NUMERICAL PREDICTION OF AERODYNAMIC AND AEROACOUSTIC CHARACTERISTICS OF AXISYMMETRICAL FLOW GENERATED BY SHROUDED TAIL ROTOR

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Outline

1. Goals
2. Problem formulation
3. Mathematical model
4. Numerical results:
    1. Aerodynamic characteristics
    2. Acoustic characteristics
5. Summary

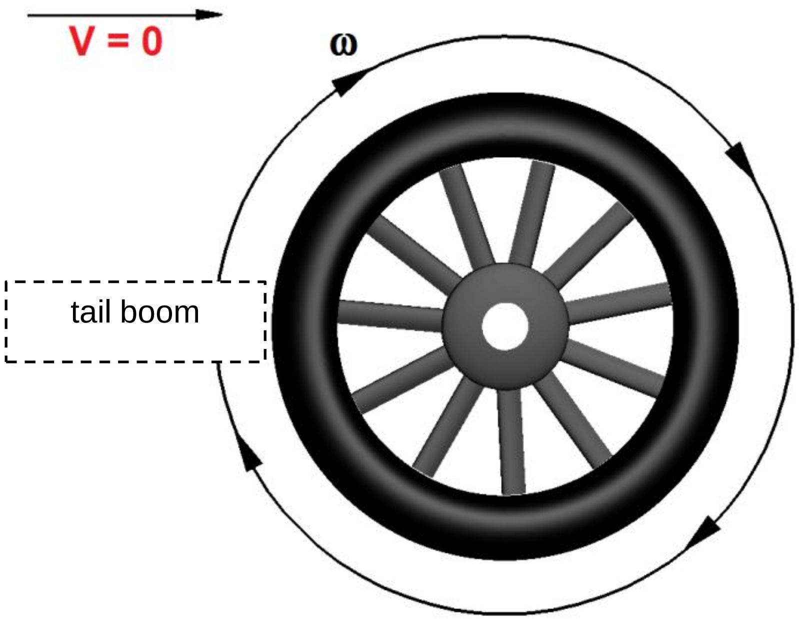
Goals

To evaluate aerodynamic and acoustic characteristics of ducted rotor for various rotor angular velocity and various pitch angles of rotor blades using inviscid-flow approach

Problem formulation (1/4)

11-blade tail rotor in ring

Rotor radius — 0.7 м



Upstream flow velocity: $V = 0\,\mathrm{m/s}$

1. Zero upstream velocity

⇩

Axial symmetry

⇩

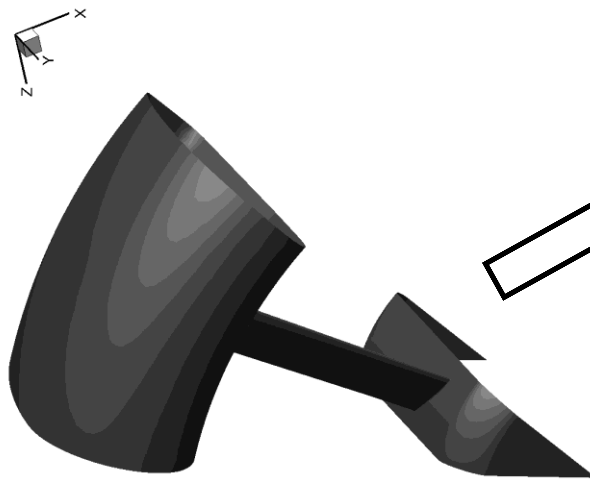
1) Simulation of single-blade in a 32.72° sector

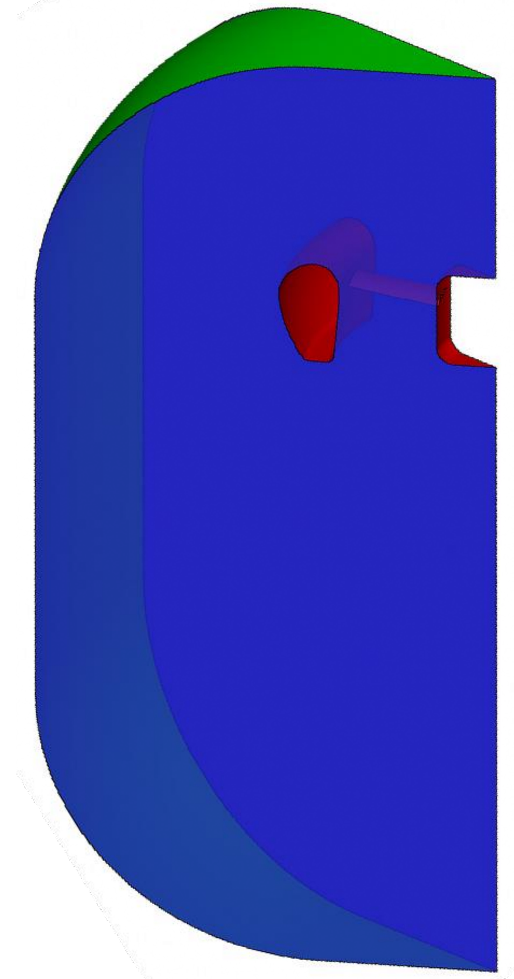
2) Periodic boundary conditions in the azimutal direction

	1 mode	2 mode
Rotation frequency	$f = 46.6\,\mathrm{Hz}$	$f \approx 40.926\,\mathrm{Hz}$
Angular velocity	$\omega = 292.80\,\mathrm{rad/s}$	$\omega \approx 257.14\,\mathrm{rad/s}$
Blade tip velocity	$V_{tip} \approx 205\,\mathrm{m/s}$	$V_{tip} = 180\,\mathrm{m/s}$

Problem formulation (2/4)

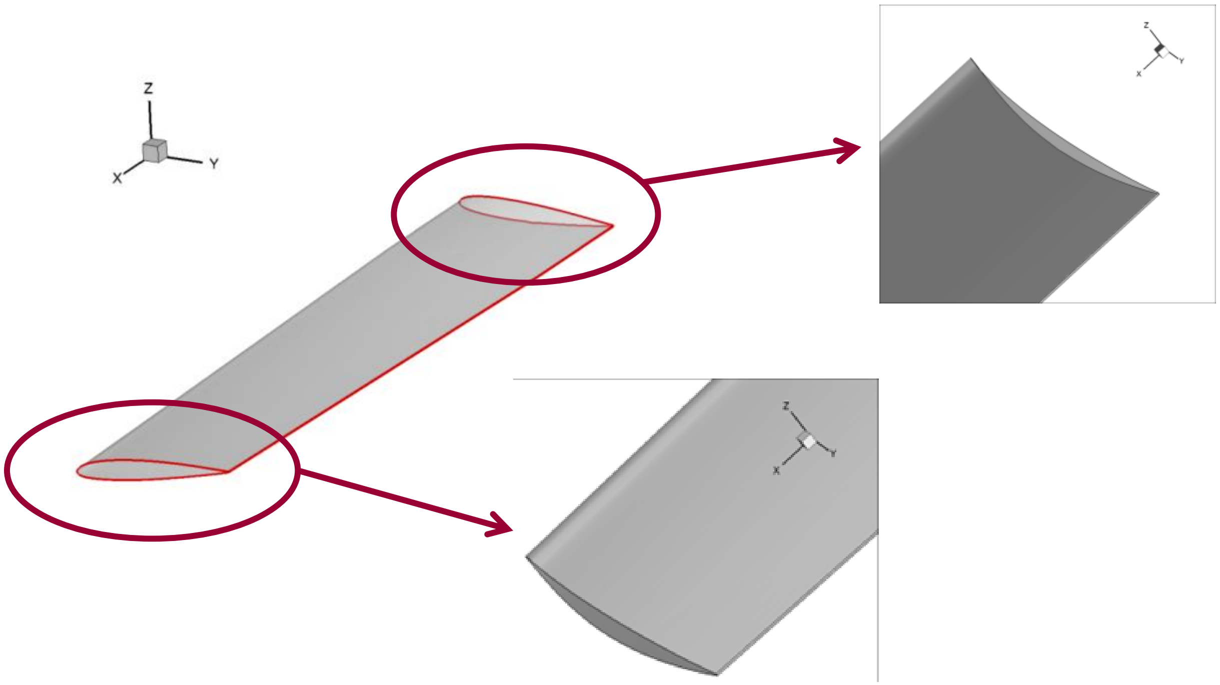
Geometry, Computational domain, Boundary Surfaces

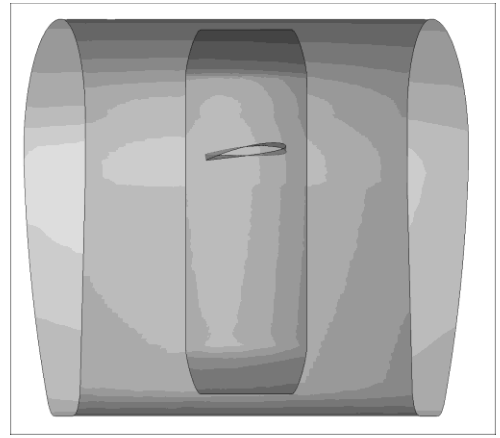




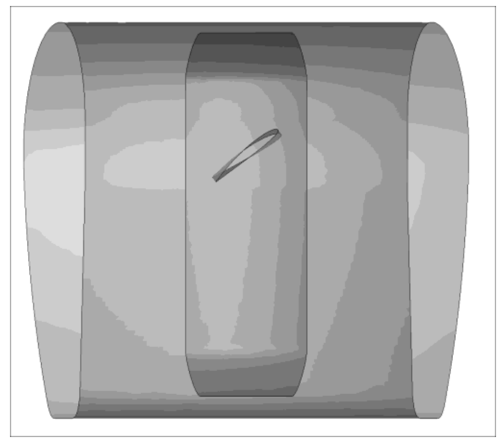
Problem formulation (3/4)

Blade geometry and pitch angle of rotor blade





Blade pitch angle — 10º



Blade pitch angle — 40º

Blade profile— “CB 11%”

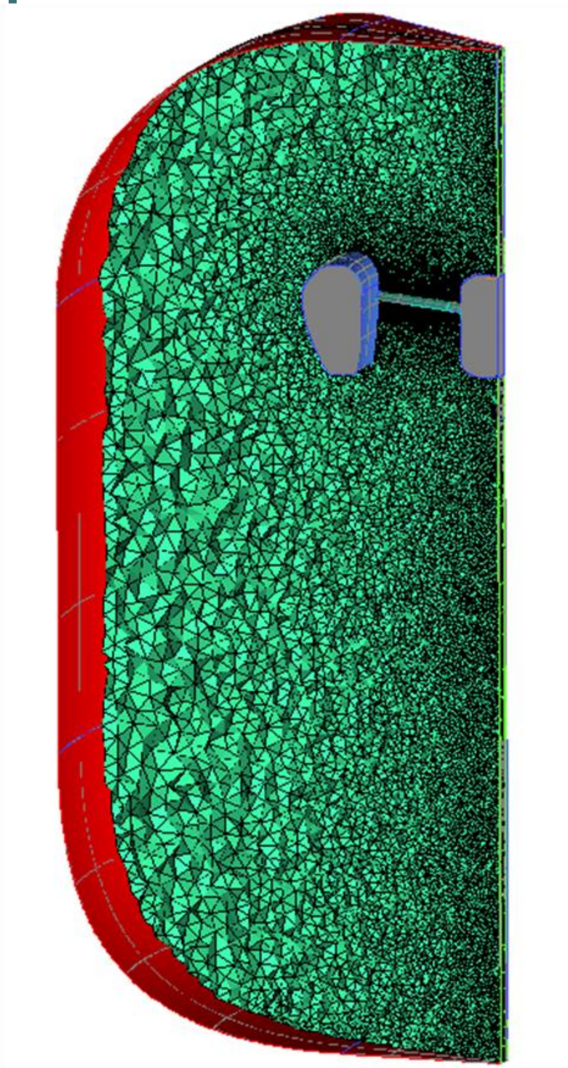
Blade chord— 89 mm

Blade twist angle — -8º

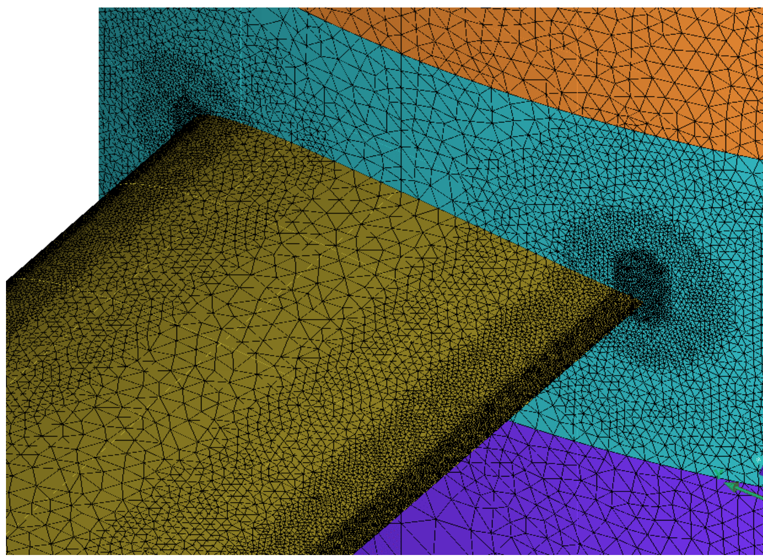
Blade pitch angles — 10º .. 40º with 10º step

Problem formulation (4/4)

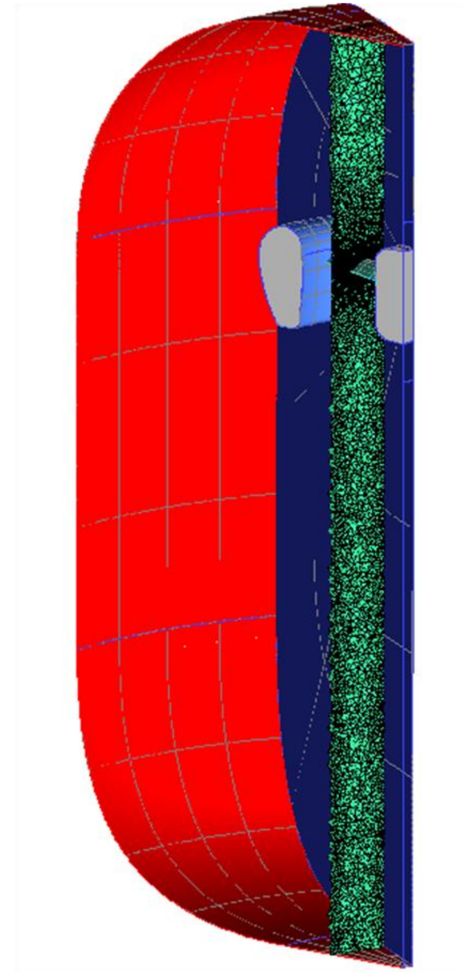
Mesh



	Number of nodes	Number of tetras
10°	2 372 528	13 606 625
20°	2 533 298	14 524 100
30°	2 648 158	15 172 126
40°	2 657 445	15 172 391



Mesh refinement in the places of junction



Mathematical formulation (1/2)

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

$$\frac{\partial \rho}{\partial t} + \operatorname{div} \rho \mathbf{u}' = 0$$

$$\frac{\partial \rho \mathbf{u}'}{\partial t} + \operatorname{Div} \rho \mathbf{u}' \otimes \mathbf{u}' + \nabla p = -\rho \boldsymbol{\omega} \times \left(\boldsymbol{\omega} \times \mathbf{r} \right) - 2\rho (\boldsymbol{\omega} \times \mathbf{u}')$$

$$\frac{\partial E}{\partial t} + \operatorname{div} \mathbf{u}' \left(E + p \right) = 0$$

Euler equations

in a non-inertial rotating frame of reference

Titarev, 2011

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

$$\frac{\partial \rho}{\partial t} + \operatorname{div} \rho \left(\mathbf{u} - \mathbf{V} \right) = 0$$

$$\frac{\partial \rho \mathbf{u}}{\partial t} + \operatorname{Div} \rho \left(\mathbf{u} - \mathbf{V} \right) \otimes \mathbf{u} + \nabla p = -\rho \left(\boldsymbol{\omega} \times \mathbf{u} \right)$$

$$\frac{\partial E}{\partial t} + \operatorname{div} \left(\mathbf{u} - \mathbf{V} \right) E + \operatorname{div} \mathbf{u} p = 0$$

Formulation

for ***velocity vector*** **u**

in ***absolute frame of reference***

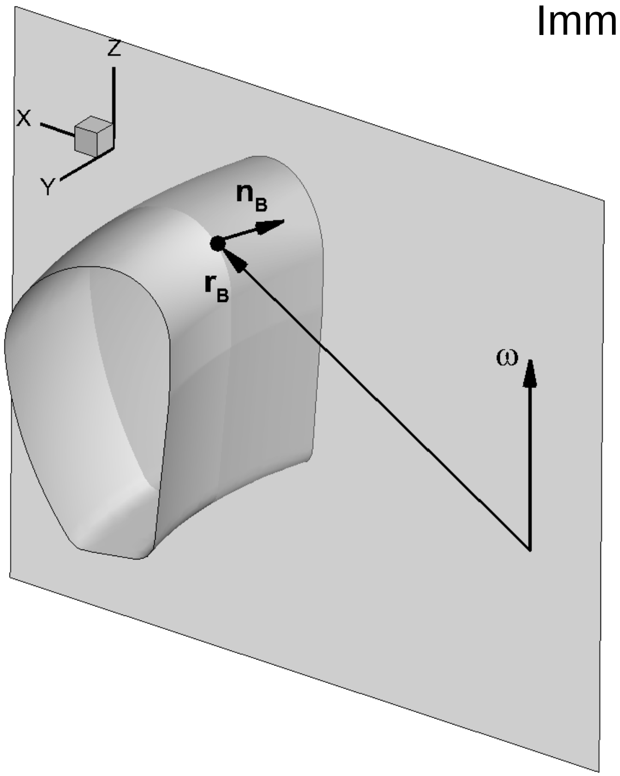
Mathematical formulation (2/2)

Boundary conditions on solid surfaces

Boundary conditions (BC) on the moving solid surface - slip BC

$$\mathbf{u}' \cdot \mathbf{n}\big|_B = 0$$

Immovable solid surface - a surface of revolution about vector $\boldsymbol{\omega}$



$$\Downarrow$$

The vector normal to the surface lies in the plane of the vectors $\mathbf{r}$ и $\boldsymbol{\omega}$

$$\mathbf{n}_B = \alpha\boldsymbol{\omega} + \beta\mathbf{r} \qquad \boldsymbol{\omega} \times \mathbf{r} \cdot (\alpha\boldsymbol{\omega} + \beta\mathbf{r}) = 0$$

$$\Downarrow$$

$$\mathbf{u} \cdot \mathbf{n}\big|_B = \mathbf{u}' \cdot \mathbf{n}\big|_B + (\boldsymbol{\omega} \times \mathbf{r}) \cdot \mathbf{n}\big|_B = 0$$

Slip BC are the same

for rotational and immovable solid surfaces

Numerical implementation

Unstructured tetrahedral meshes

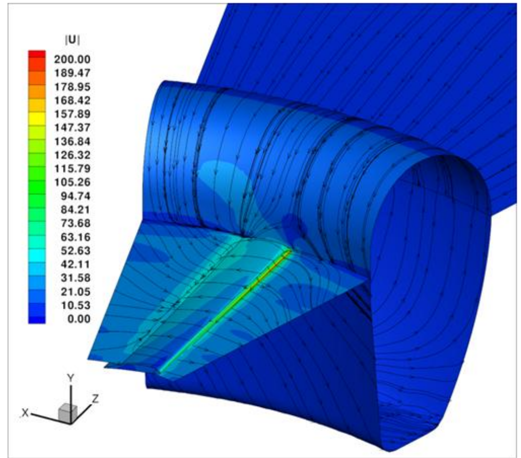
In-house code ***NOISEtte*** (CAA Lab)

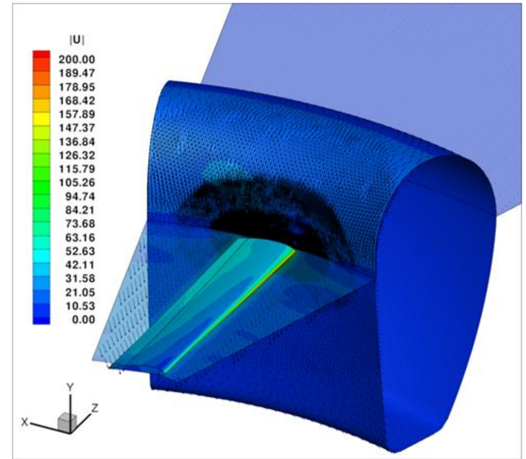
ANSYS® ICEM CFD for meshing

Numerical results (2/12)

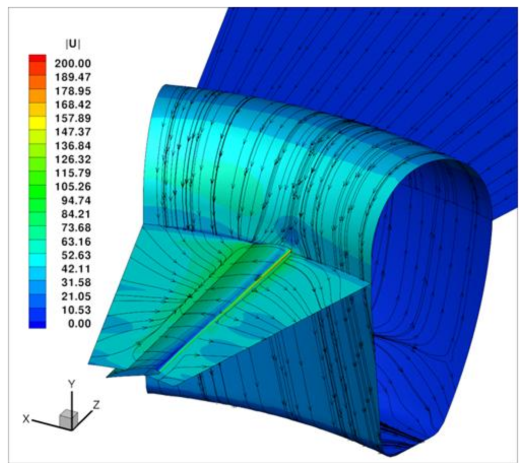
Module on the absolute velocity on the blade in the Y=0 plane and on the ring segment

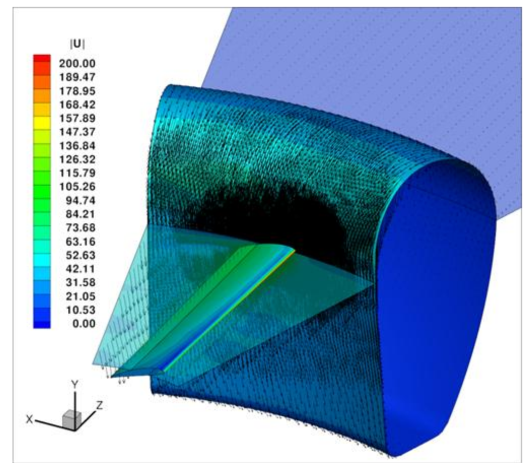
Blade pitch angle 10^0





Blade pitch angle 20^0

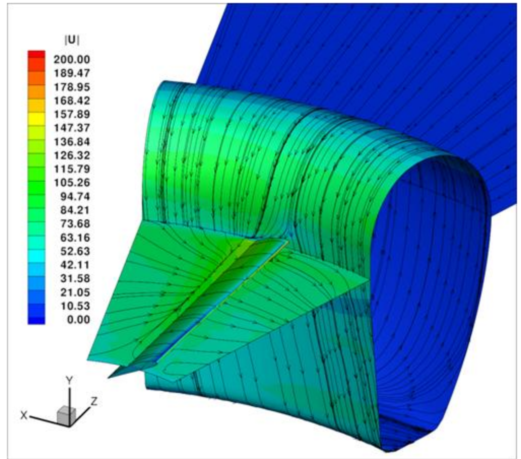


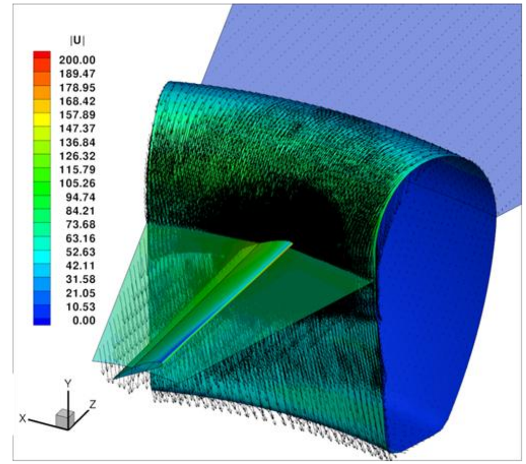


Numerical results (3/12)

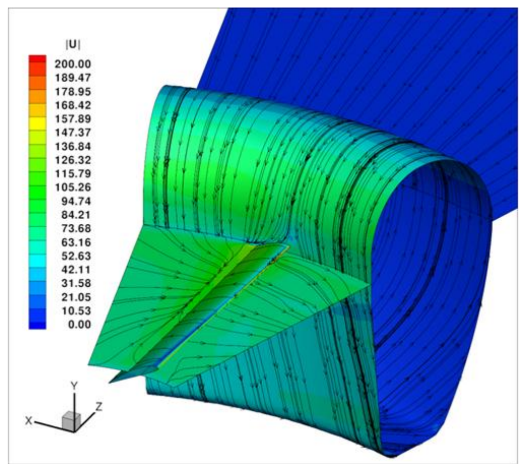
Module on the absolute velocity on the blade in the Y=0 plane and on the ring segment

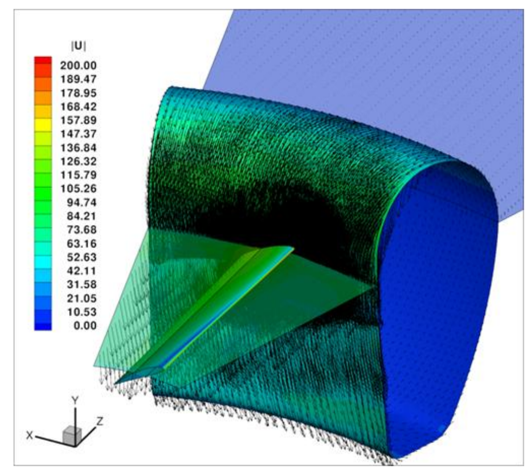
Blade pitch angle 30^0





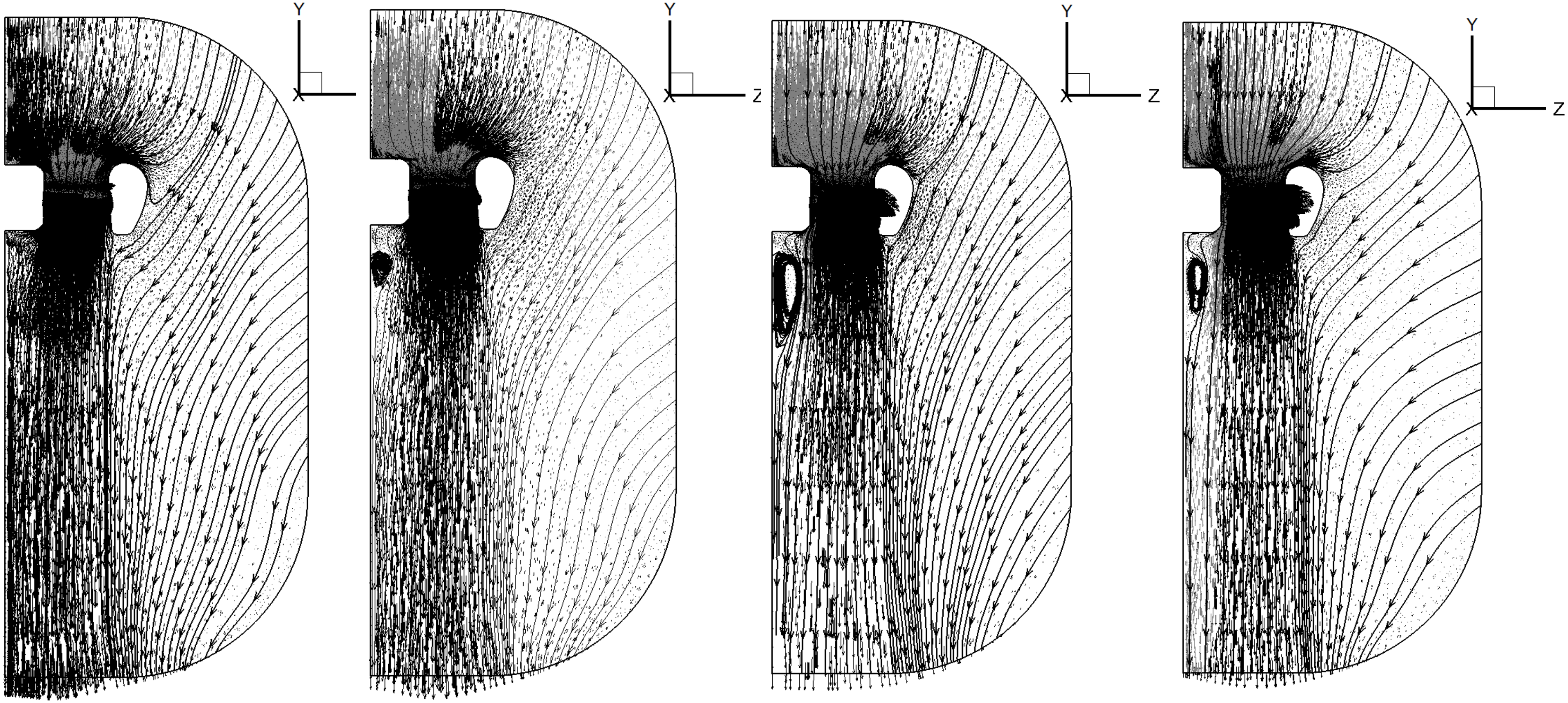
Blade pitch angle 40^0





Numerical results (4/12)

Absolute-velocity vector field and the streamlines in X = 0 plane

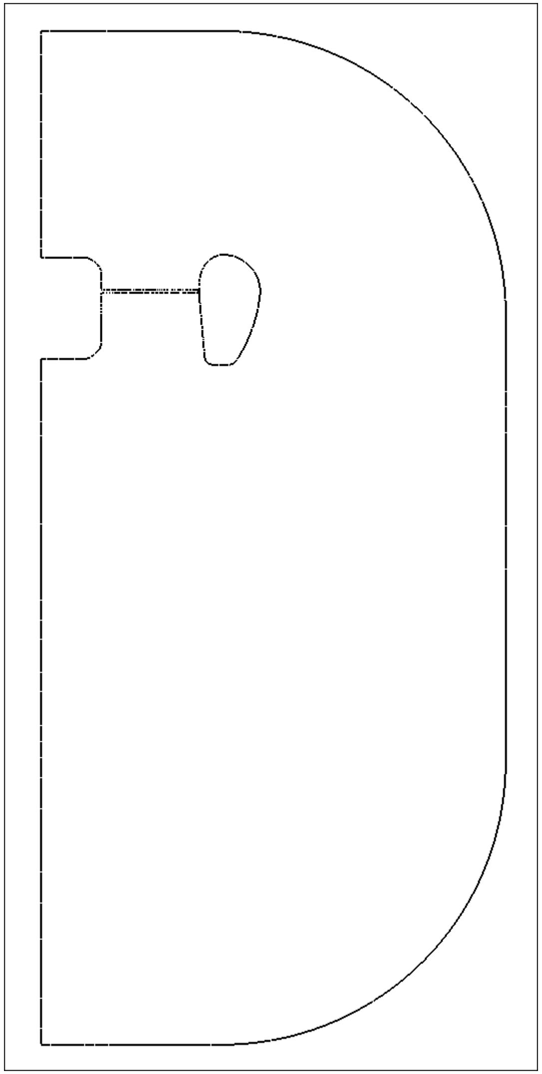


Blade pitch angle

10^0 20^0 30^0 40^0

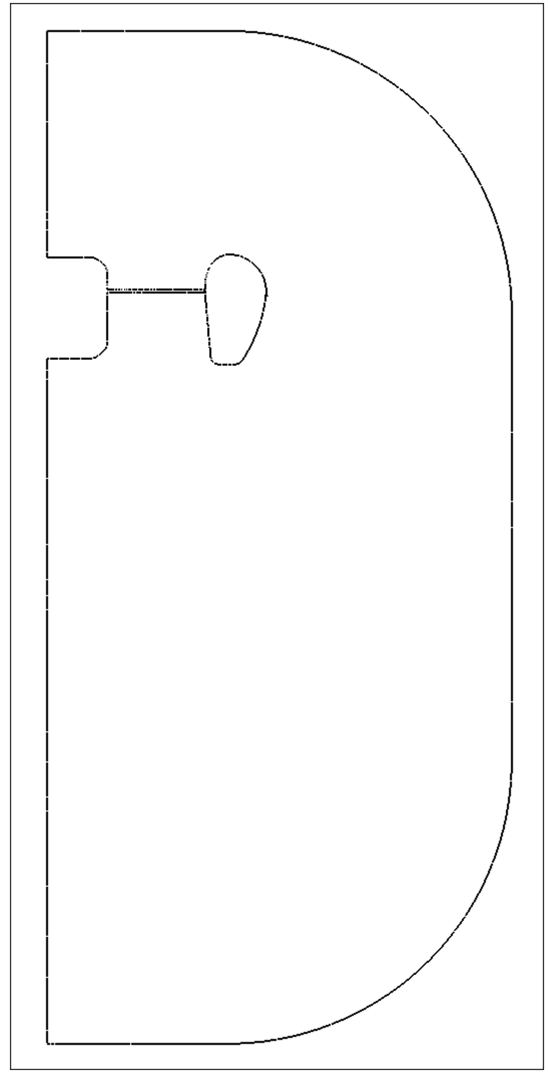
Numerical results (5/12)

Absolute velocity vector field and streamlines



Blade pitch angle10^0

V_{tip} = 205 m/s

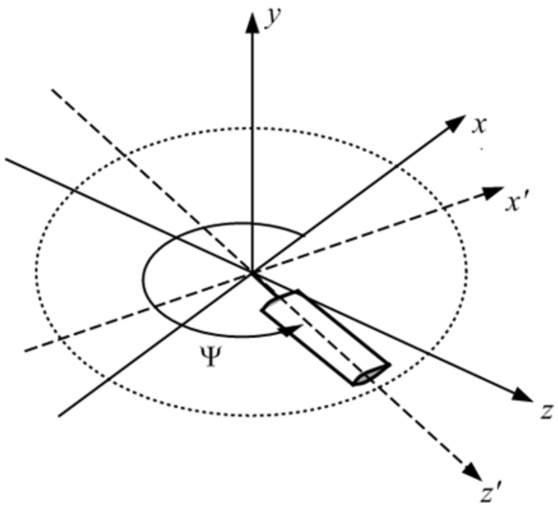


Blade pitch angle 40^0

V_{tip} = 180 m/s

Numerical results (6/12)

Aerodynamic forces



$\Psi = \omega t$

$p(x,y,z)$ — pressure distribution on surface S

n_x, n_y, n_z — external unit normal

average pressure in the azimutal angle

$$\tilde{p}(r,z) = \int_0^{2\pi} \tilde{p}(r,\Psi,z)\, d\Psi$$

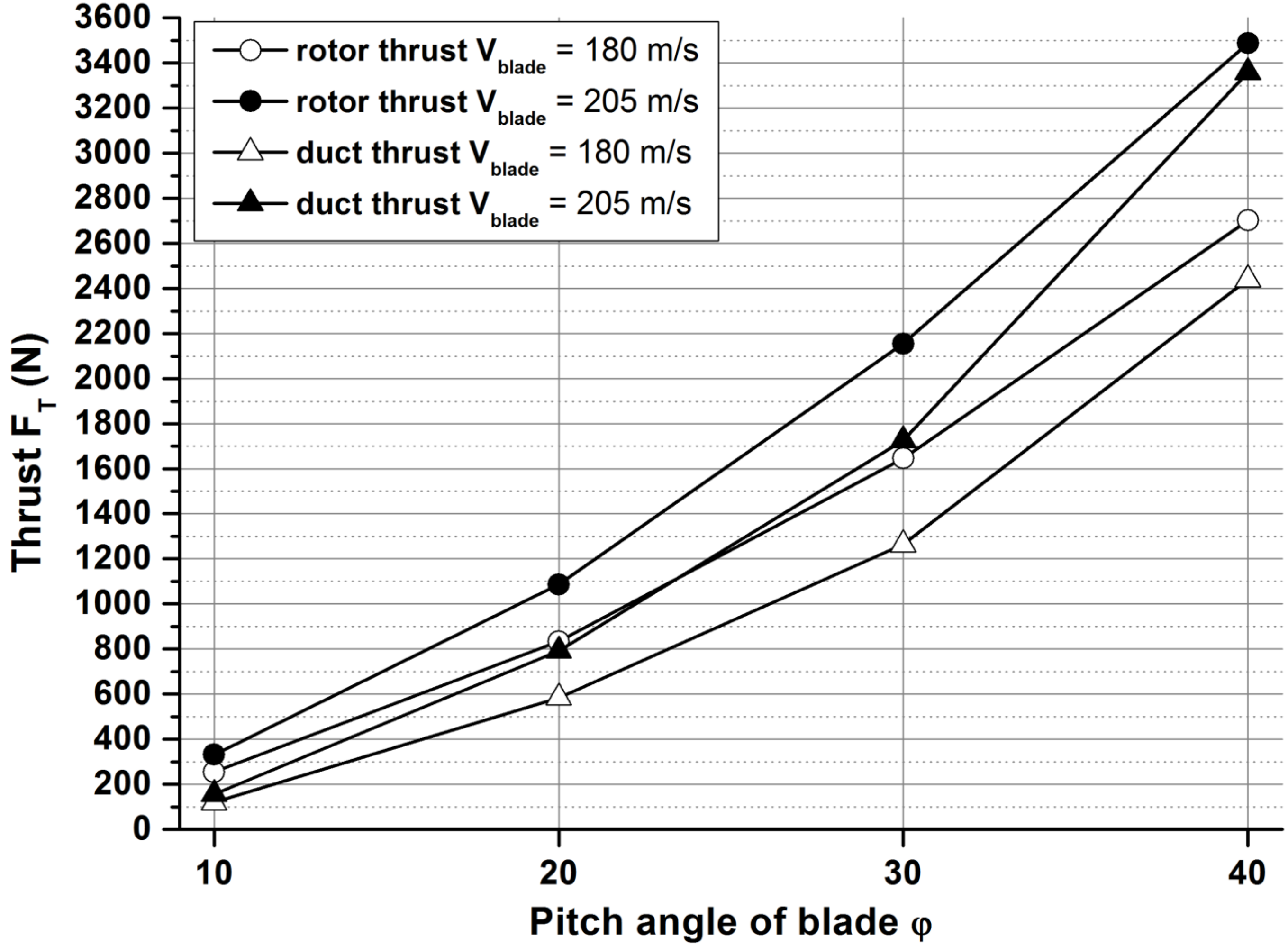
	Thrust	Torque
Rotor	$F_T^B = NF_y = N\oint\!\!\oint_S p n_y ds$	$Q^B = N\oint\!\!\oint_S z p n_x ds$
Duct	$F_T^K = \oint\!\!\oint_S \tilde{p} n_y ds$	$Q^K = \oint\!\!\oint_S \tilde{p}(z n_x - x n_z) ds$

$$C_T = \frac{2F_T}{\rho_0 A(\omega R)^2},\ C_Q = \frac{2Q}{\rho_0 R A(\omega R)^2},\ A = \pi R^2$$

$$C_T = \frac{2\left(F_T^{\mathrm{rotor}} + F_T^{\mathrm{duct}}\right)}{\rho_0 A(\omega R)^2},\ C_Q = \frac{2\left(Q^{\mathrm{rotor}} + Q^{\mathrm{duct}}\right)}{\rho_0 R A(\omega R)^2}$$

Numerical results (7/12)

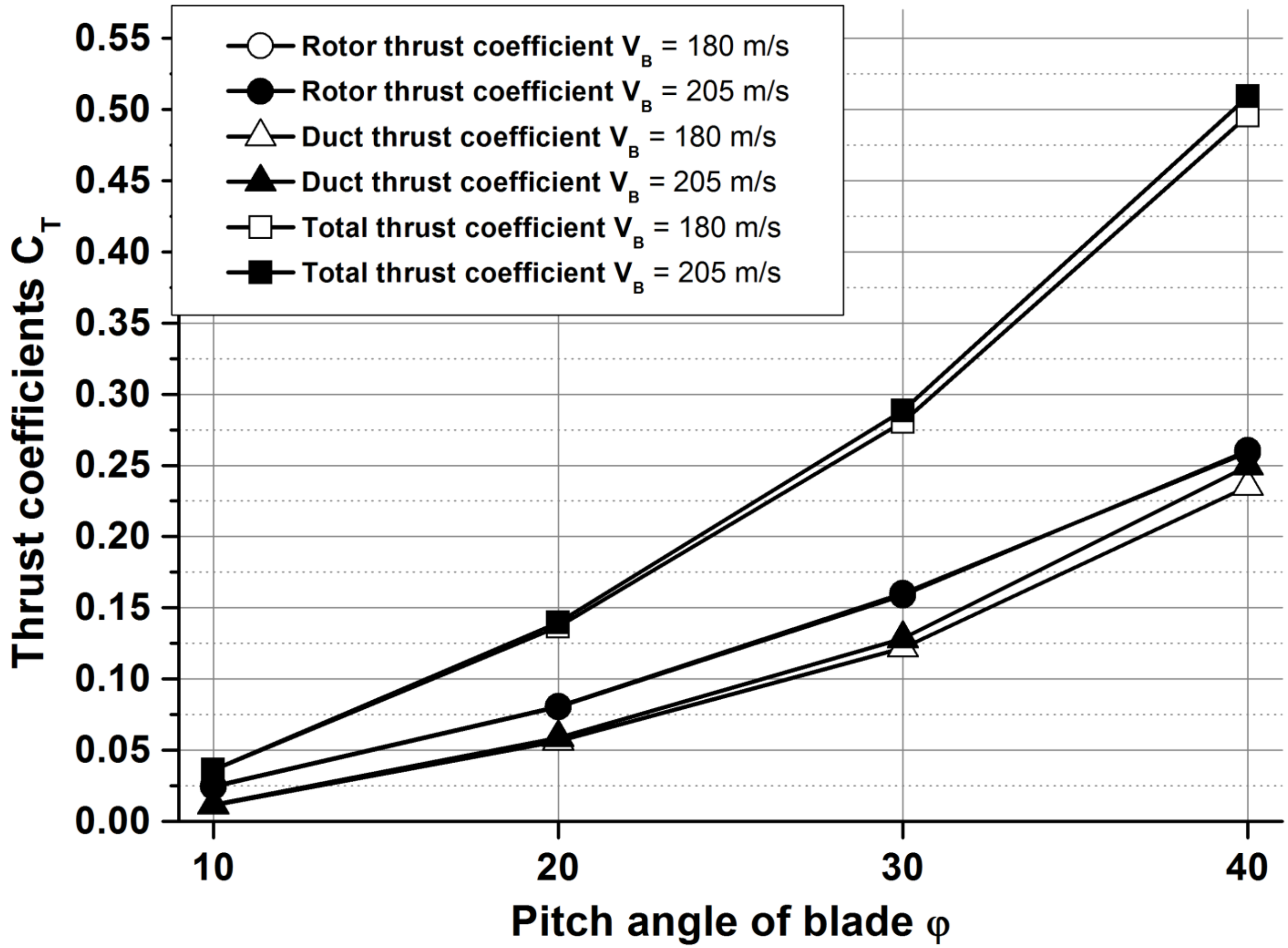
Aerodynamic forces



Rotor and ring thrust

Numerical results (8/12)

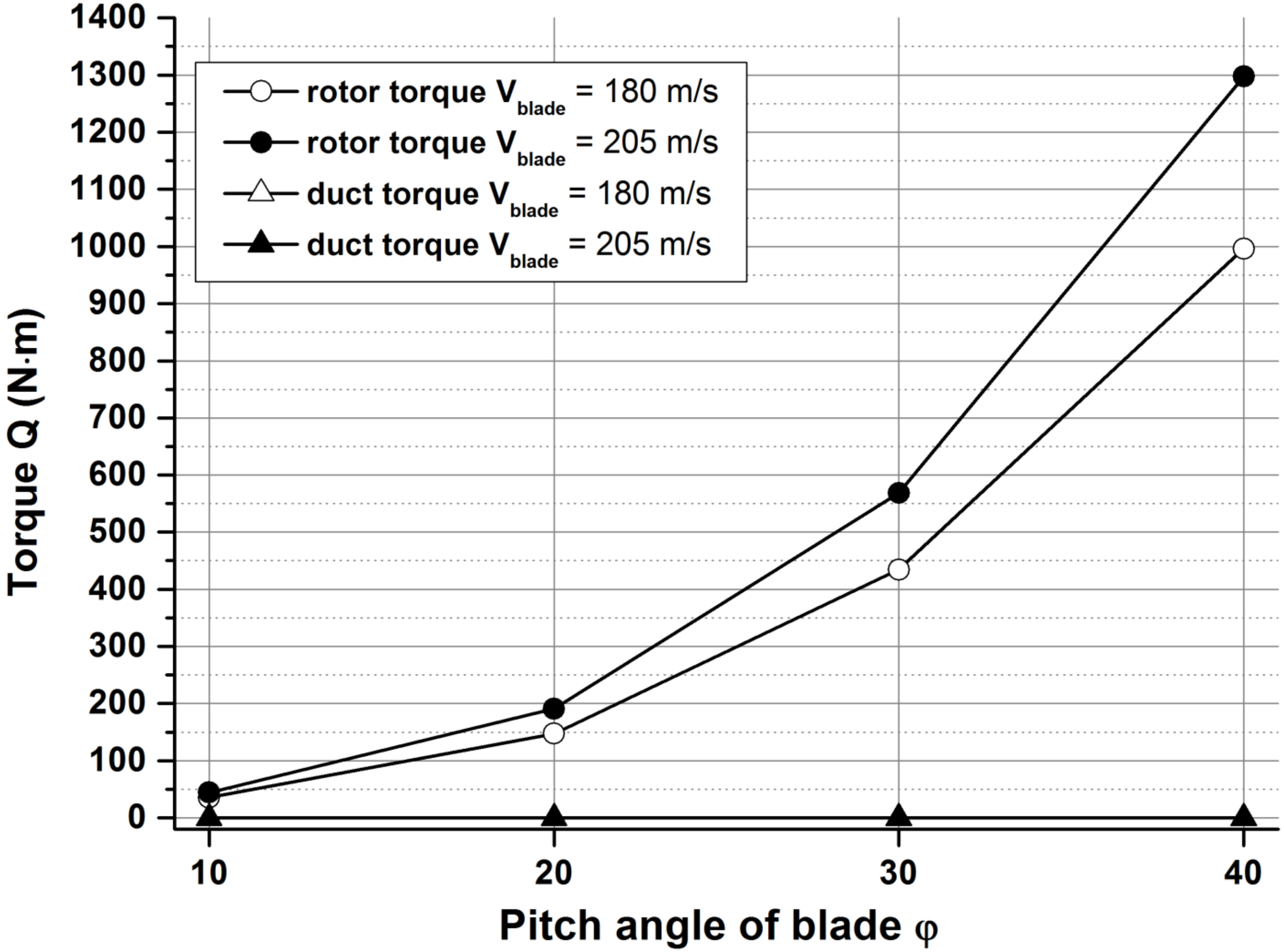
Aerodynamic forces



Rotor, ring and total thrust coefficients

Numerical results (9/12)

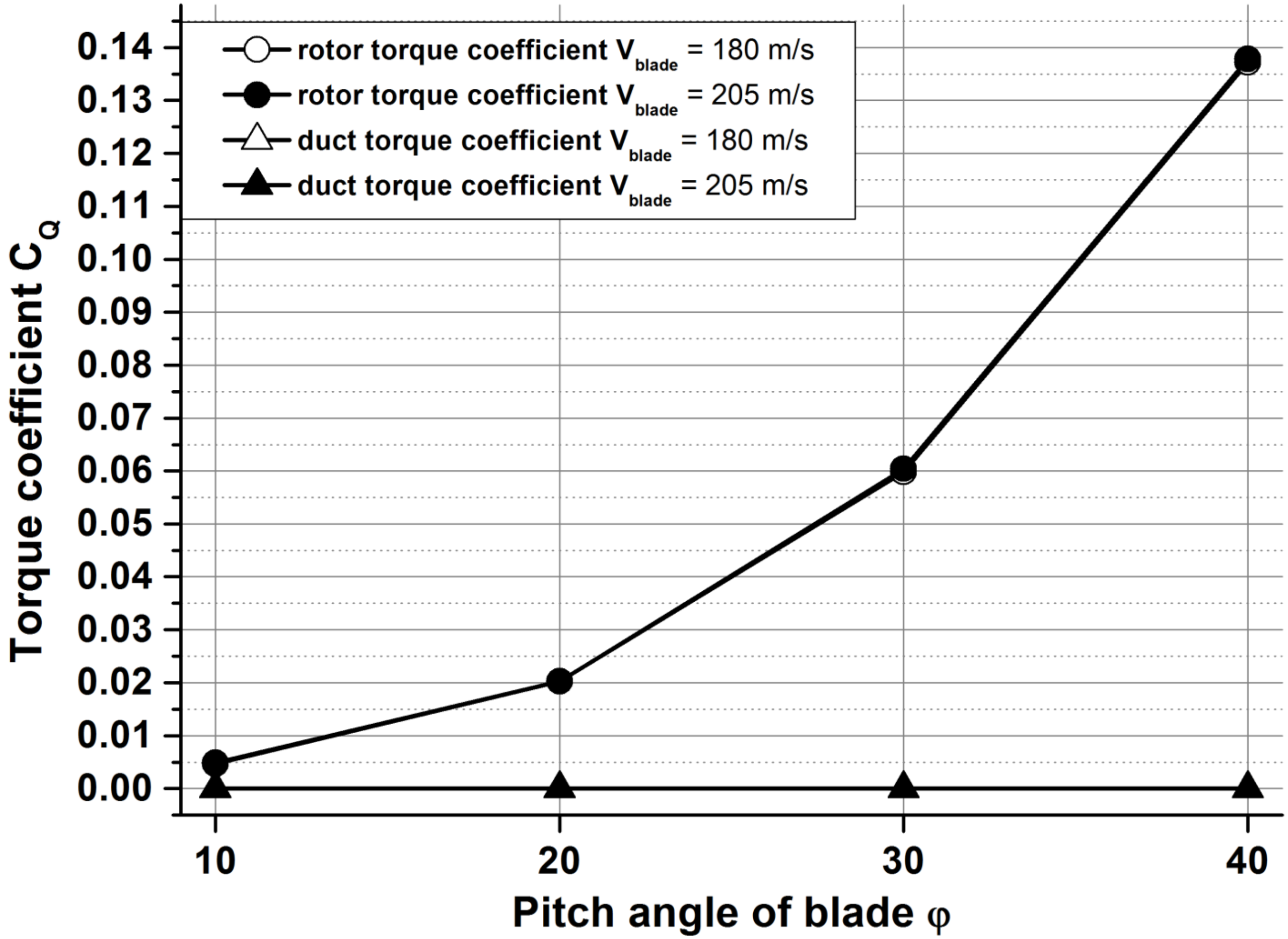
Aerodynamic forces



Rotor, ring torque

Numerical results (10/12)

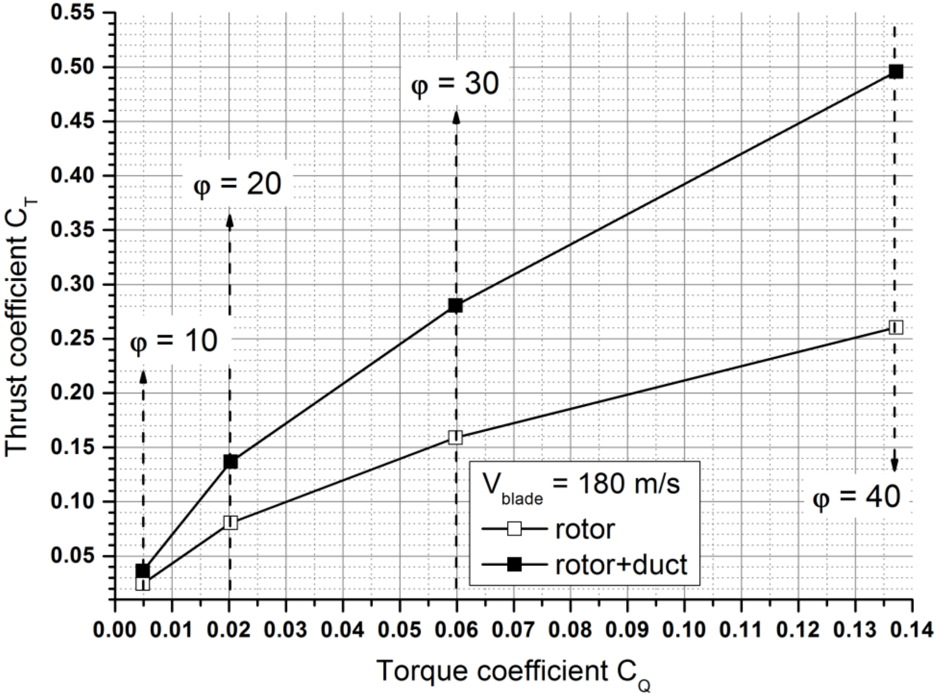
Aerodynamic forces

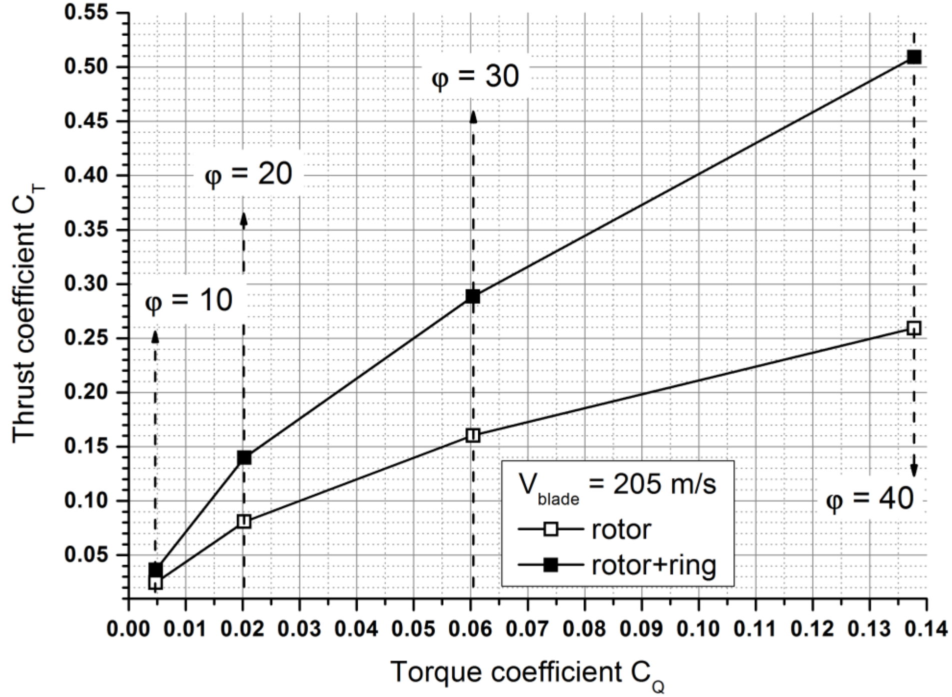


Rotor, ring torque coefficient

Numerical results (11/12)

Aerodynamic forces



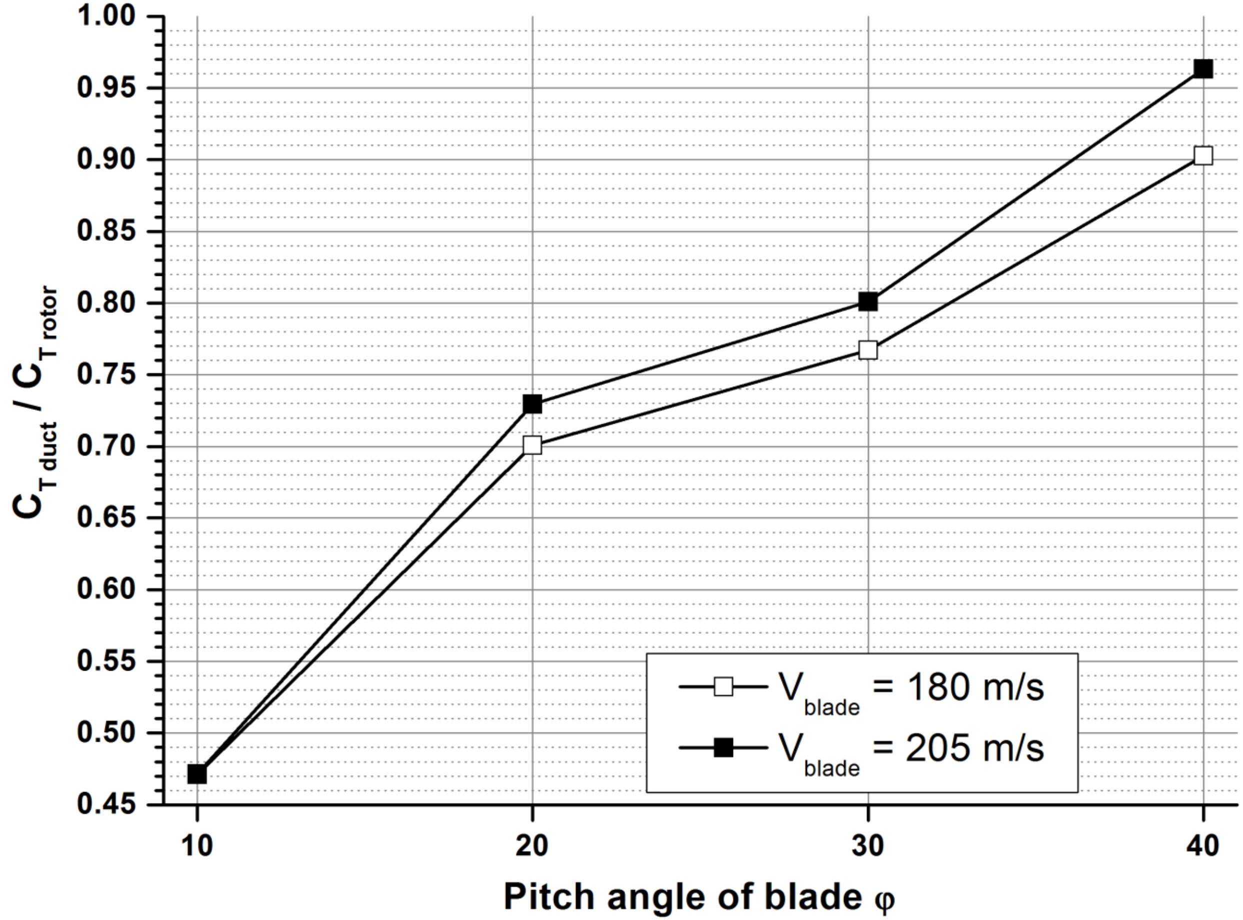


Rotor, rotor&ring thrust coefficient vs. torque coefficient plots

for V_{tip}=180 m/s and V_{tip}=205 m/s

Numerical results (12/12)

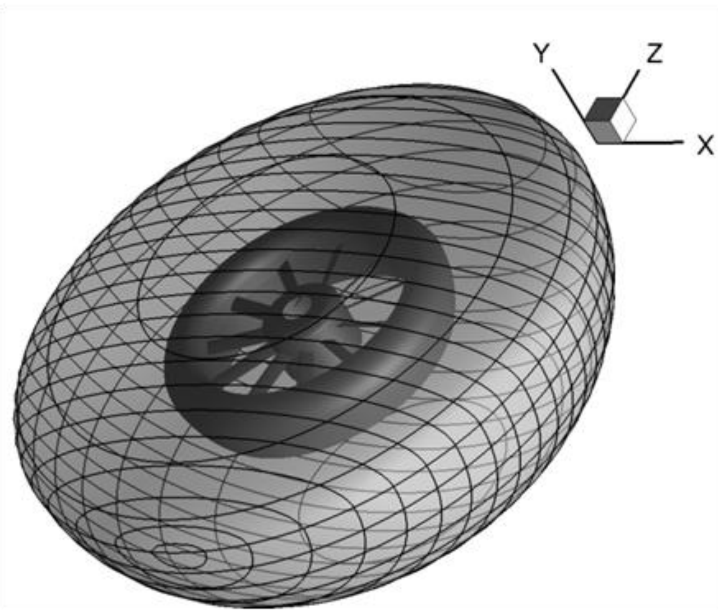
Aerodynamic forces



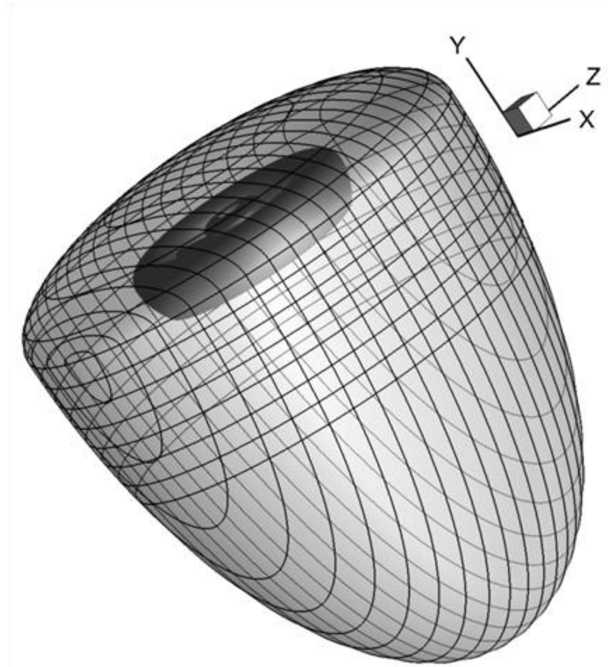
Relation of ring thrust coefficient to ring thrust coefficient depending on blade pitch angle

Far field pressure pulsations (1/5)

Ffowcs-Williams and Hawking (FW-H): control surface



Control surface 1



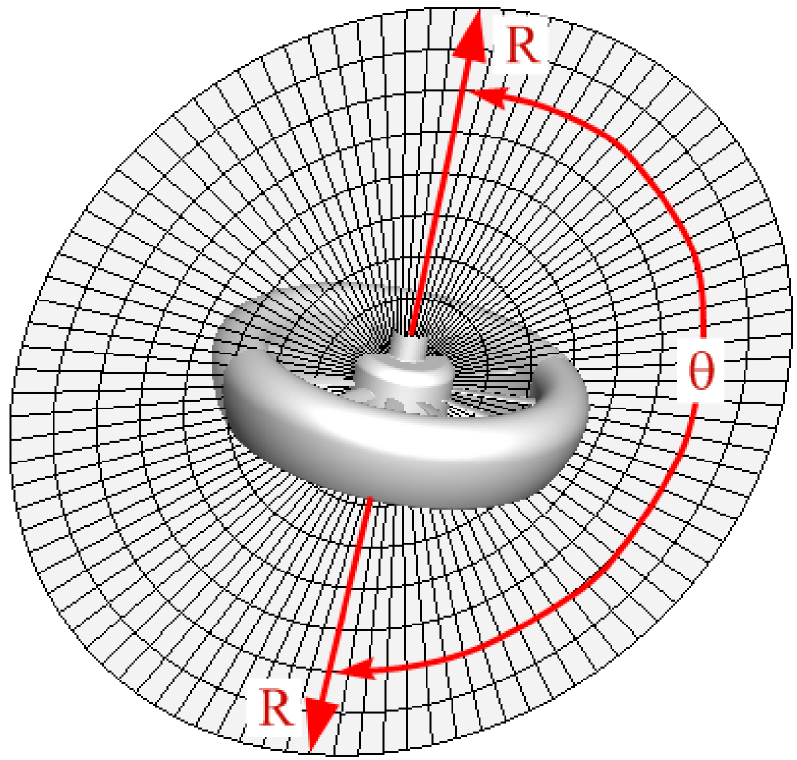
Control surface 2

Far field pressure pulsations (2/5)

FW-H: integration method

$$p'(\mathbf{R},T)=\frac{1}{4\pi}\int_{S_0}\left[\frac{1}{r}\frac{\partial}{\partial t}\left(u_j n_j-\rho'\frac{r_j n_j}{r}\right)\right]_{t=T-|\mathbf{R}-\mathbf{x}_0|,\ \mathbf{r}=\mathbf{R}-\mathbf{x}_0} ds$$

1. The terms $O(r^{-2})$ are neglected
2. Stationary control surface



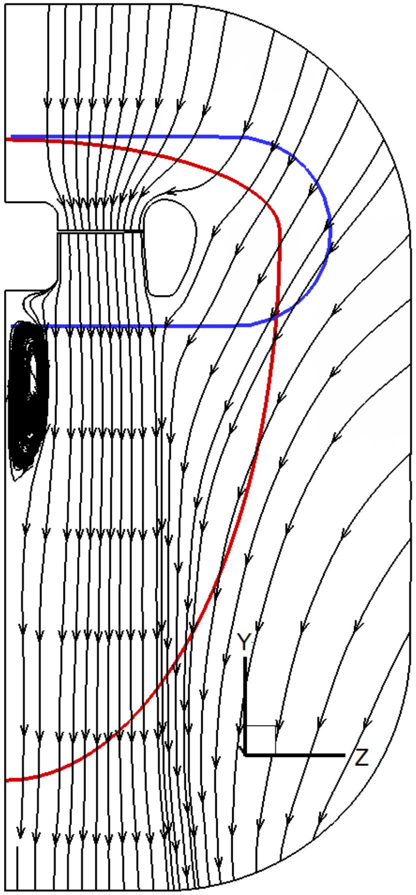
Azimutal angle $-\frac{\pi}{2}\le\theta\le\frac{\pi}{2}$

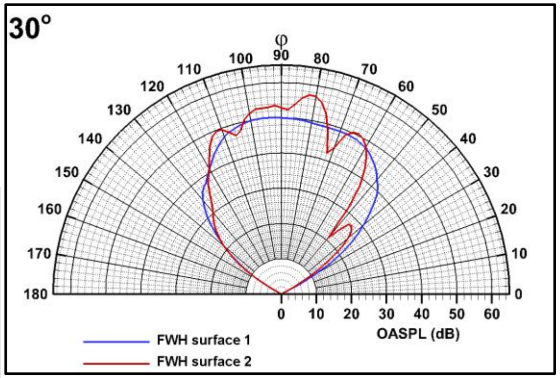
Directivity diagram plane

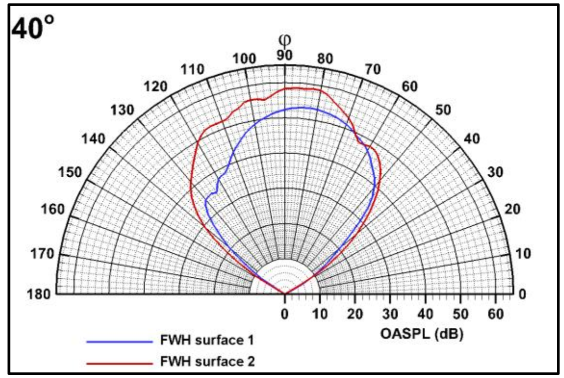
$$0\le\varphi=\theta+\frac{\pi}{2}\le\pi$$

Far field pressure pulsations (3/5)

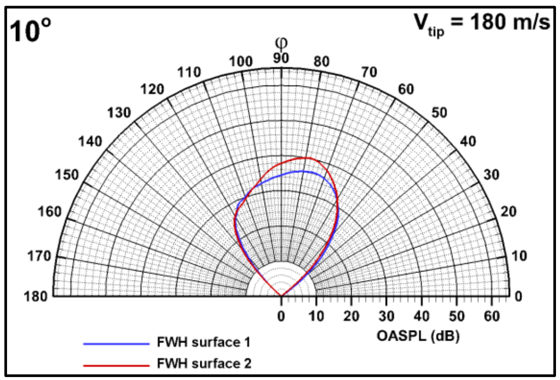
FW-H: Directivity diagram depending on control surface

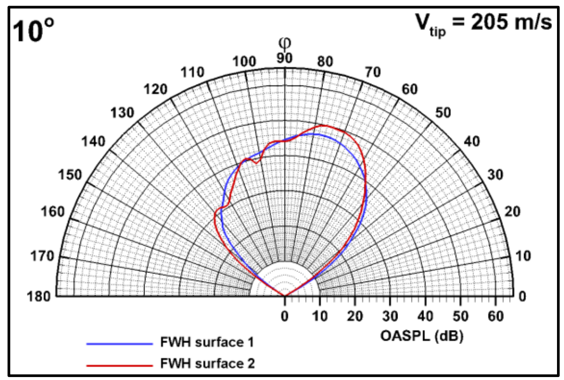


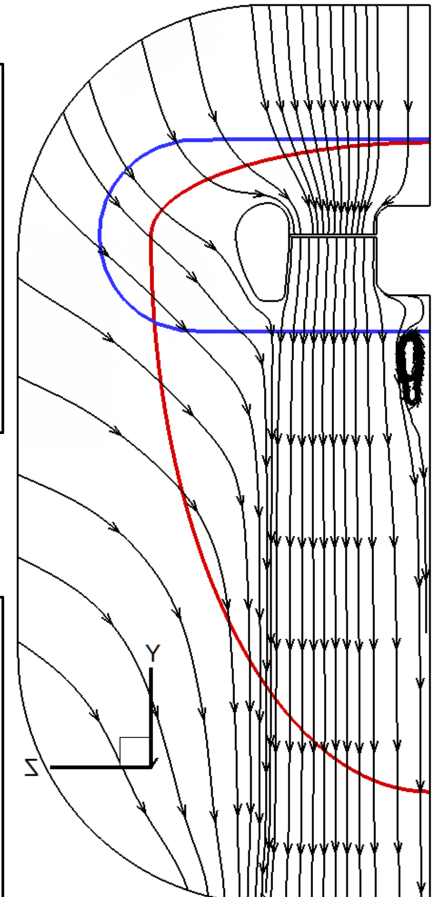




$$V_{tip} = 205\,\mathrm{m/s}$$





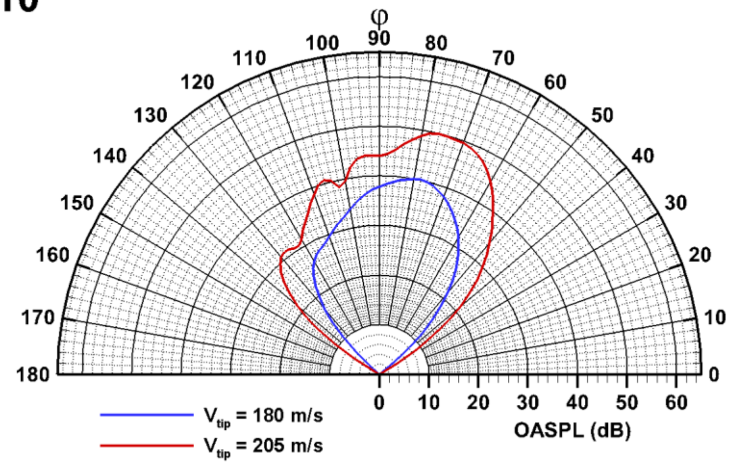


Overall Sound Pressure Level (**OASPL**) at the distance 150m

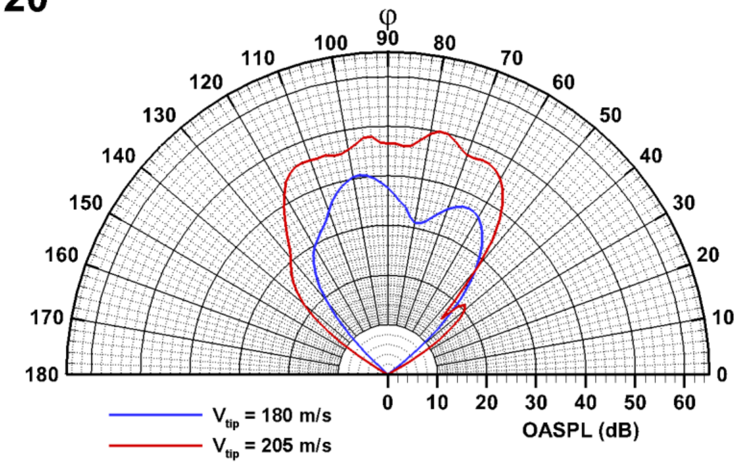
Far field pressure pulsations (4/5)

FW-H: Directivity diagram

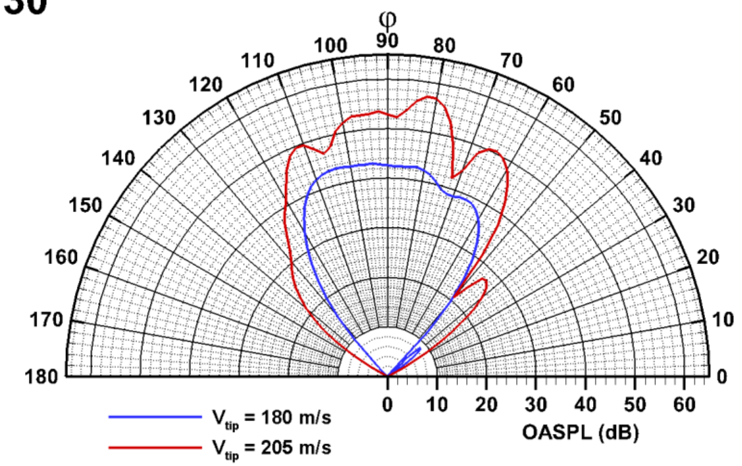
10°



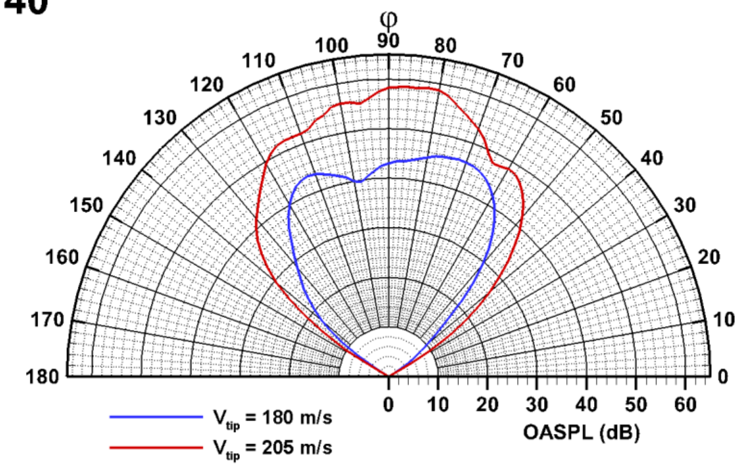
20°



30°



40°



Overall Sound Pressure Level (**OASPL**) at the distance 150m

Summary

- numerical simulation shows that the duct presence improves rotor aerodynamic characteristics
- acoustics simulation confirms that the highest noise level is reached on the plane of rotor rotation

Plans

- to implement Navier-Stokes + turbulence models for non-inertial rotating frame of reference
- to implement techniques for sliding meshes