \operatorname{div} \mathbf{u} p = \operatorname{div} \mathbf{q} + \operatorname{div} \mathbf{S} \mathbf{u} \end{cases}$$

Mathematical model and numerical method

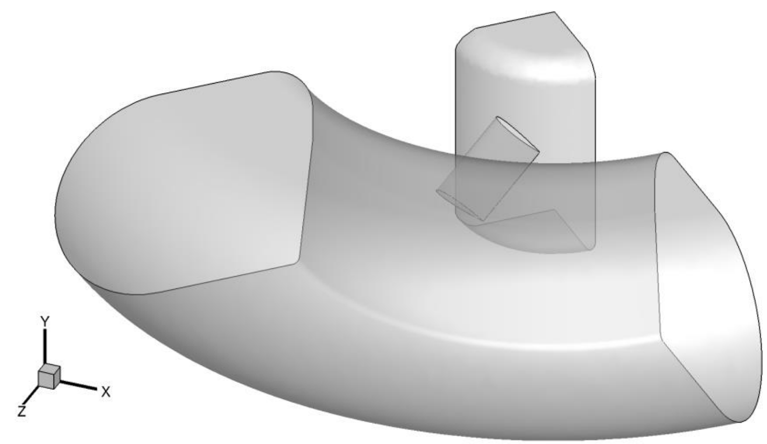
Single sector modeling

Computational region: sector with single blade



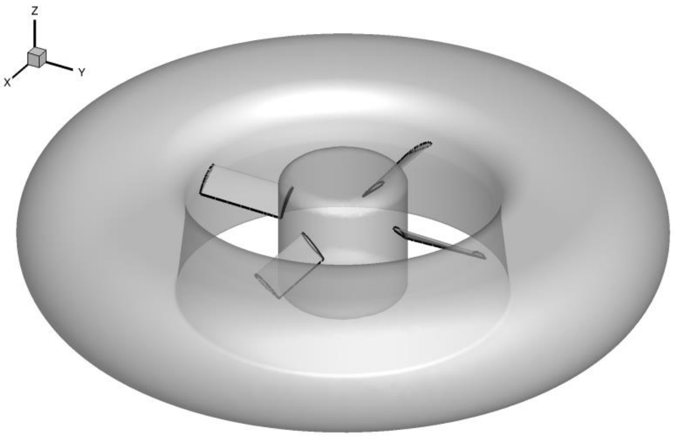
Axial symmetry + **Absence of external flow**

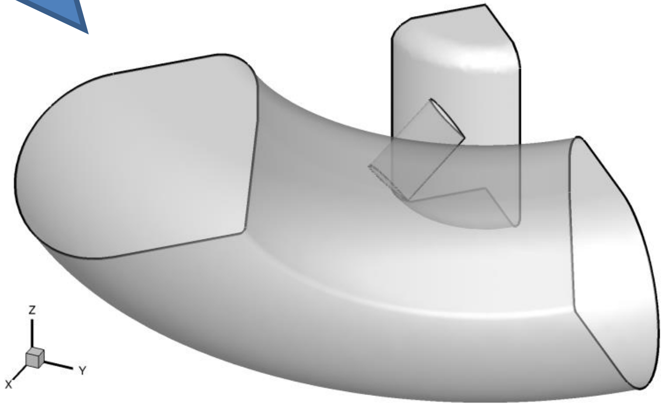
1) Single blade in sector 2π/N (N – number of blades)
2) Periodic boundary conditions in azimuthal direction

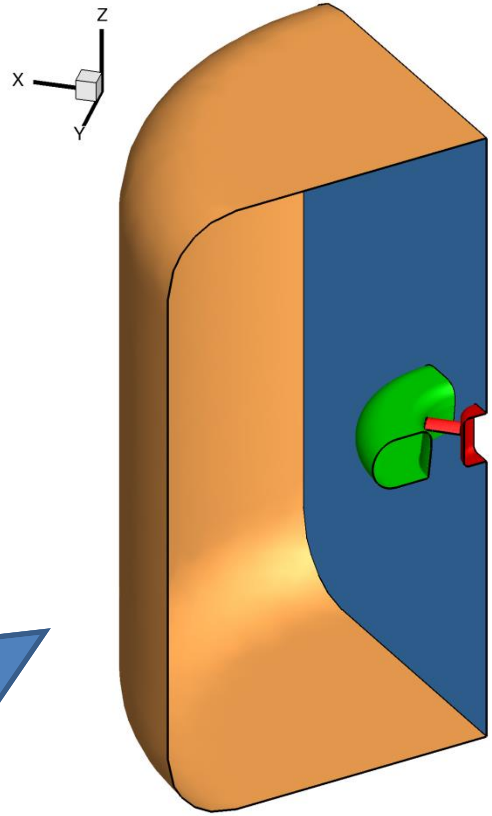


Mathematical model and numerical method

Boundary conditions



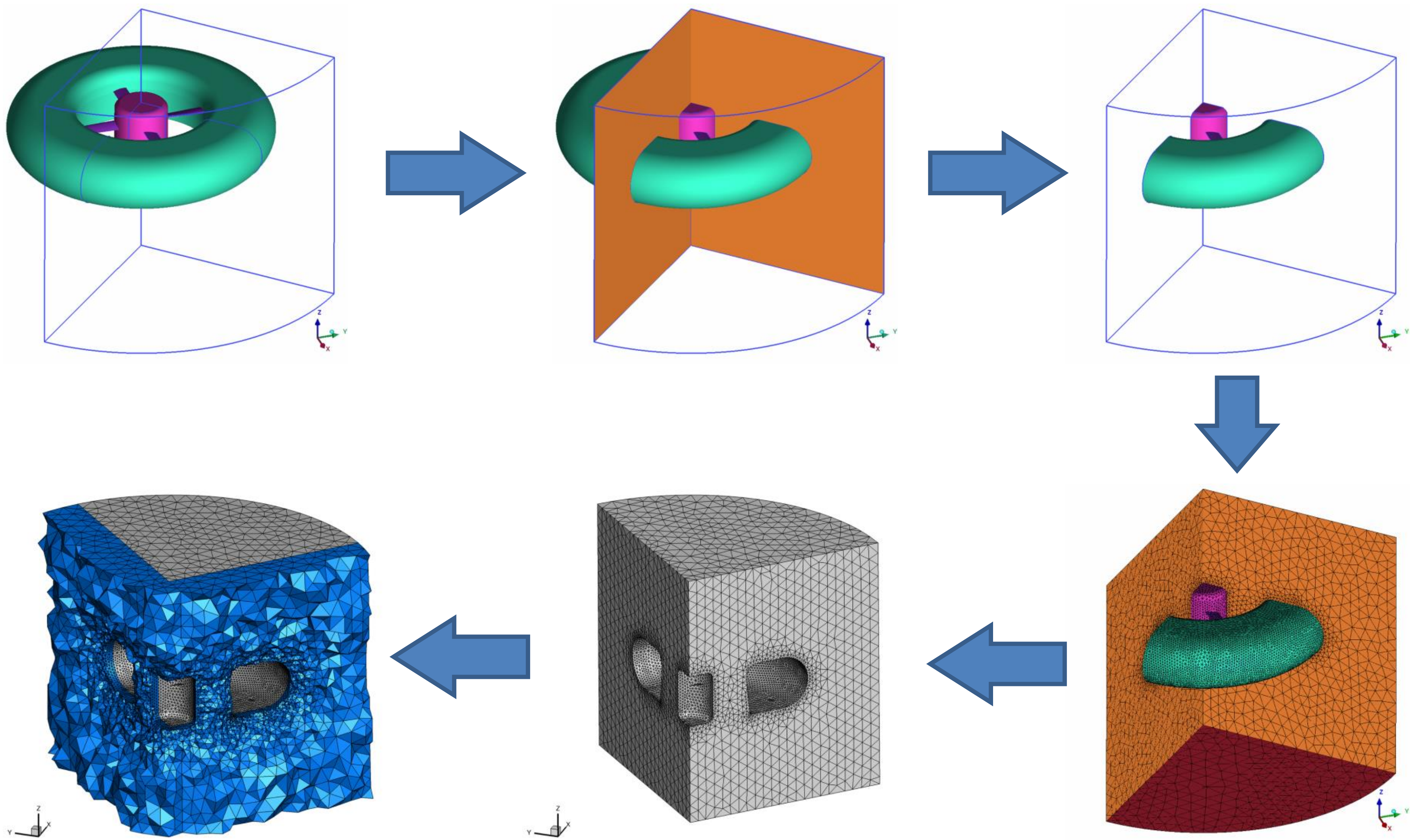




- non-reflecting BC
- periodical BC
- “immovable” no-slip BC
- rotating no-slip BC

Mathematical model and numerical method

Single sector with blade: meshing



Roadmap of Models

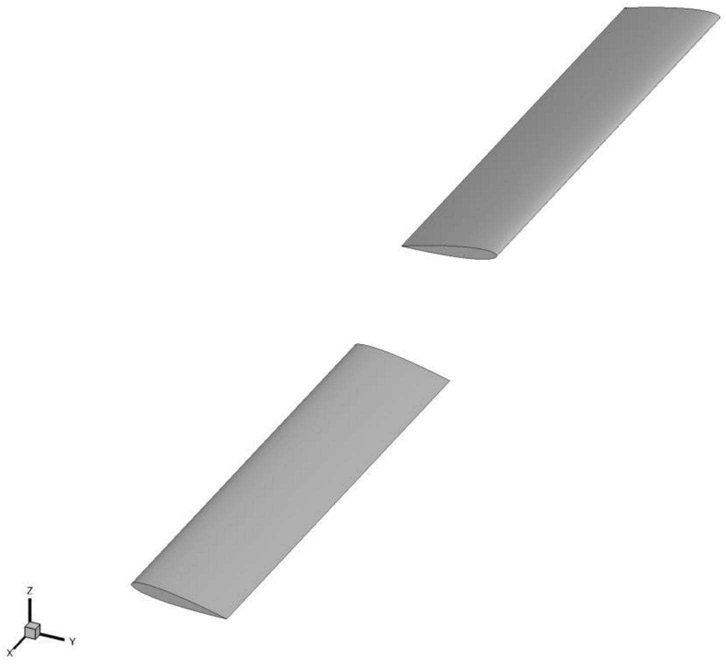
Flight mode	Properties	Sector	EE	RANS	DES
Hovering, vertical climbing, slow descent (with negligible blade-vortex interaction effects)	Thrust	+	+	+	+
	Torque	+	–	+	+
	Tonal noise	+	+	+	+
	Broadband noise	+	–	–	+
Descent	Thrust	+	+	+	+
	Torque	+	–	+	+
	Tonal noise	+	+	+	+
	Broadband noise	±	–	–	+
Cruising fight	Thrust	–	+	+	+
	Torque	–	–	+	+
	Tonal noise	–	+	+	+
	Broadband noise	–	–	–	+

VALIDATION

CARADONNA-TANG[1] ROTOR

[1] Caradonna, F.X. and Tung, C. Experimental and Analytical Studies of a Model Helicopter Rotor in Hover. Technical report, NASA Technical Memorandum TM-81232, 1981

Caradonna-Tang: problem setup



Blades count *N*	2
Rotor radius *R*	1.143 m
Blade chord *b*	0.1905 m
Blade base profile	NACA 0012
Pitch angle	8º
Rotation speed	650 RPM
Blade tip velocity V_{tip}	77.8 m/s

$$\rho_0 = 1.2041\,\mathrm{kg/m^3},\ \mu_0 = 1.827\times10^{-5}\ \mathrm{N\cdot cm/m^2}$$

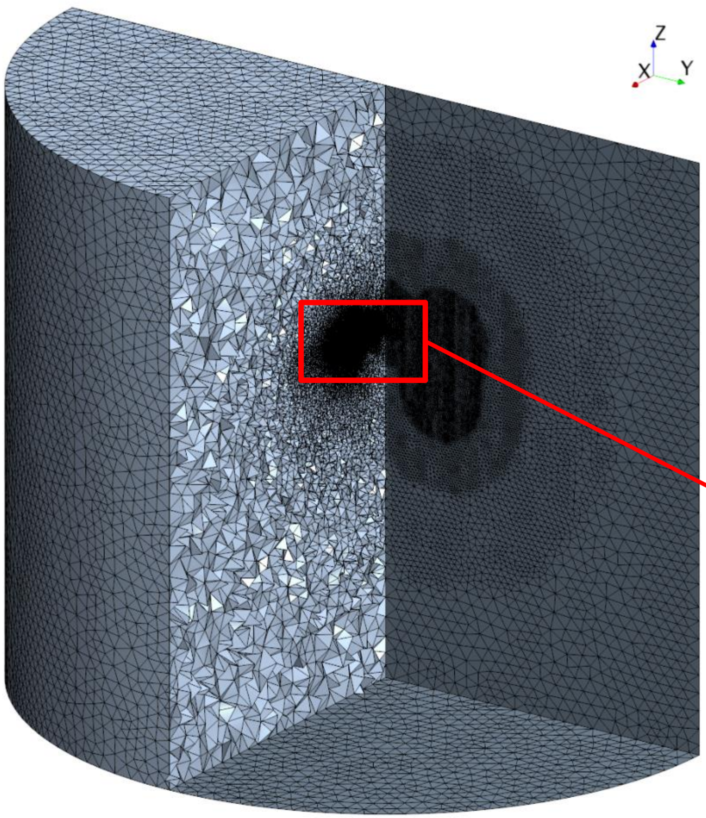
$$\mathrm{Re} = \frac{\rho_0 V_{tip} b}{\mu_0} = 6.28\times10^5$$

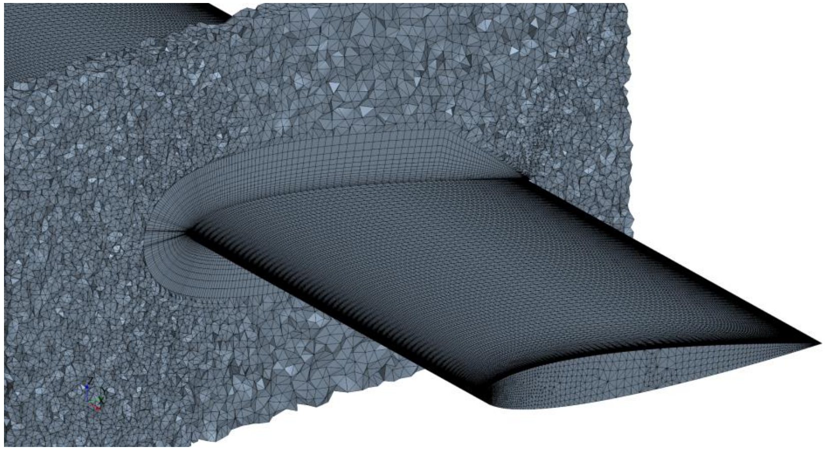
Caradonna-Tang: mesh

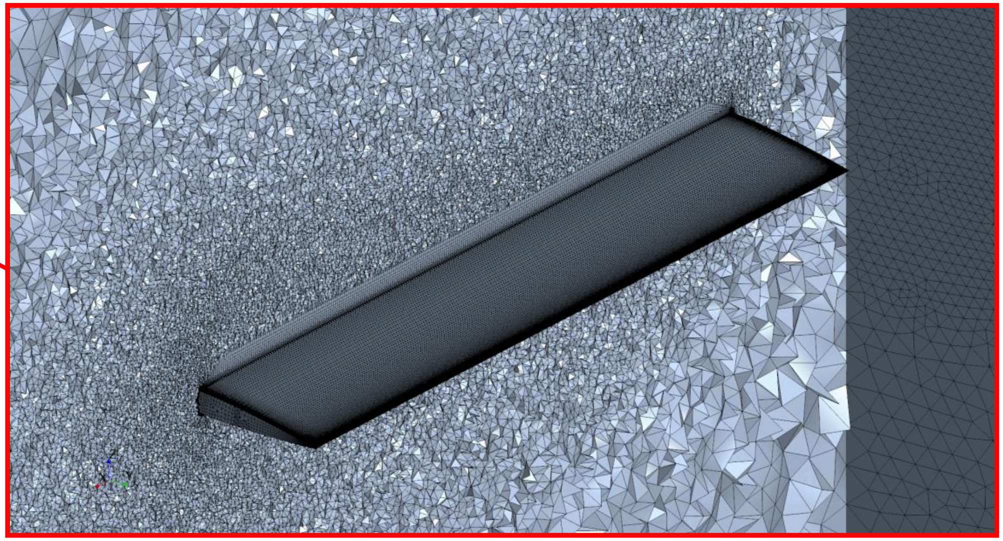
Hybrid mesh:

7 039 966 nodes

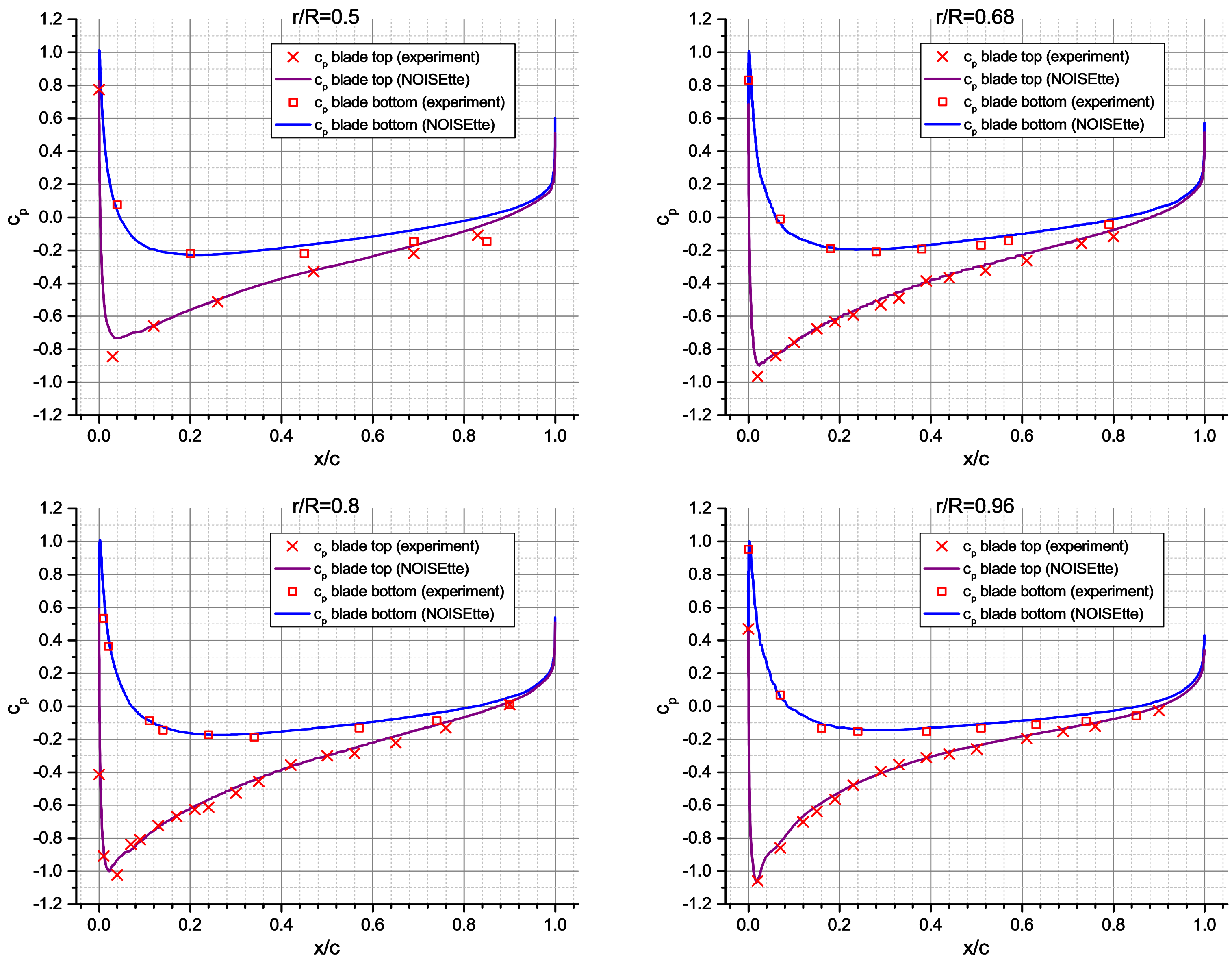
37 526 305 cells



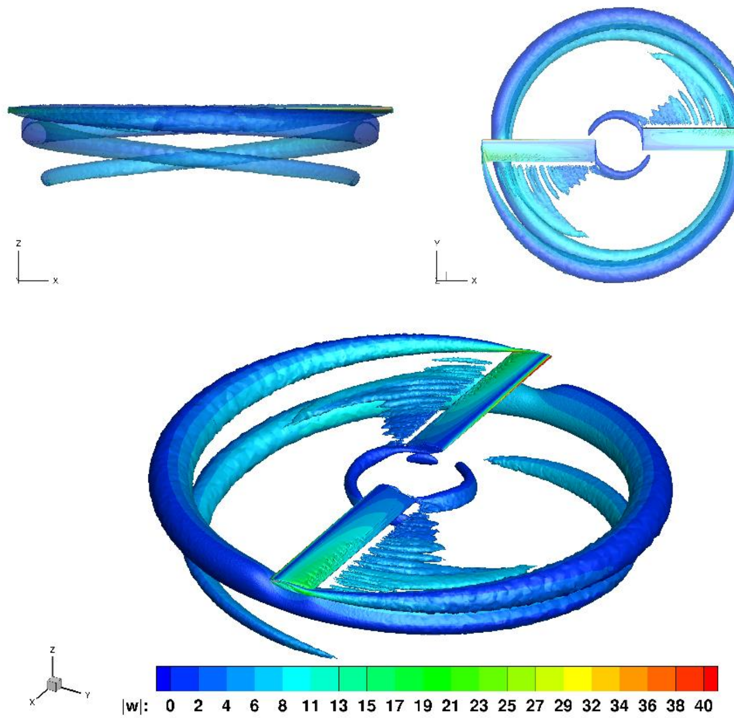




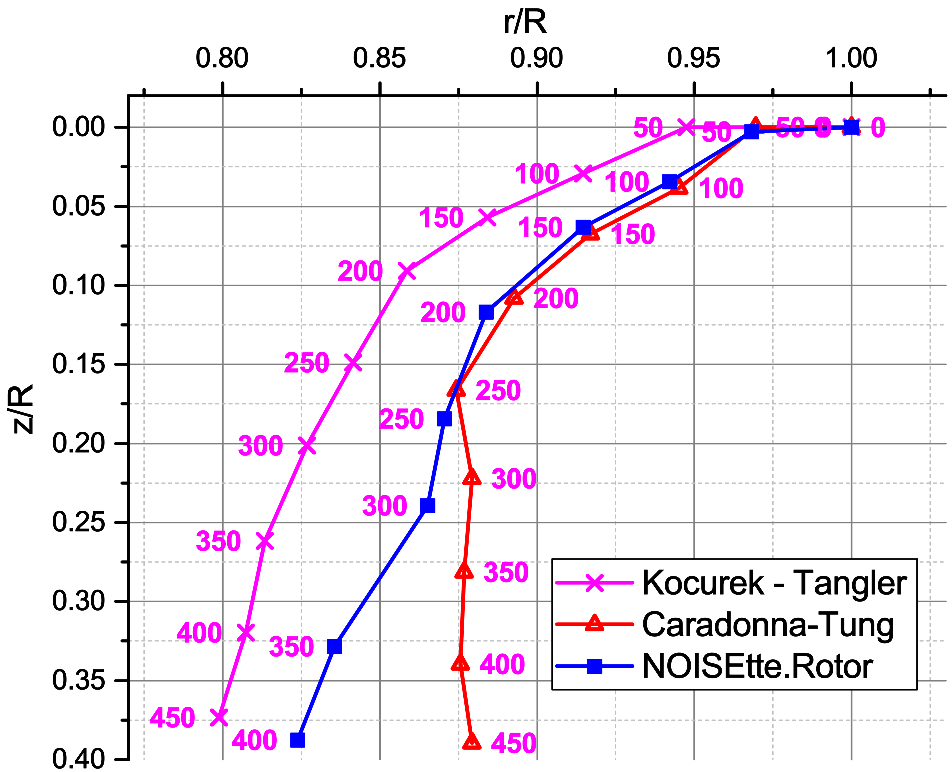
Caradonna-Tang: pressure coefficient



Caradonna-Tang: tip vortex evolution



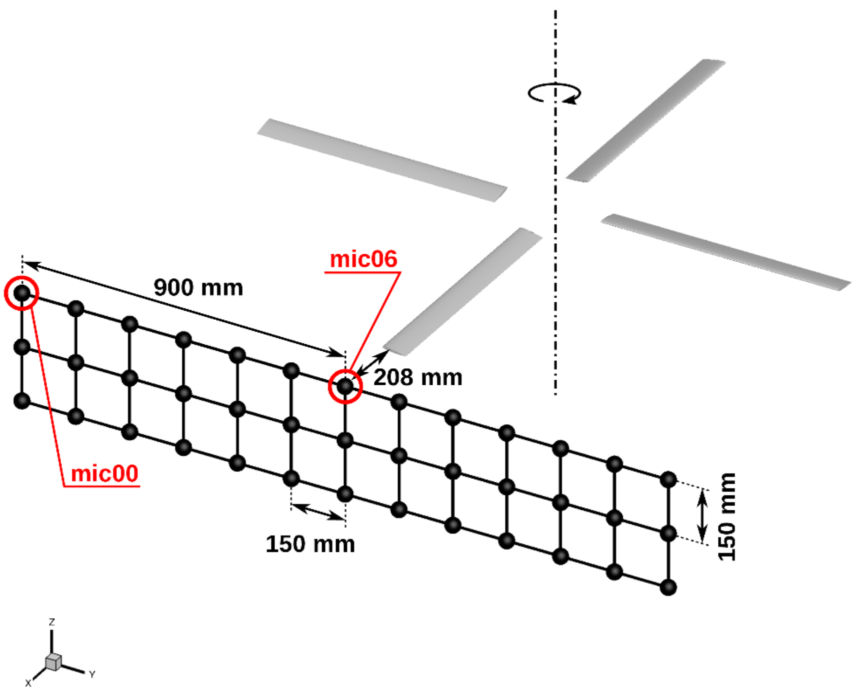
Q-criterion isosurface, q=0.01



Tip vortex horizontal and vertical displacement

KAI SCALED MAIN ROTOR

KAI scaled main rotor: problem setup



Blades count N	4
Rotor radius R	0.8 m
Blade chord b	0.065 m
Blade base profile	NACA 0012
Pitch angle	8º
Rotation speed	1100 RPM
Blade tip velocity V_{tip}	92.4 m/s

$$\rho_0 = 1.193\,\mathrm{kg/m^3},\ \mu_0 = 1.822027\times10^{-5}\ \mathrm{N\cdot s/m^2}$$

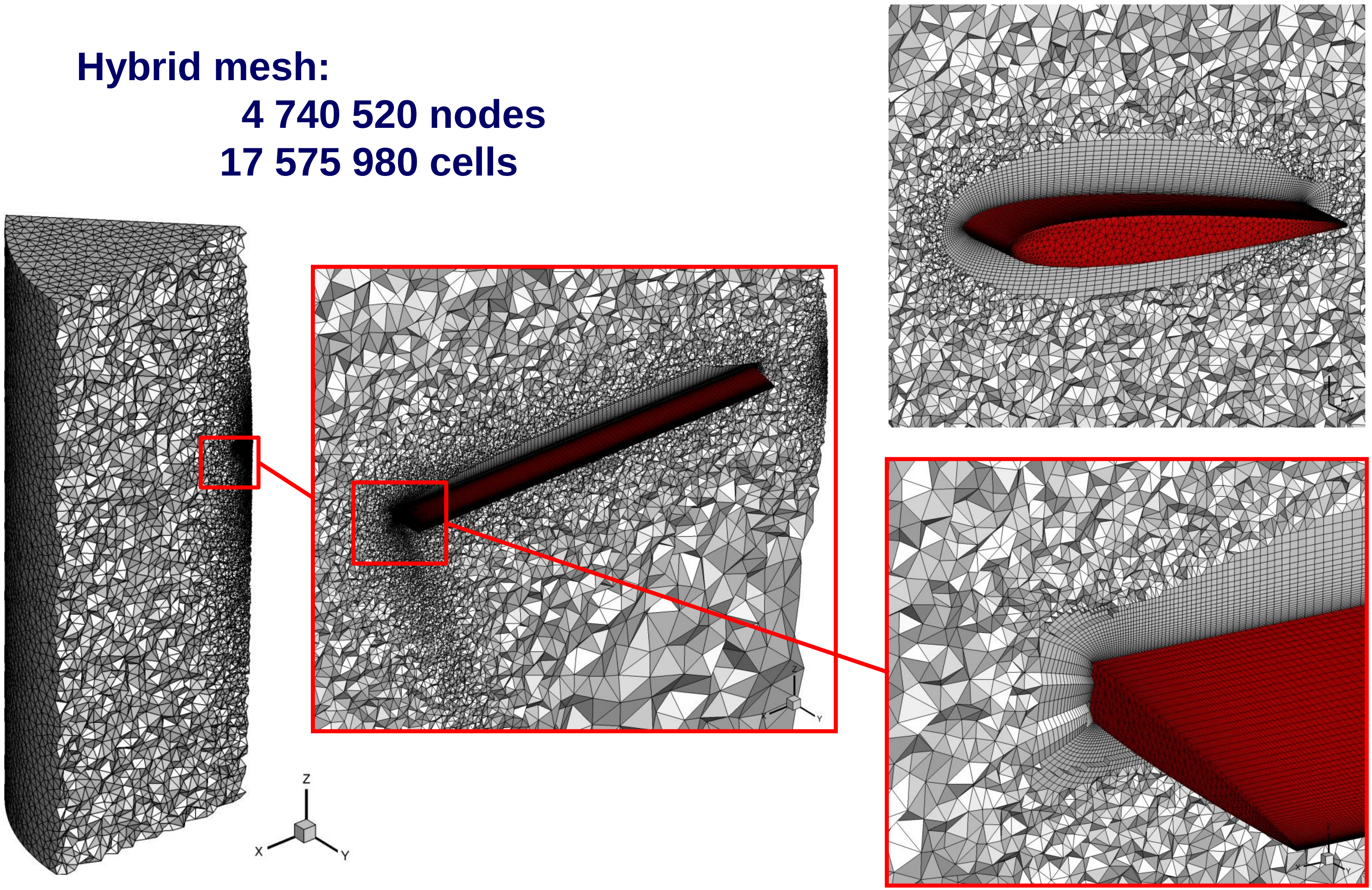
$$\mathrm{Re} = \frac{\rho_0 V_{tip} b}{\mu_0} \approx 1.4\times10^6$$

KAI scaled main rotor: mesh

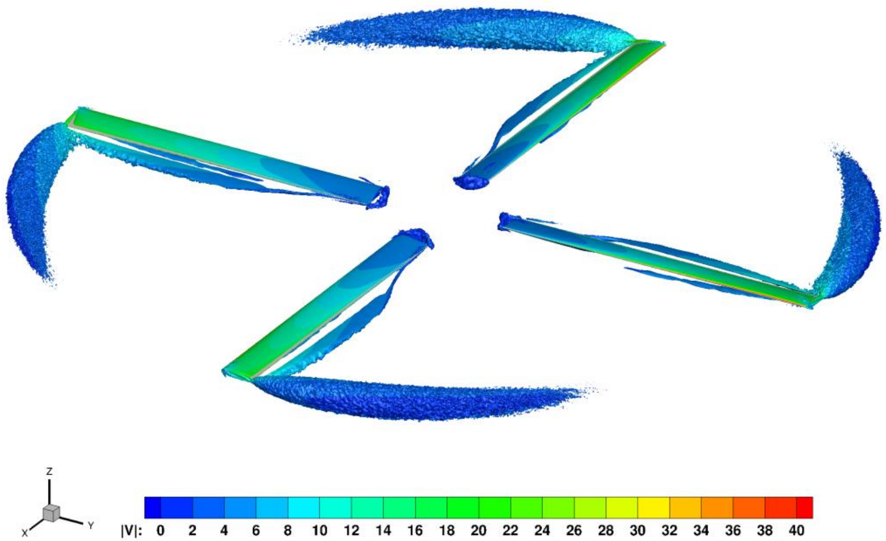
Hybrid mesh:

4 740 520 nodes

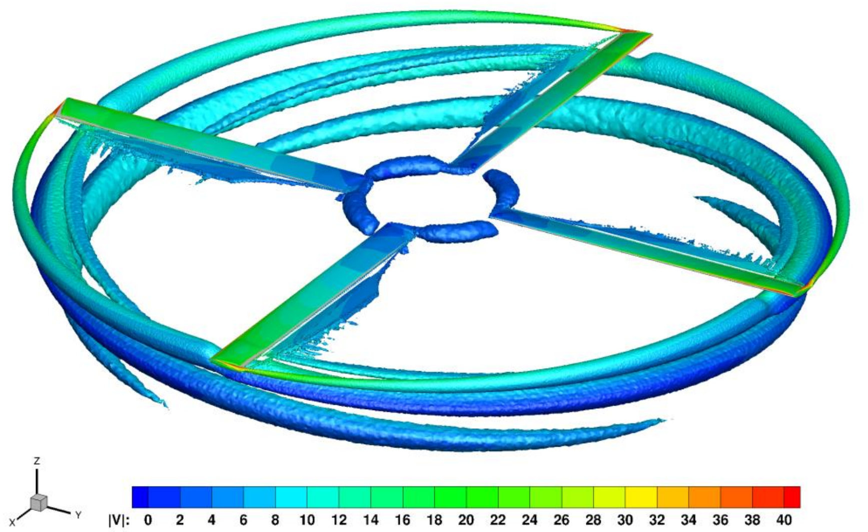
17 575 980 cells



KAI scaled main rotor: order and accuracy

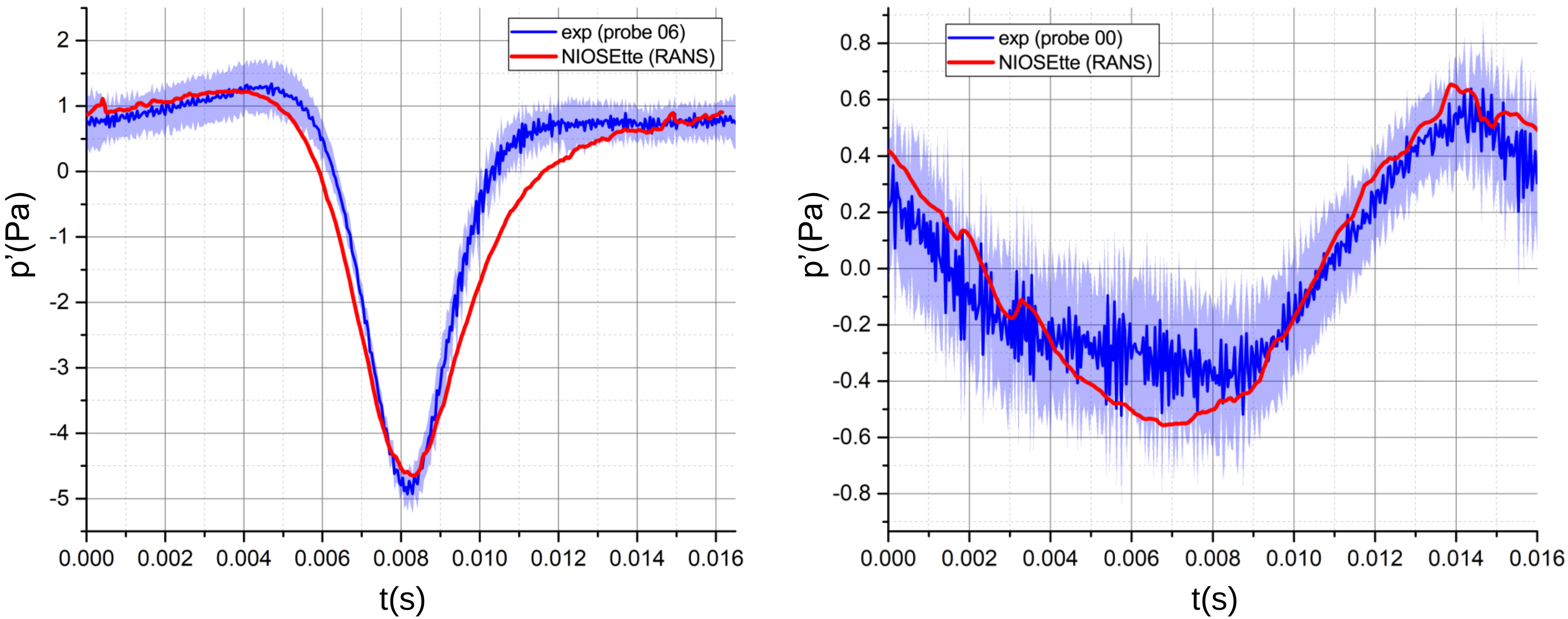


1st order



EBR3

KAI scaled main rotor: near field acoutics



Pressure pulsations in probe mic06 (left) and mic00(right)

APPLICATION

KAMOV SHROUDED ROTOR

Kamov shrouded rotor: problem setup

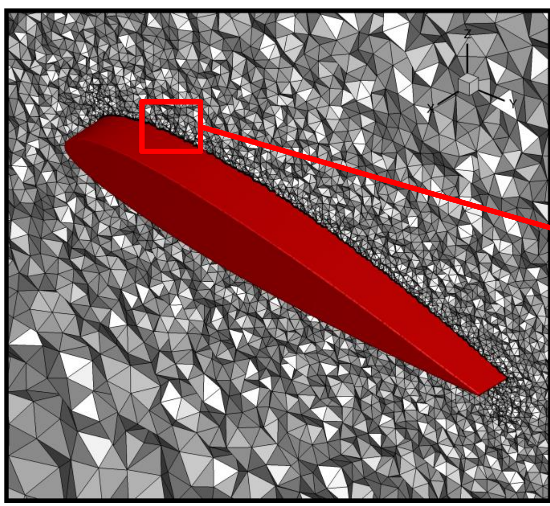
Blades count N	4
Rotor radius R	1.2 m
Blade chord b	0.13 m
Hub radius	0.248 m
Blade base profile	TSAGI SV-11
Blade twist	linear, $\varphi(r)=\frac{40}{3}\left(0.7-\frac{r}{0.6}\right)$
Channel inner radius	0.605 m
Channel outer radius	1.25 m
Rotation speed	1166.4 RPM
Blade tip velocity V_{tip}	73.3 m/s

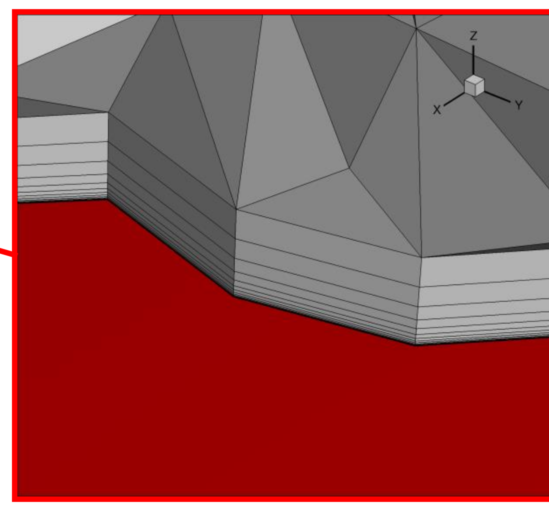
$$\rho_0 = 1.2041 \mathrm{kg/m^3},\ \mu_0 = 1.827\times10^{-5}\ \mathrm{N\cdot s/m^2}$$

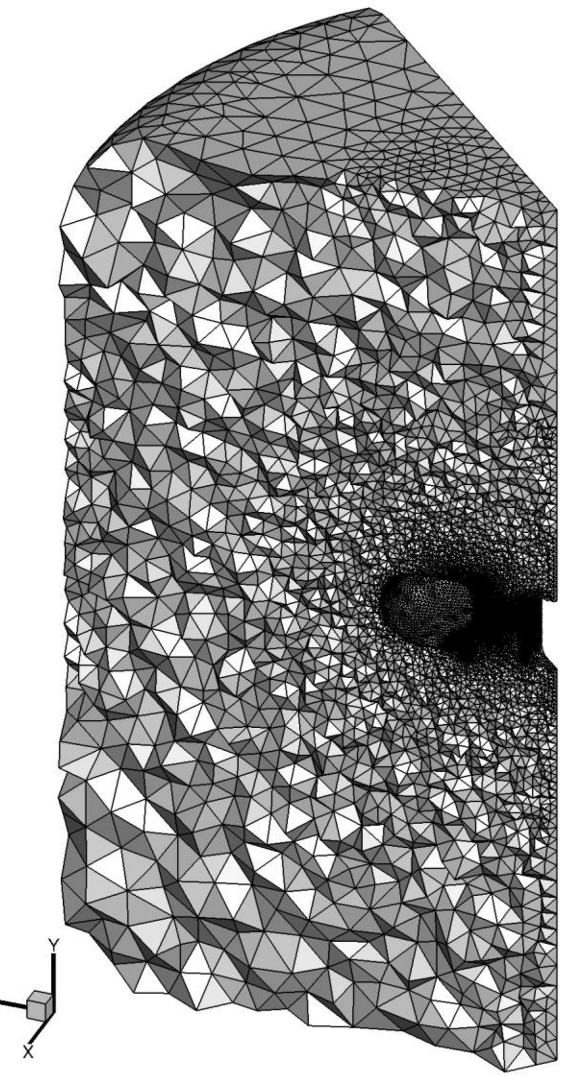
$$\mathrm{Re}=\frac{\rho_0 V_{лоп} b}{\mu_0}=6.28\times10^5$$

Kamov shrouded rotor: meshes

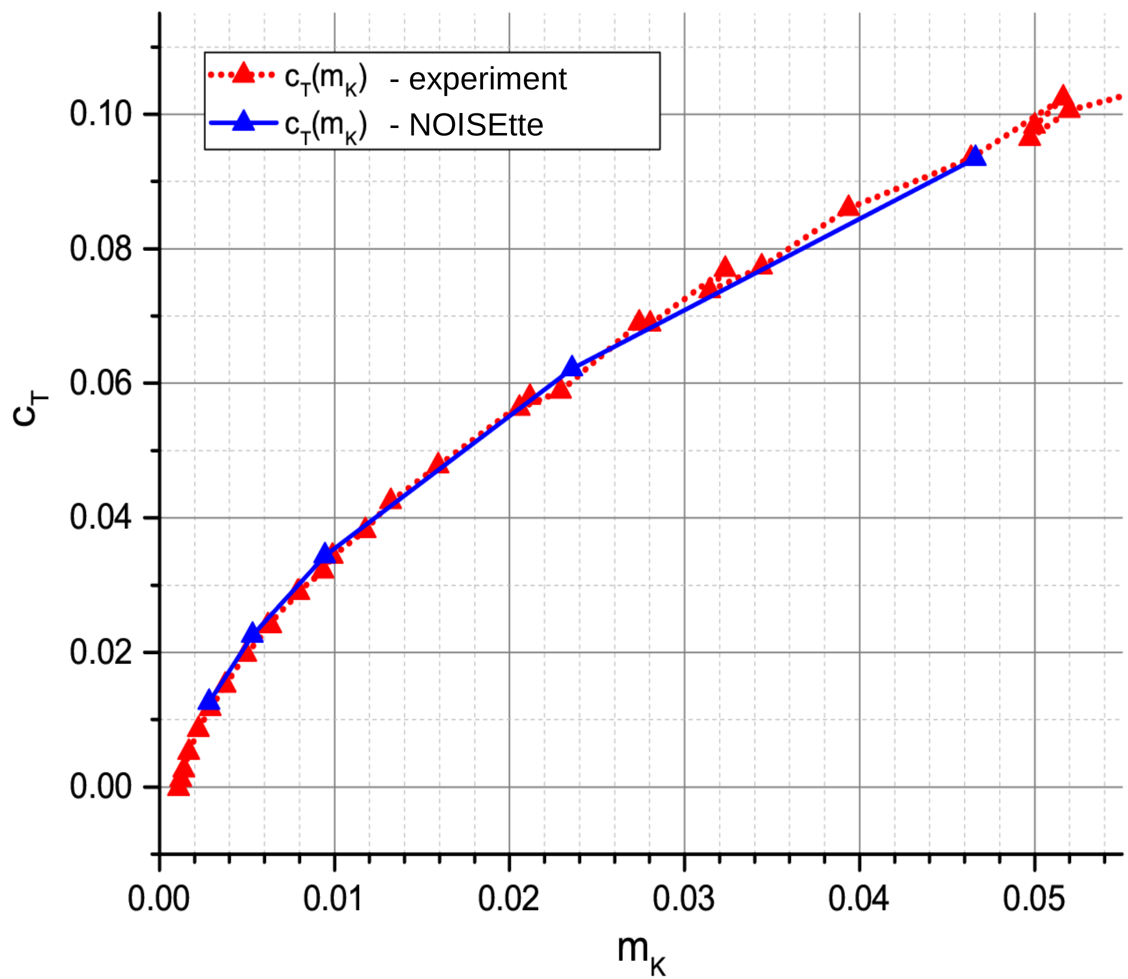
Pitch angle	Nodes count	Cells count
10º	2 326 941	13 589 791
15º	2 371 707	13 859 009
15º (Hybrid)	2 374 581	7 352 927
20º	2 511 582	14 669 900
30º	2 555 652	14 936 402
30º (Hybrid fine)	6 478 232	21 016 355
40º	2 592 469	15 154 418





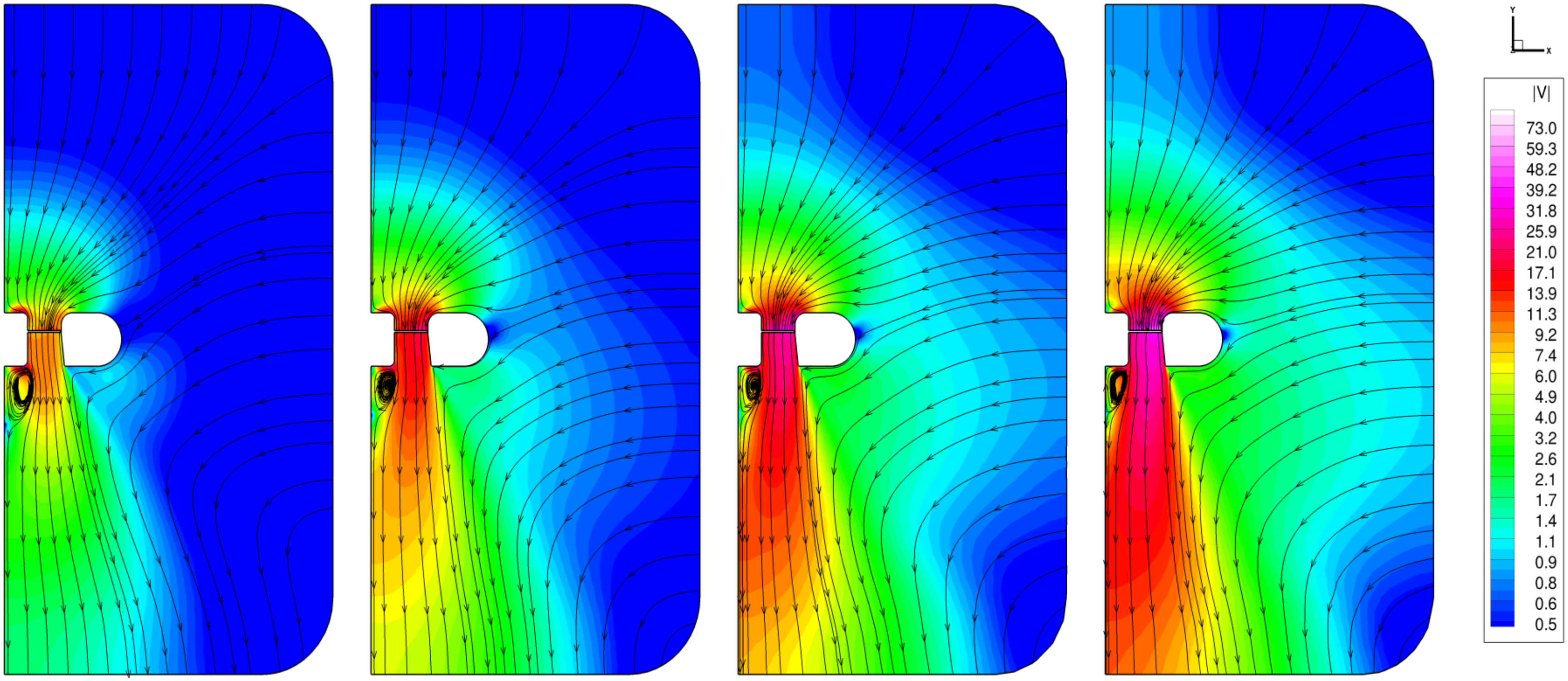


Kamov shrouded rotor: aerodynamics



Polar graph (thrust coefficient against torque coefficient)

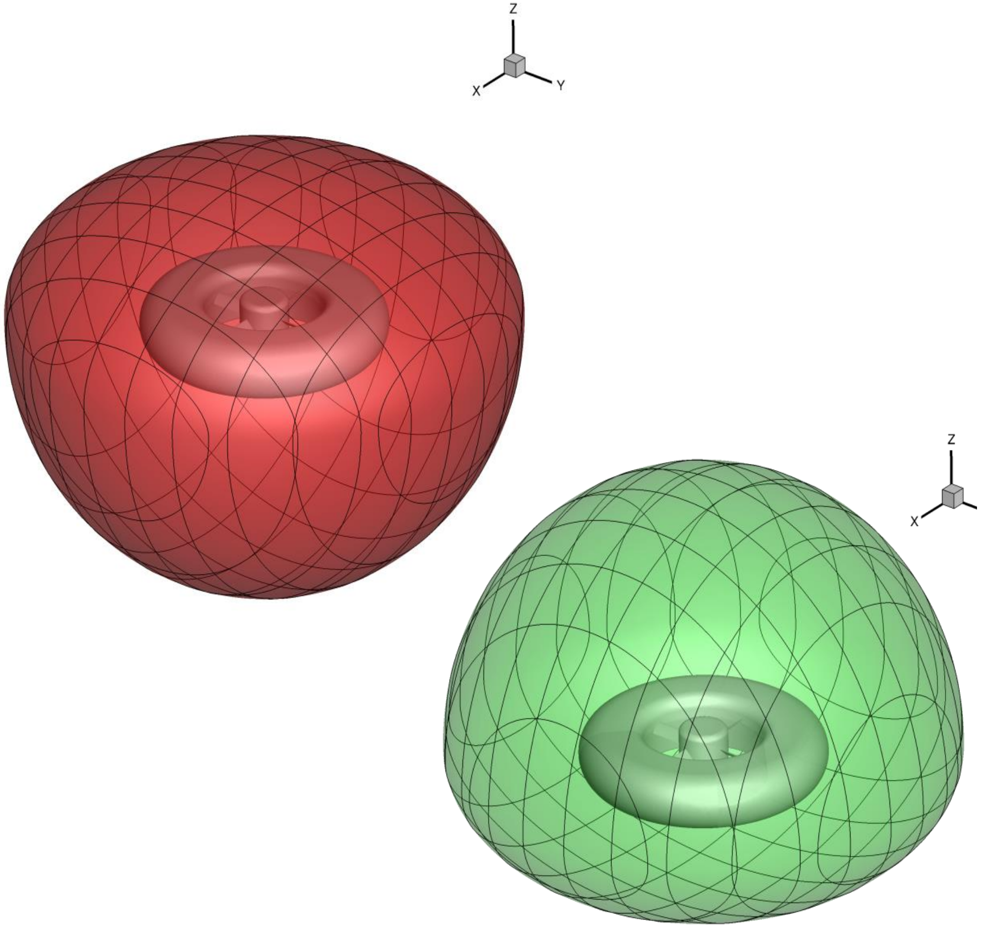
Kamov shrouded rotor: velocity field

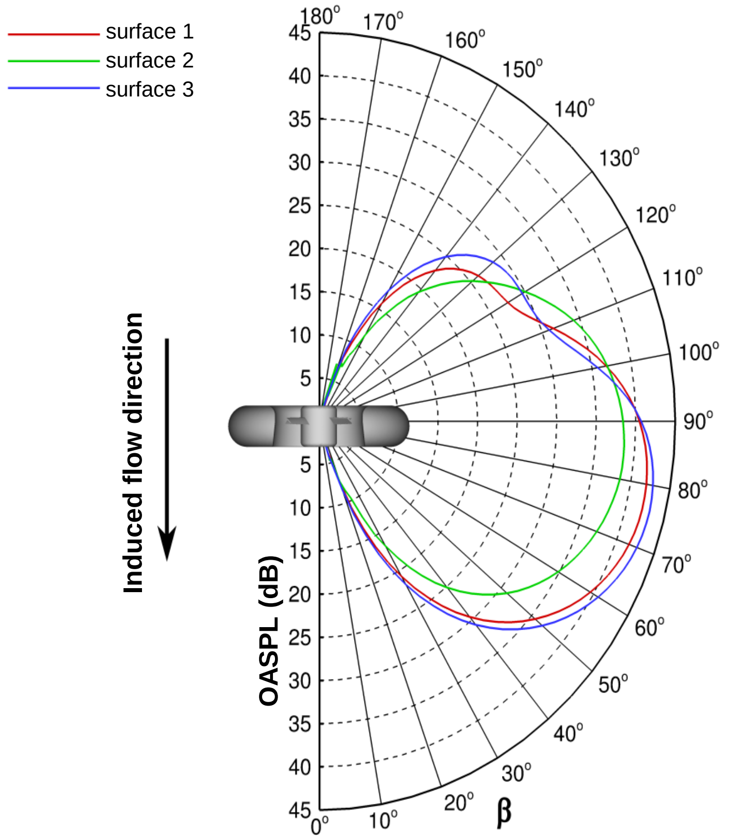


10° 20° 30° 40°

Absolute velocity fields for the pitch angles

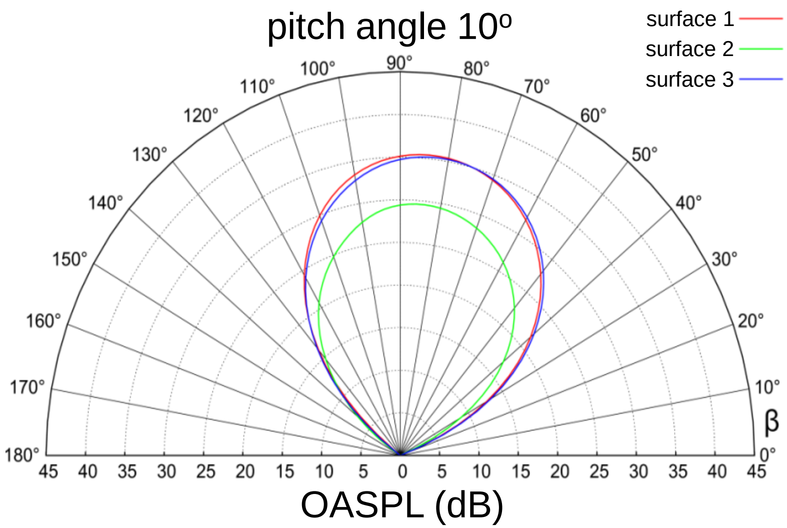
Kamov shrouded rotor: acoustics

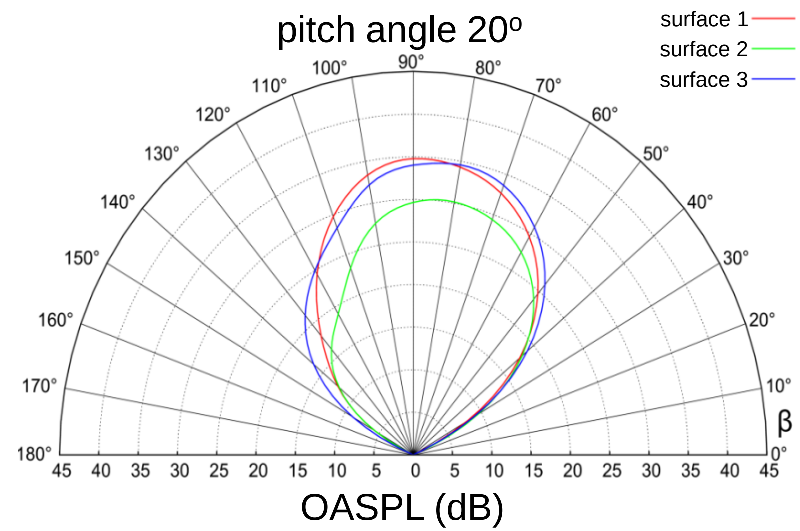


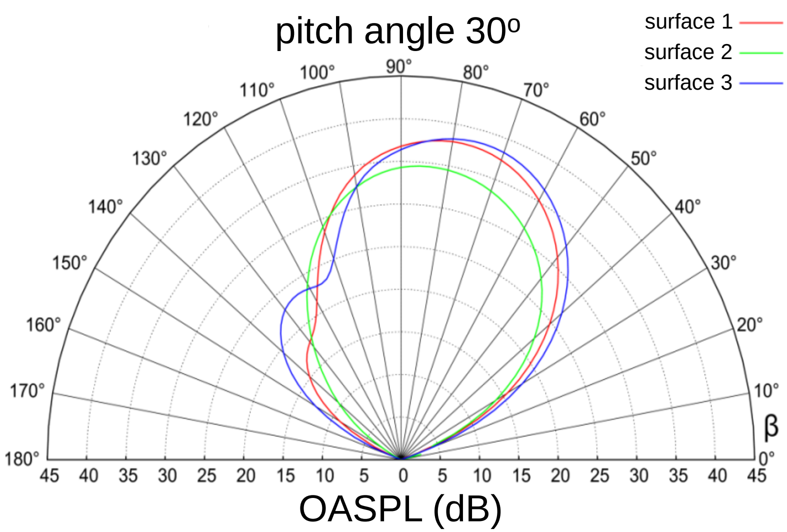


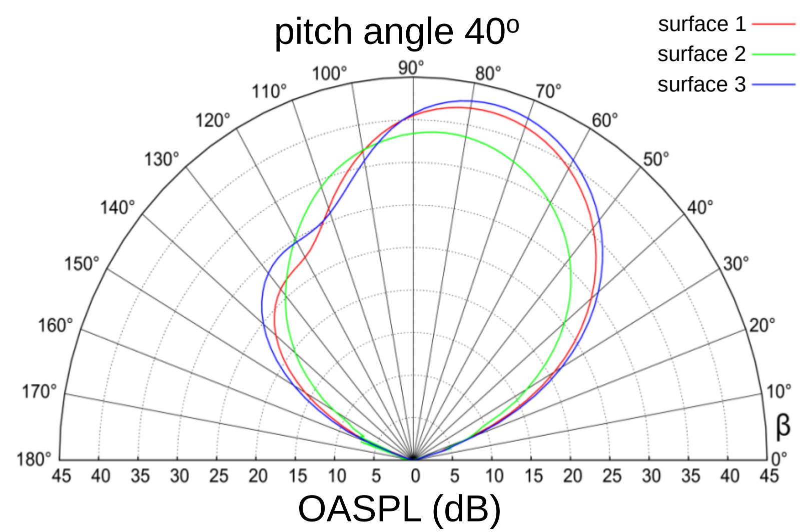
FWH control surfaces

Kamov shrouded rotor: acoustics









Overall sound pressure level diagrams

KAMOV SCALED MAIN ROTOR

Kamov shrouded rotor: problem setup

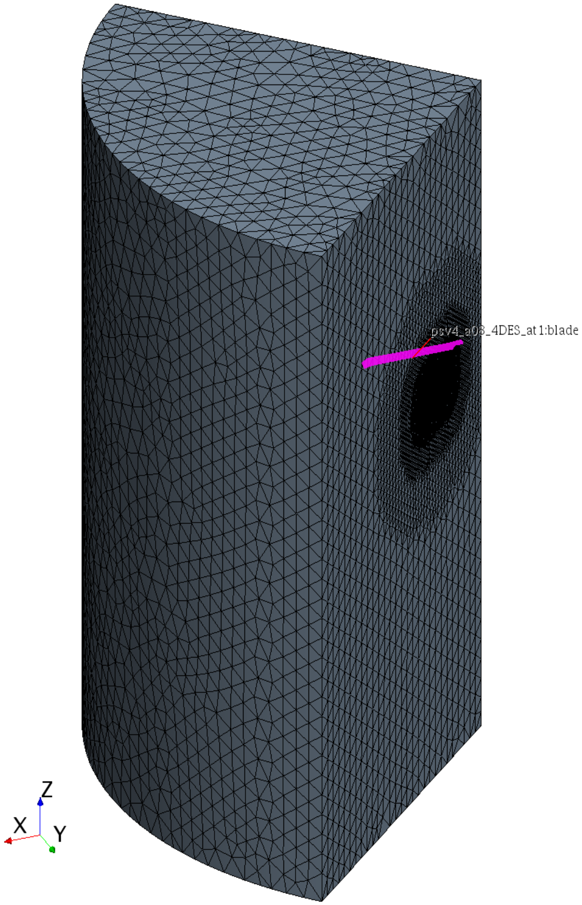
Blades count *N*	4
Rotor radius *R*	1.952 m
Blade chord *b*	0.18 m
Blade base profile	5 unsymmetrical profiles + tapered tip
Pitch angle	8°
Rotation speed	584.5 RPM
Blade tip velocity V_{tip}	119.5 m/s

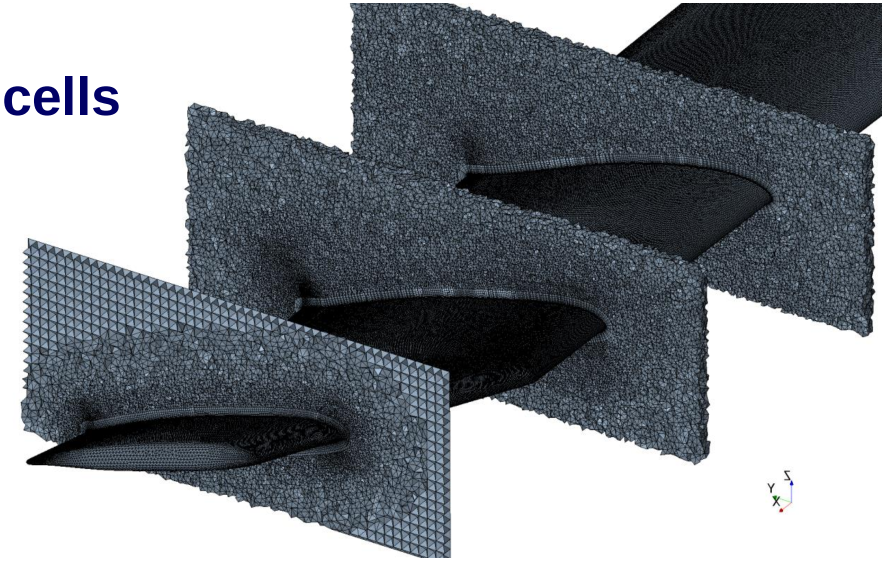
$$\rho_0 = 1.193\,\mathrm{kg/m^3},\ \mu_0 = 1.822027\times10^{-5}\ \mathrm{N\cdot s/m^2}$$

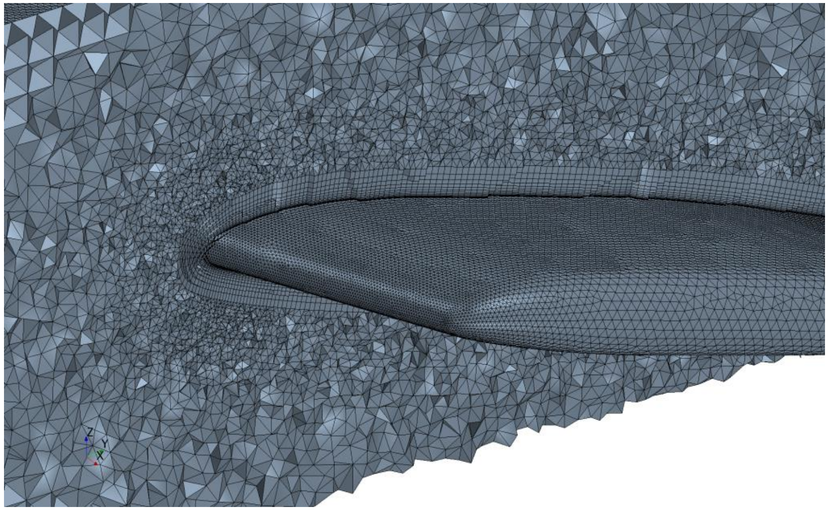
$$\mathrm{Re} = \frac{\rho_0 V_{tip} b}{\mu_0} \approx 1.4\times10^6$$

Kamov shrouded rotor: problem setup

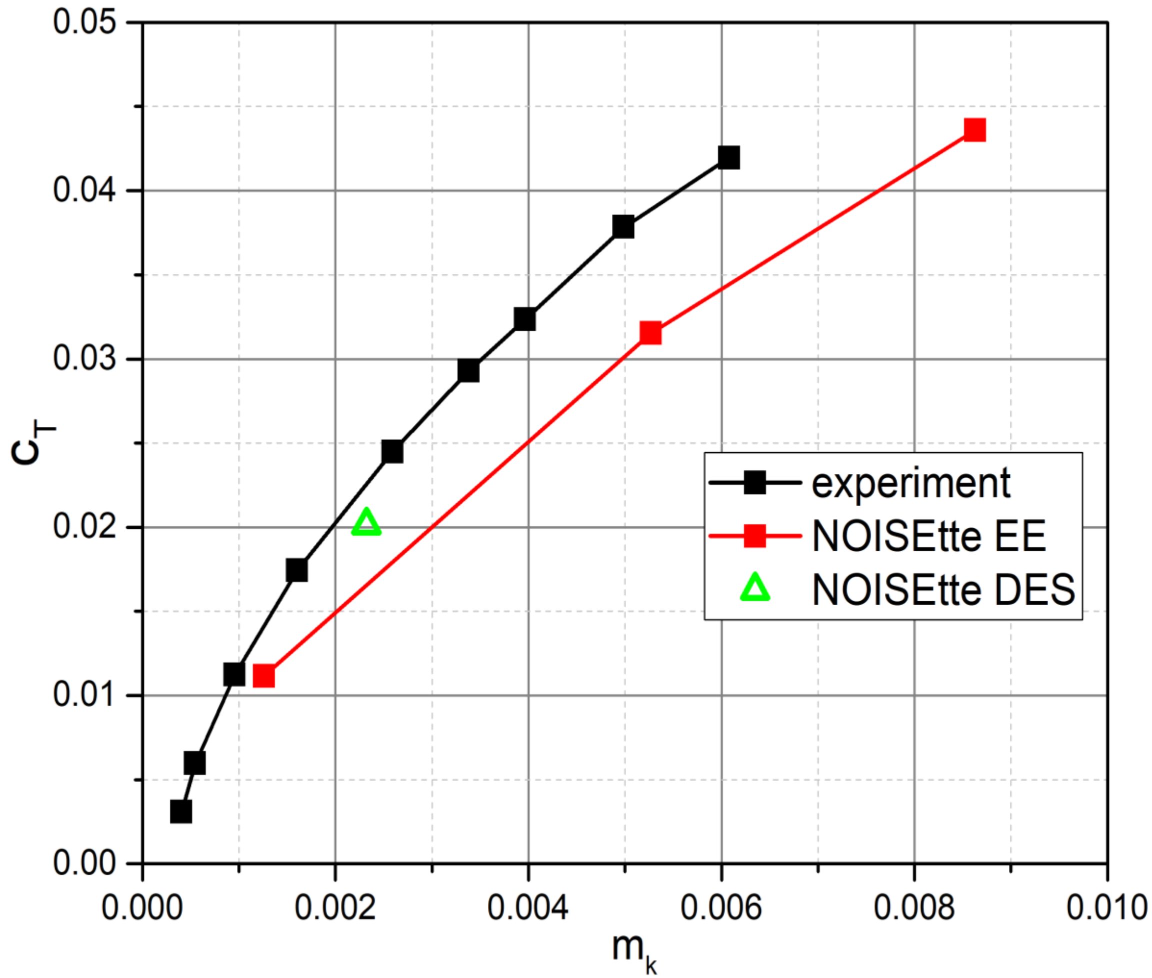
Hybrid mesh:
Single sector: 19M nodes, 99M cells
Full configuration: 75M nodes, 392M cells





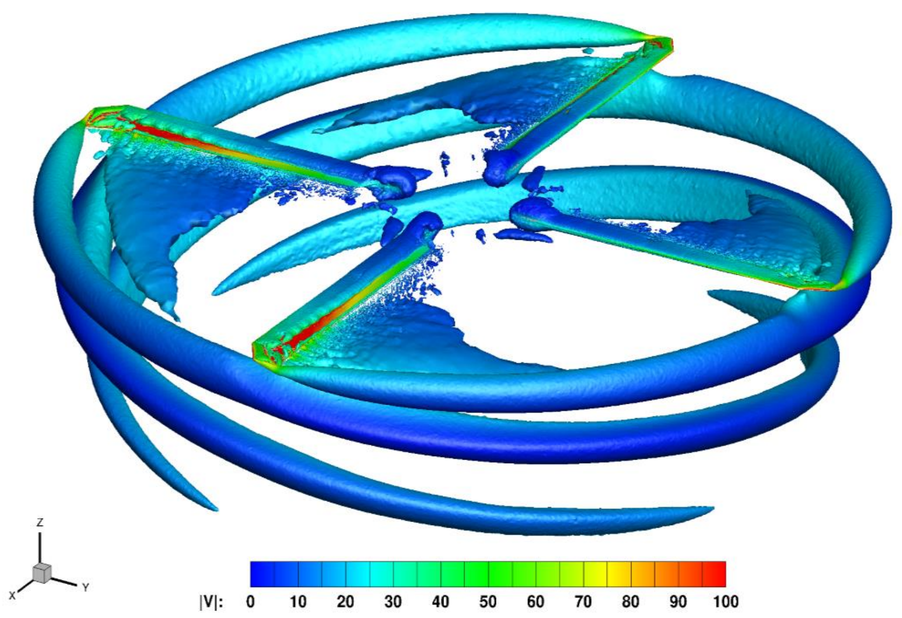


Kamov shrouded rotor: aerodynamics

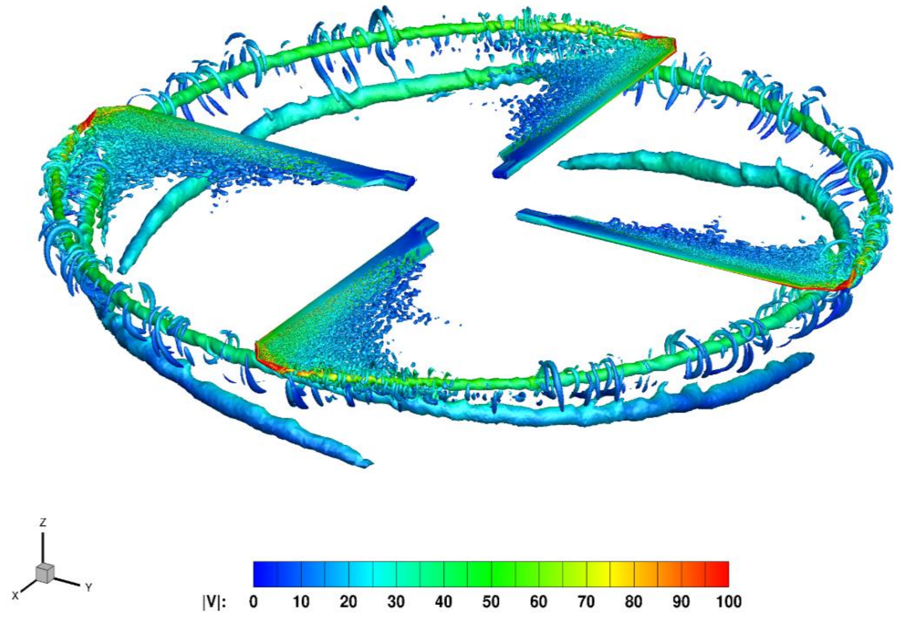


Polar graph (thrust coefficient against torque coefficient)

Kamov shrouded rotor: vortices structure

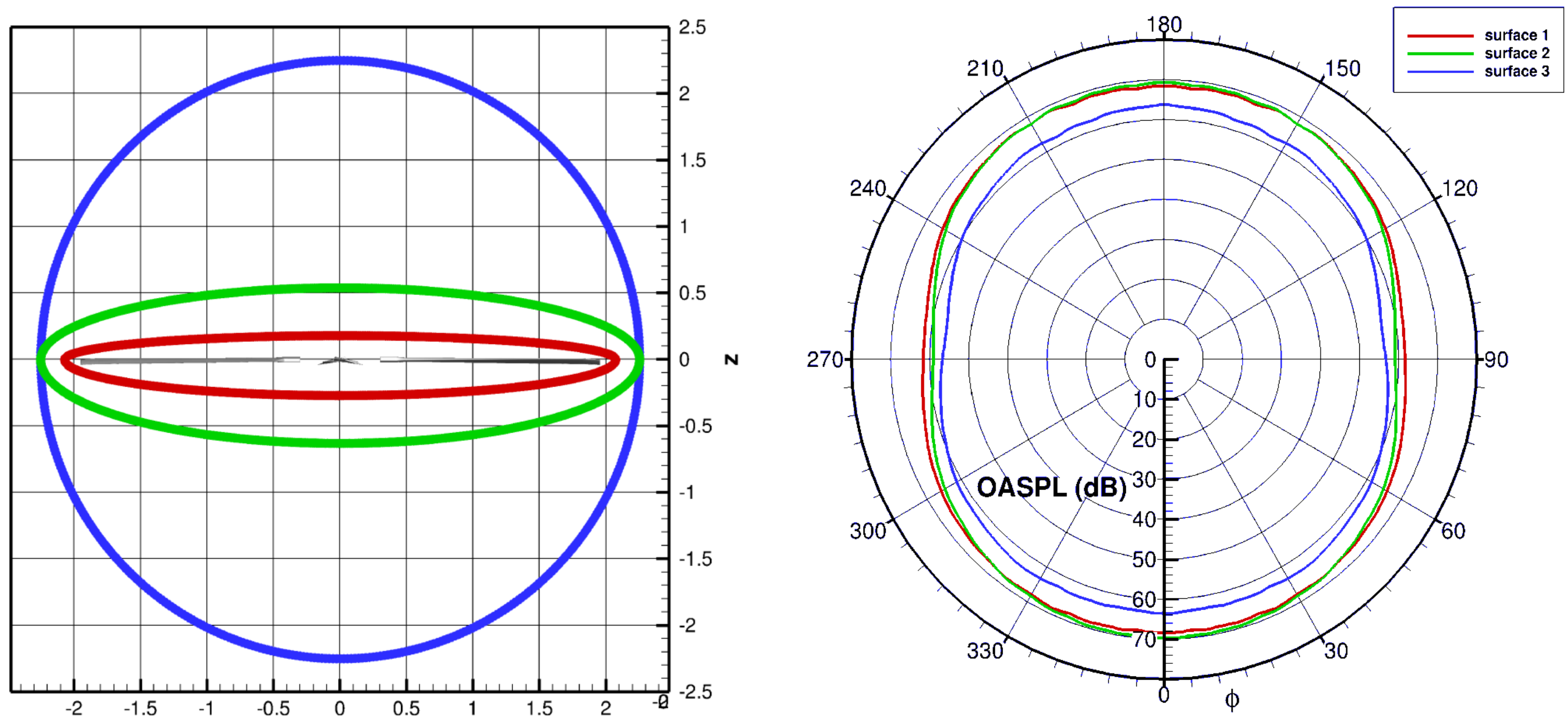


NOISEtte RANS SA



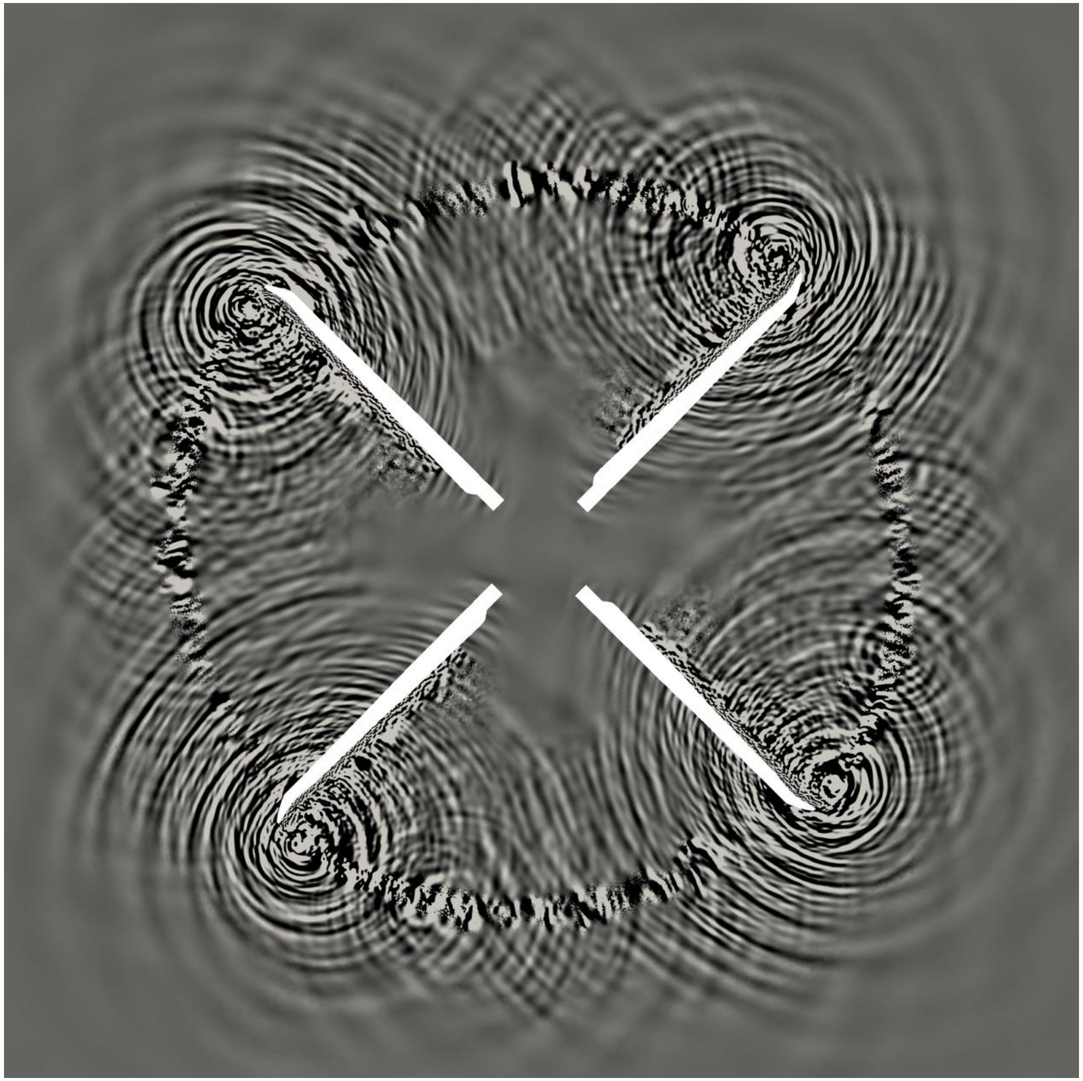
NOISEtte DES SA

Kamov shrouded rotor: acoustics



FWH control surfaces (left) and OASPLs (right)

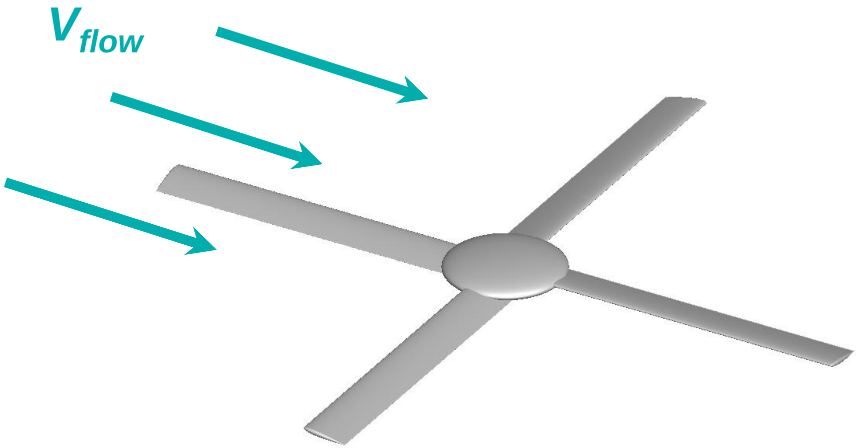
Kamov shrouded rotor: acoustics



Density gradient field in rotor plane section

PAVLOV SCALED MAIN ROTOR

PAVLOV scaled main rotor: problem setup



Blades count ***N***	4
Rotor radius ***R***	1.2 m
Blade chord ***b***	0.15 m
Blade base profile	NACA 0012
Pitch angle	8º
Rotation speed	360 RPM
Blade tip velocity V_{tip}	45.2 m/s
Background flow V_{flow}	6.8, 11.3 m/s

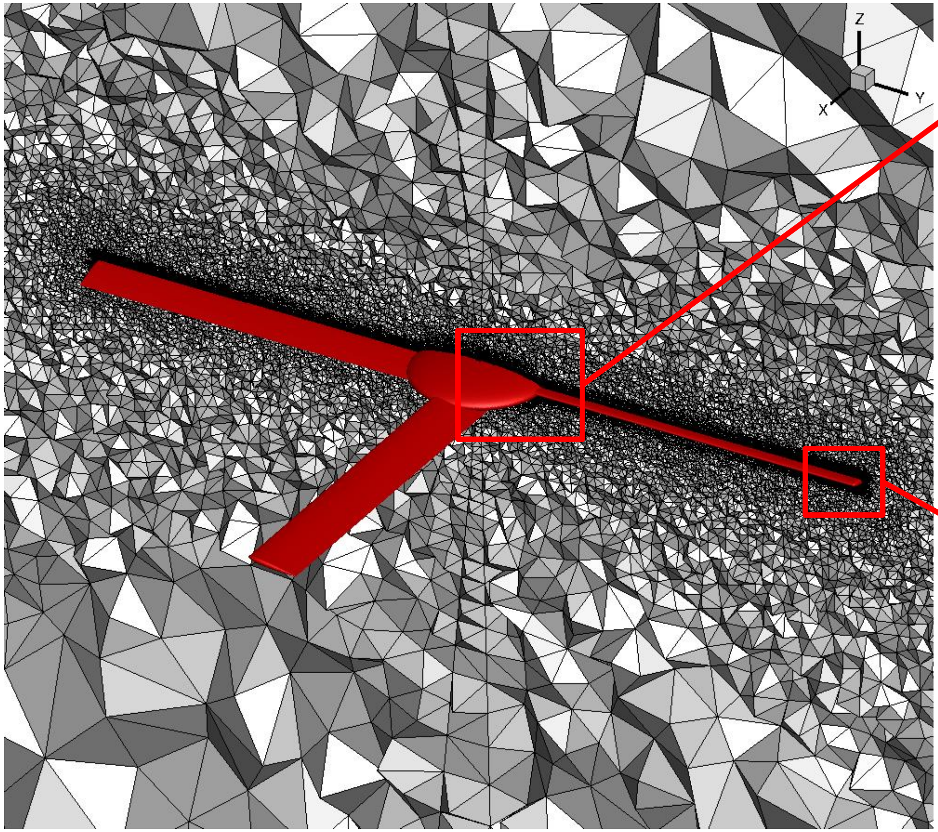
$$\rho_0 = 1.225\, kg/m^3\,, \mu_0 = 1.827 \times 10^{-5}\, N \cdot s/m^2\,, Re = \frac{\rho_0 V_{tip} b}{\mu_0} \approx 0.6 \times 10^6$$

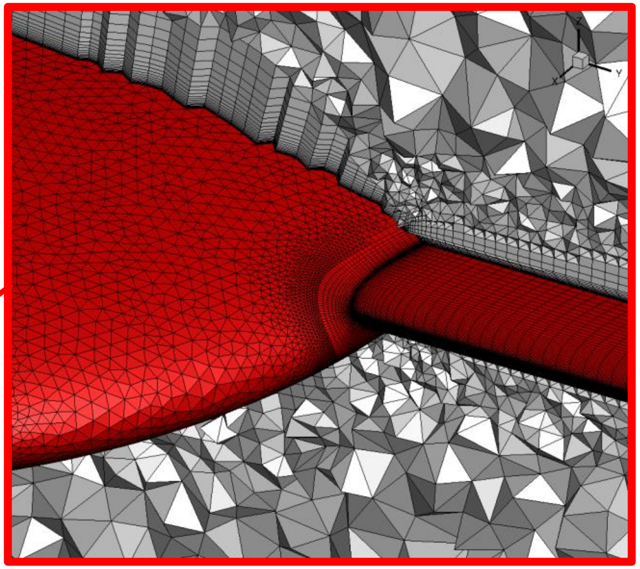
PAVLOV scaled main rotor: mesh

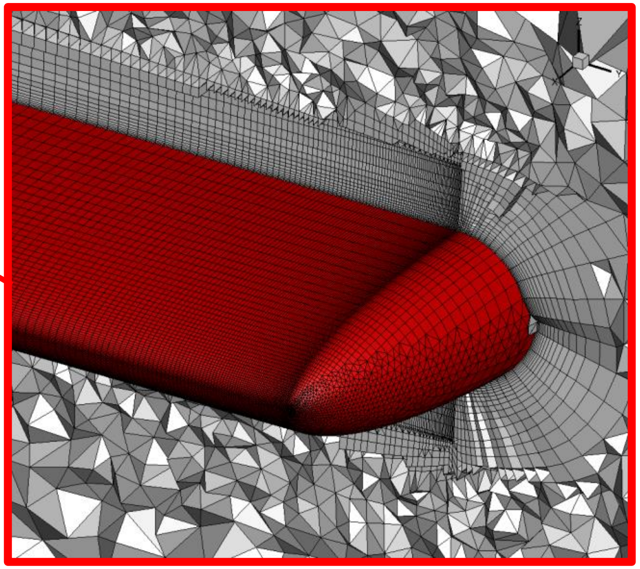
Hybrid mesh:

9 272 990 nodes

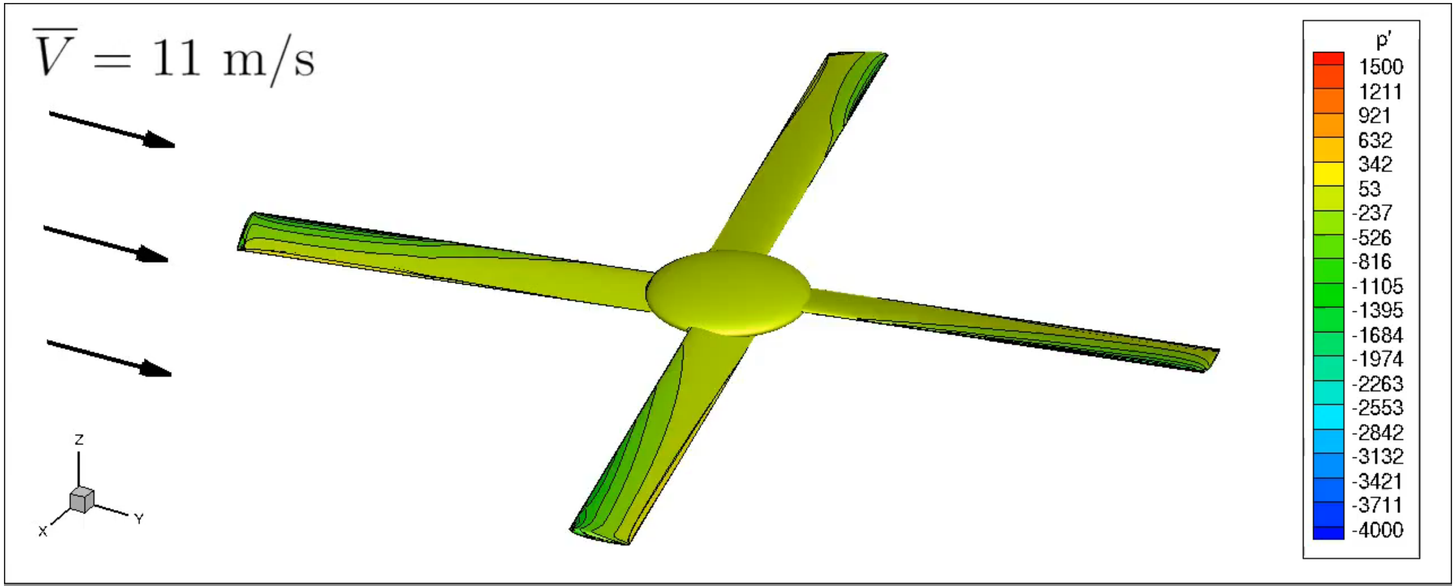
24 283 736 cells

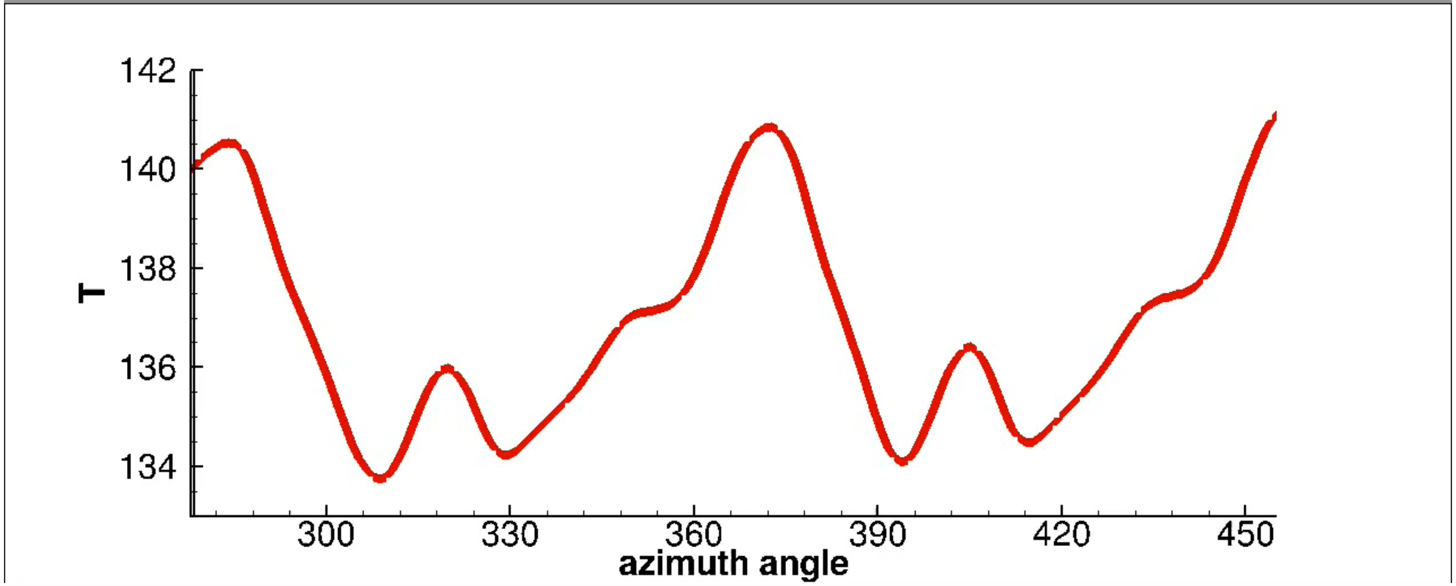






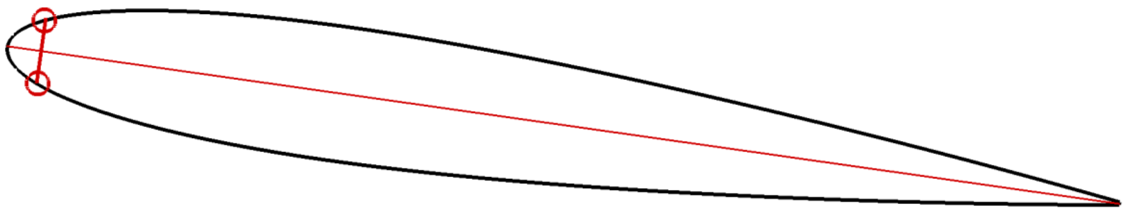
PAVLOV scaled main rotor: aerodynamics

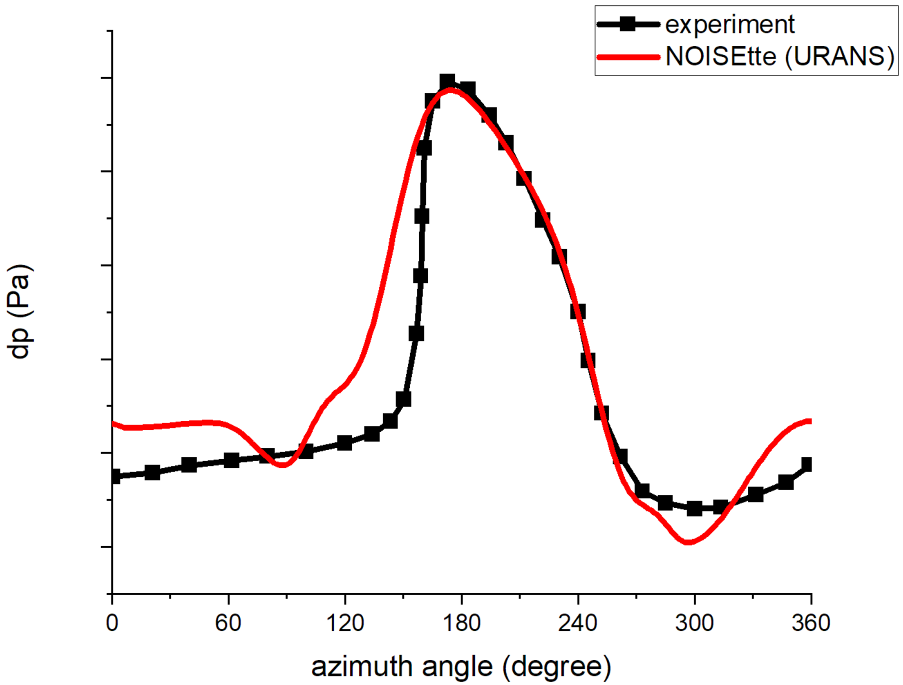




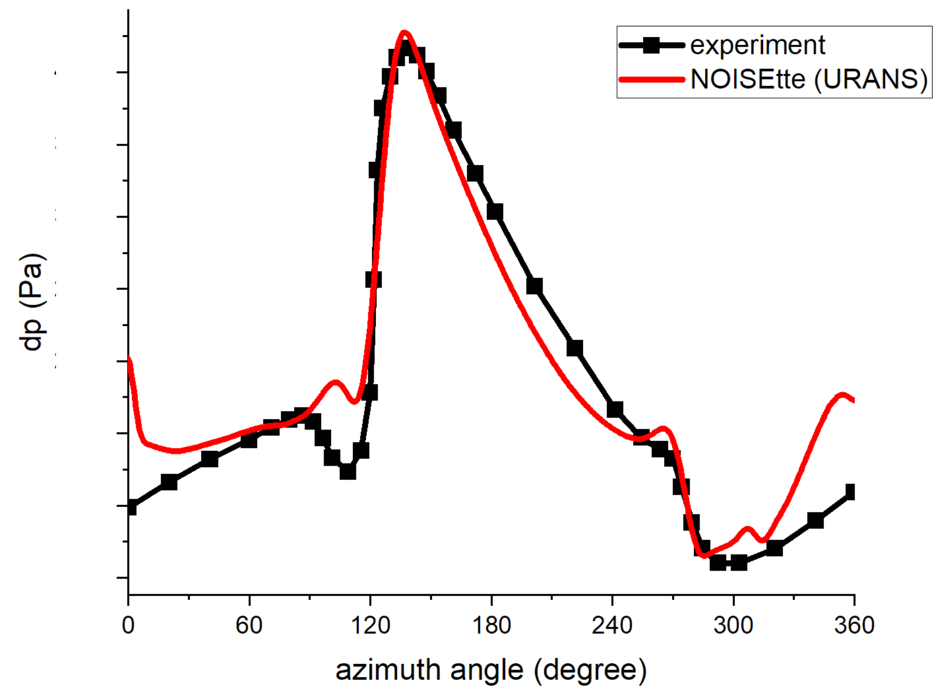
PAVLOV scaled main rotor: aerodynamics

r/R=0.8: dp=$p_{point1} - p_{point2}$





V_{flow} = 6.8m/s



V_{flow} = 11.3m/s

CONCLUSION

Result

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Future work

- Dynamic change of blades pitch angle (deformable meshes, sliding meshes)
- Rotor broadband noise analysis and verification

Thank you!

Any questions?

Mathematical model and numerical method

- Navier-Stockes equations in rotating frame reference[1]
- SA RANS + wall law (wall functions) [2]
- Hybrid turbulent model SA DDES ($\Delta = \Delta_{SLA}$ – Shear Layer Adapted)[3]
- Modified «1A» Farassat formulation for FWH equation[4]

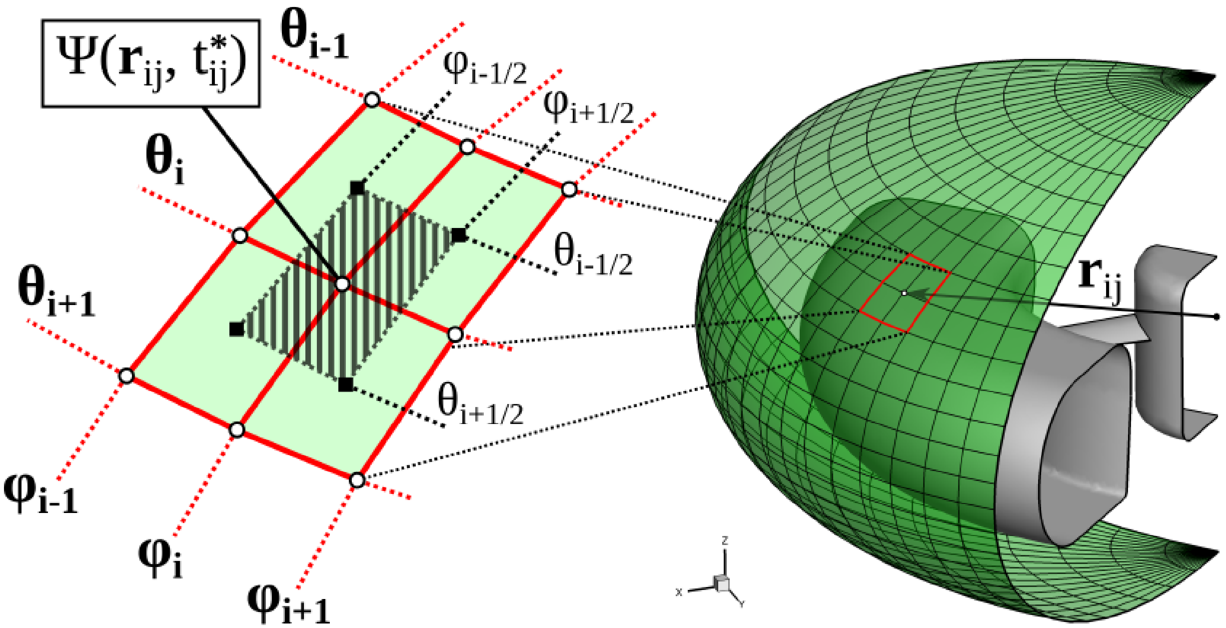
[1] *Abalakin, I.V., Anikin, V.A., Bakhvalov, P.A. et al. Fluid Dyn. (2016) 51: 419.* *https://doi.org/10.1134/S0015462816030145*

[2] *Knopp T.* Universal Wall Functions for Aerodynamic Flows: Turbulence Model Consistent Design, Potential and Limitations In book: MEGADESIGN and MegaOpt, NNFM 107, 55-71

[3] *Shur M., Spalart P., Strelets M., Travin A*. An Enhanced Version of DES with Rapid Transition form RANS to LES in Separated Flows // Flow Turb. Comb., 2015, **95**(4), 709-737

[4] *Bakhvalov, P.A., Bobkov, V.G. & Kozubskaya, T.K. Math. Models Comput. Simul. (2017) 9: 716.* *https://doi.org/10.1134/S2070048217060035*

FWH



$$p'(\mathbf{R},T) = \frac{1}{4\pi}\int\limits_{S_0} \Psi\left(\mathbf{r},t^*\right) ds = \frac{1}{4\pi}\int\int \Psi\left(\mathbf{r},t^*\right) r^2(\theta) \cos\theta \, d\theta d\phi \approx$$

$$\approx \frac{1}{4\pi}\sum_{i=0}^{N_\theta}\sum_{j=0}^{N_\phi} \Psi\left(\mathbf{r}_{ij}, t^*_{ij}\right) r^2_{ij} \left(\sin\theta_{i+1/2} - \sin\theta_{i-1/2}\right)\left(\phi_{j+1/2} - \phi_{j-1/2}\right)$$

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https://doi.org/10.1134/S2070048217060035

Граничные условия

Граничные условия на поверхности

условия прилипания

на вращающейся поверхности лопасти

$$\Downarrow$$

$$\mathbf{u} - \boldsymbol{\omega} \times \mathbf{r} = 0$$

Граничные условия на внешней границе

Задание **расщеплённых** по нормальному по направлению к границе характеристических скоростей **потоков**, связывающих значения газодинамических параметров внутри расчётной области $\mathbf{U}_i$, и их значений в удалённом потоке $\mathbf{U}_\infty$.

$$\mathbf{F}_B\left(\mathbf{U}_i, \mathbf{U}_\infty\right) = \mathbf{F}^+ + \mathbf{F}^- = \mathbf{A}^-\mathbf{U}_\infty + \mathbf{A}^+\mathbf{U}_i, \quad с.з.\left(\mathbf{A}^\pm\right) = \frac{1}{2}\left(u_n \pm |u_n|, \left(u_n + c\right) \pm |u_n + c|, \left(u_n - c\right) \pm |u_n - c|\right)$$

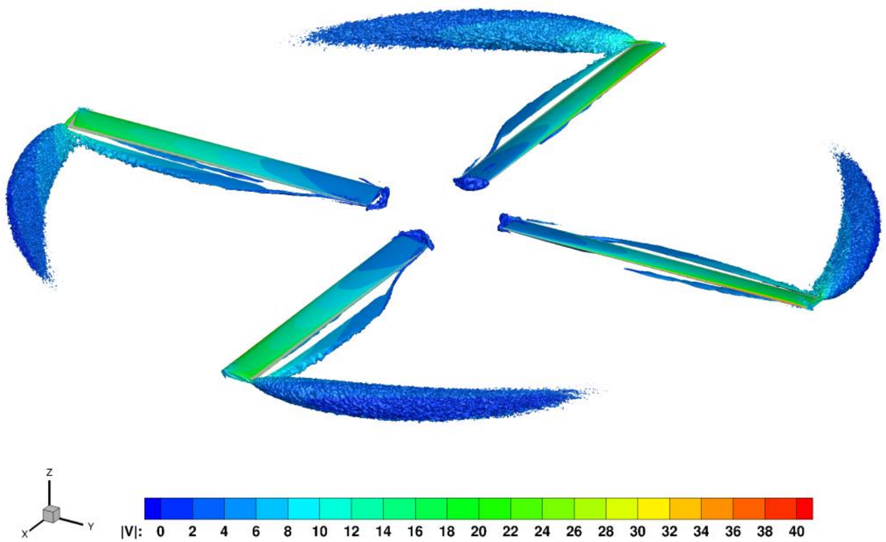
Значения $\mathbf{U}_\infty$ определяются характеристическими соотношениями для изоэнтропического газа

$$p_\infty = p_0 \qquad \rho_\infty = \rho_i\left(\frac{p_\infty}{p_i}\right)^{1/\gamma} \qquad \mathbf{U}_\infty = \mathbf{U}_i + \frac{2}{\gamma - 1}\left[\left(\gamma\frac{p_i}{\rho_i}\right)^{1/2} - \left(\gamma\frac{p_\infty}{\rho_\infty}\right)^{1/2}\right]\cdot\mathbf{n}$$

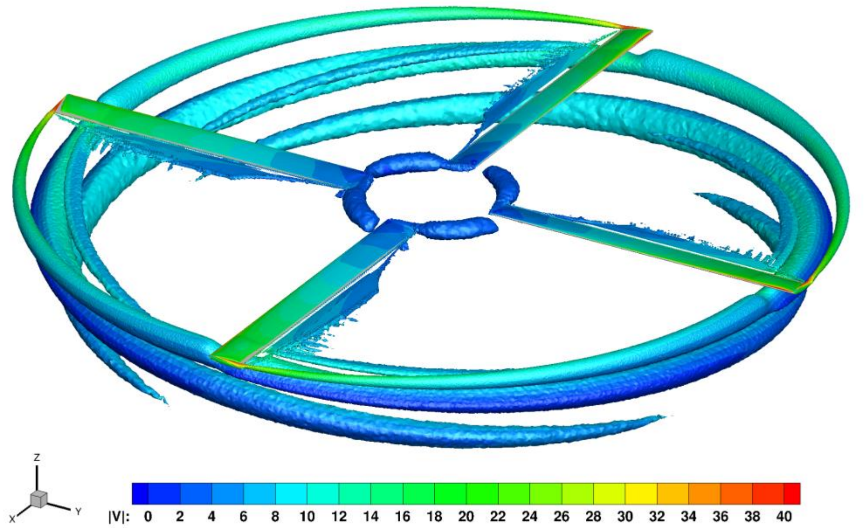
p_0 — статическое давление невозмущённого газа

$\mathbf{n}$ — внешняя нормаль к поверхности внешней границы

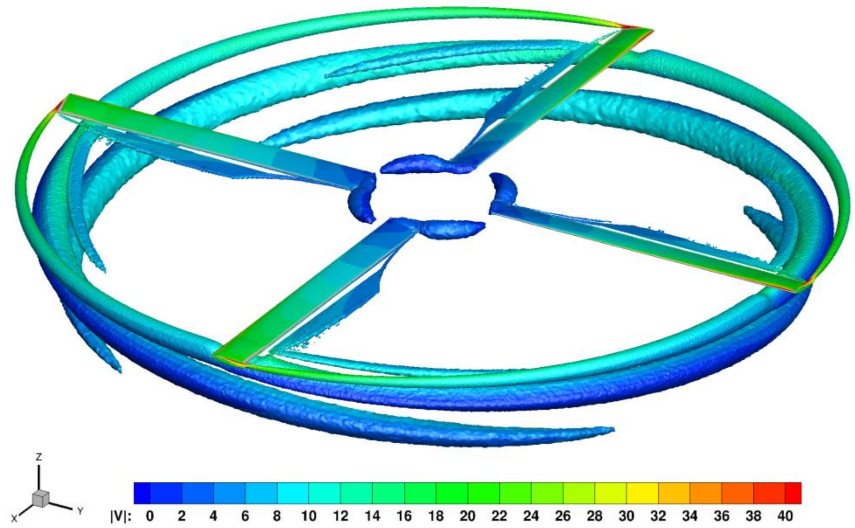
KAI scaled main rotor: order and accuracy



1st order



EBR3



EBR5