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Supported by:

Federal Ministry for Economic Affairs and Energy

on the basis of a decision by the German Bundestag

DFG Deutsche Forschungsgemeinschaft

German Research Foundation

Hydro Acoustic Noise Emission of Hubless Propellers

M. Witte, M. Hieke and F.-H. Wurm

Universität Rostock, Lehrstuhl für Strömungsmaschinen (ITU)

Outline

Outline

1. **Introduction**
2. CFD Setup and Methods
3. Measurement Setup
4. Results
5. Conclusions

Introduction

- hubless propeller as alternative propulsion devices
- compact design → integration as bow and main thruster
- less mechanical components (gears etc.)
- different wake flow characteristic compared to hub propeller can be expected

Hubless propeller (RIM – drive)

Topic 1 → DFG project together with MUB (Hamburg University of Technology)
„model scale propeller"

1. **investigation of the wake flow topology**
2. **identification of coherent structures**
3. **connection to the hydro acoustic emission → MUB**

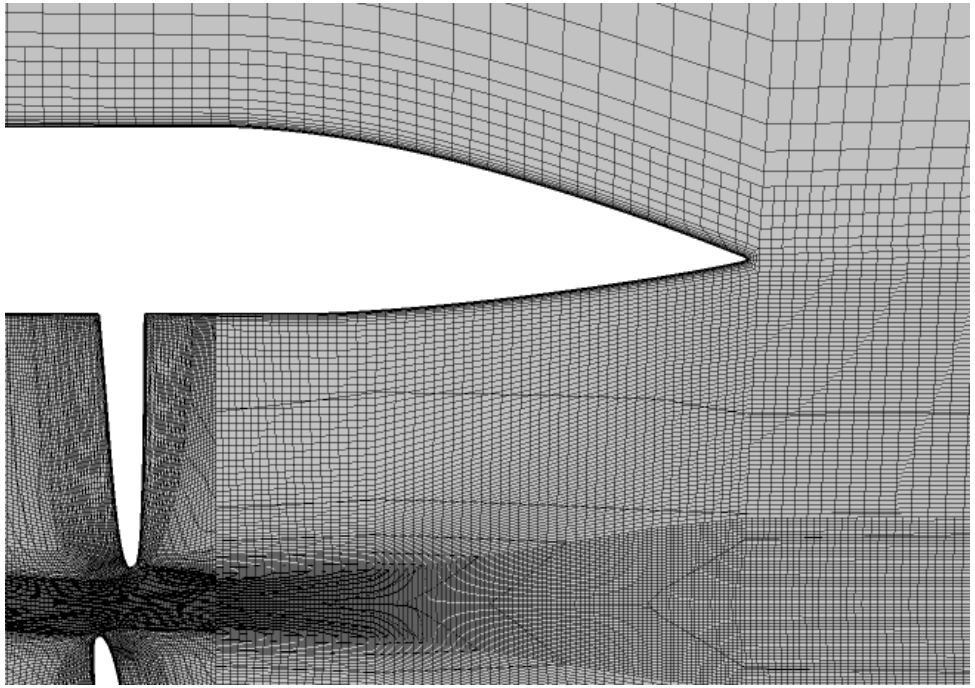
Topic 2 → BMWI project together with Voith company
„full scale propeller"

1. **development of an measurement for the localization of acoustic sources**
2. **field measurement campaign in the river Warnow in Rostock**

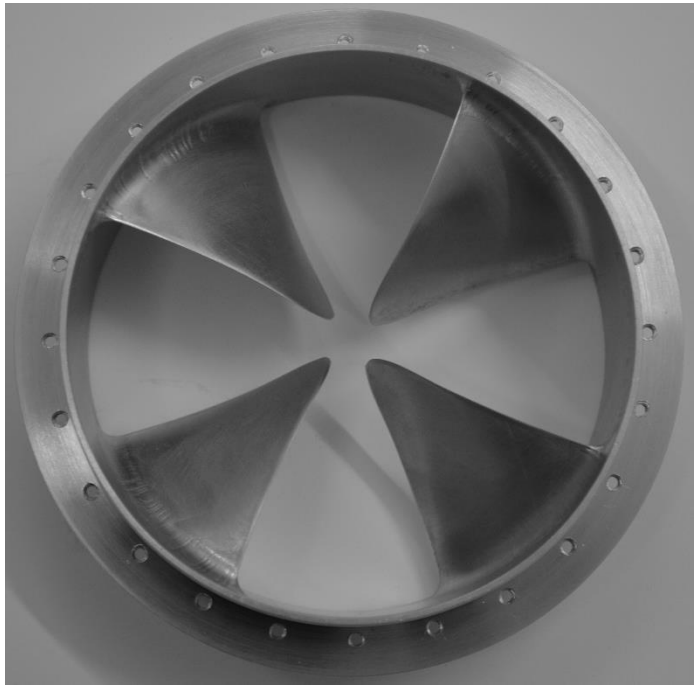
Outline

CFD Setup and Methods

meshing for URANS and DES - SBES



CFD mesh



hubless propeller model

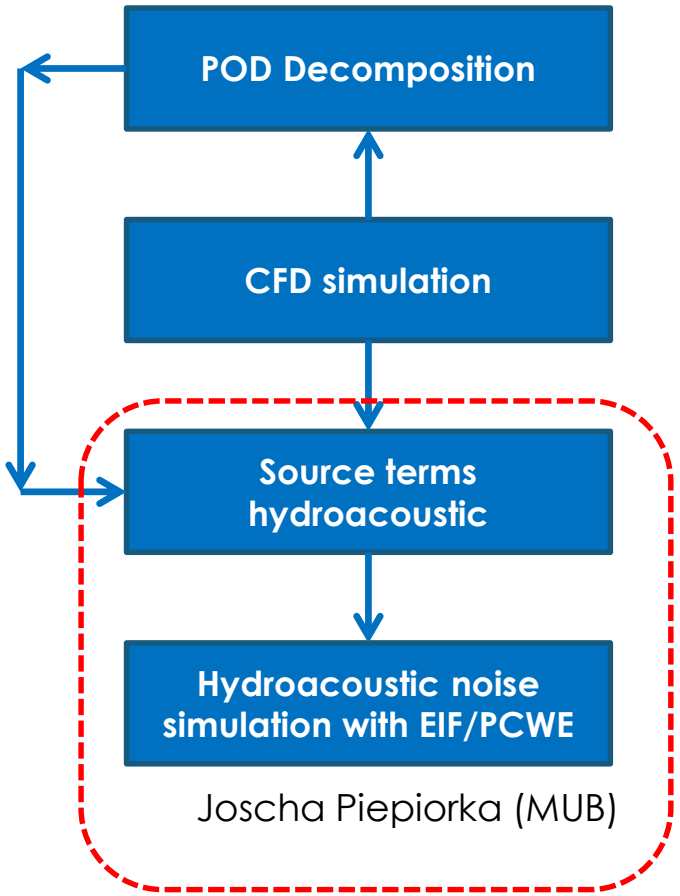
URANS: determination of the open water characteristics → only for integral quantities

DES-SBES: determination of the wake flow topology (coherent structures) and hydro acoustic emission → less dissipativ and scale resolving

	cells [M]	angle [°]	aspect ratio	volume change	y+	°/TS [s]	revolutions	n [s^{-1}]	J
URANS	20	< 18	< 60 (95%)	< 10	< 30	1	10	variable	0, 0.43-0.7
DES-SBES	33 - 95	< 27	< 60 (95%)	< 8	2 - 0.5	0.5 - 0.25	5	16.9	0

CFD Setup and Methods

general workflow for noise prediction



Hybrid approach:

1st step: CFD for incompressible flow

2nd step: Computation of acoustics

Splitting of the variable

$$p = p^{\mathrm{ic}} + p^{\mathrm{a}}, \quad \mathbf{u} = \mathbf{u}^{\mathrm{ic}} + \mathbf{u}^{\mathrm{a}}, \quad \rho = \rho_0 + \rho^{\mathrm{a}}$$

$\square^{\mathrm{ic}}$ = incompressible flow part,

$\square^{\mathrm{a}}$ = compressible, propagable acoustical part

Perturbed Convective Wave Equation (PCWE)

$$\frac{\mathrm{D}^2\psi^{\mathrm{a}}}{\mathrm{D}t^2} - c_0^2\Delta\psi^{\mathrm{a}} = -\frac{1}{\rho_0}\frac{\mathrm{D}p^{\mathrm{ic}}}{\mathrm{D}t} \quad \text{with} \quad \frac{\mathrm{D}}{\mathrm{D}t} = \frac{\partial}{\partial t} + \left(\bar{\mathbf{u}}^{\mathrm{ic}} \cdot \boldsymbol{\nabla}\right)$$

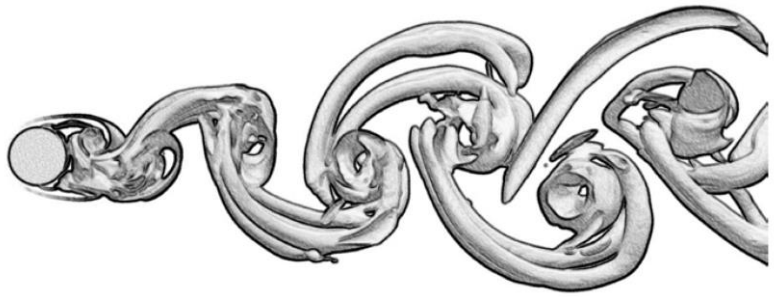
Acoustic potential ψ^{a} with $\mathbf{u}^{\mathrm{a}} = -\nabla\psi^{\mathrm{a}}$

Sound pressure $p^{\mathrm{a}} = \rho_0 \frac{\mathrm{D}\psi^{\mathrm{a}}}{\mathrm{D}t}$

CFD Setup and Methods

Proper **O**rthogonal **D**ecomposition and coherent structures

- fundamentals of POD were developed by Kari Karhunen and Michel Loève in the 40's
- transfer into the field of fluid mechanics by Berkooz, Holmes and Lumley (1993)



starting point: field quantity φ is known at K time instances t_i

$$\boxed{\varphi = \bar{\varphi} + \varphi' = \bar{\varphi} + \tilde{\varphi} + \varphi''}$$

Galerkin approximation:

$$\varphi(x, t_i) :\approx \bar{\varphi} + \sum_{k=1}^{K} M_k(x) \cdot a_k(t_i) \quad i, k = 1,2, \dots, K$$

Eigenvalue problem:

$$(C_{kl} - \lambda \cdot \delta_{kl}) \cdot b_k = 0$$

Correlation matrix:

$$C_{kl} = \frac{1}{K} \int_V \left(\phi'(x, t_k) \cdot \phi'(x, t_l)\right) dV$$

POD time coefficient:

$$a_k(t_i) = b_k(t_i) \cdot \sqrt{K \cdot \lambda_k}$$

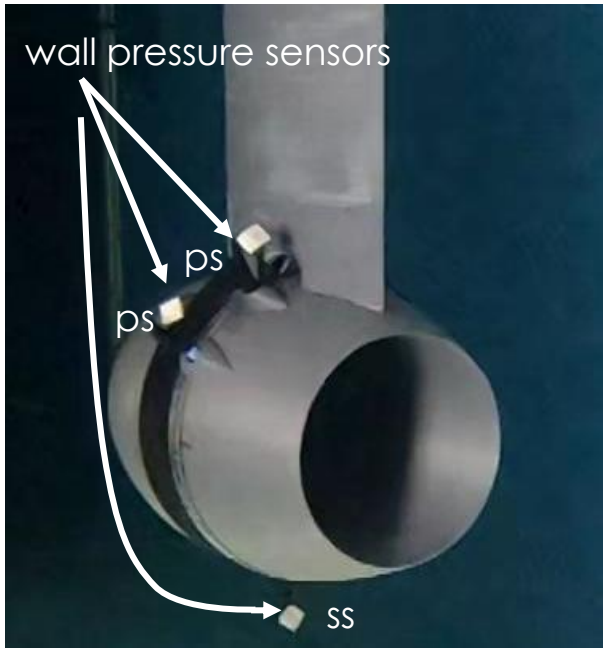
POD modes:

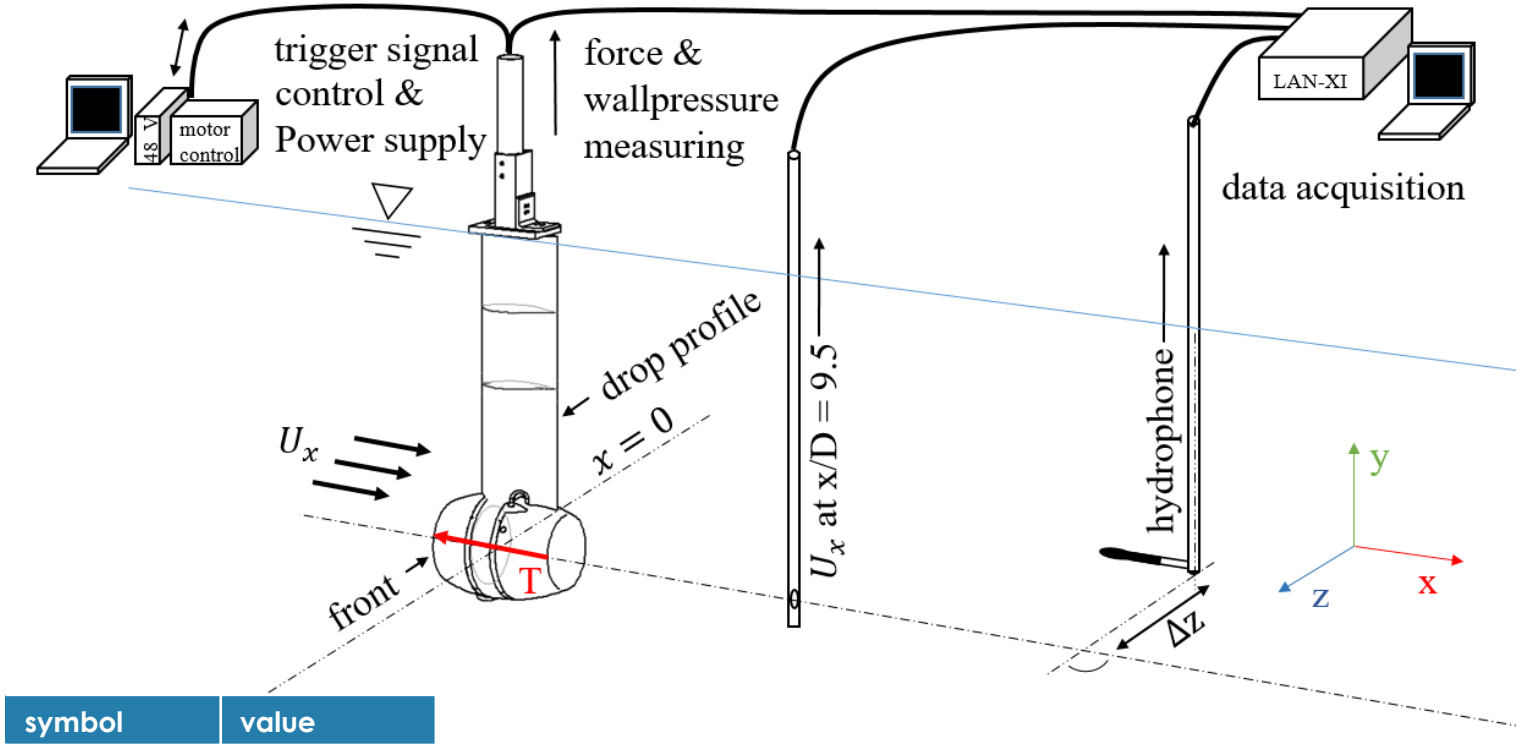
$$M_k = \frac{1}{\sqrt{K \cdot \lambda_k}} \cdot \sum_{i=1}^{K} b_k(t_i) \cdot \varphi'(x, t_i) \quad i = 1,2, \dots, K$$

Outline

MVDR Beamformer: frequency = 9865 Hz; $f_{Rotation}$= 13.1 Hz

Measurement Setup – *Topic 1*



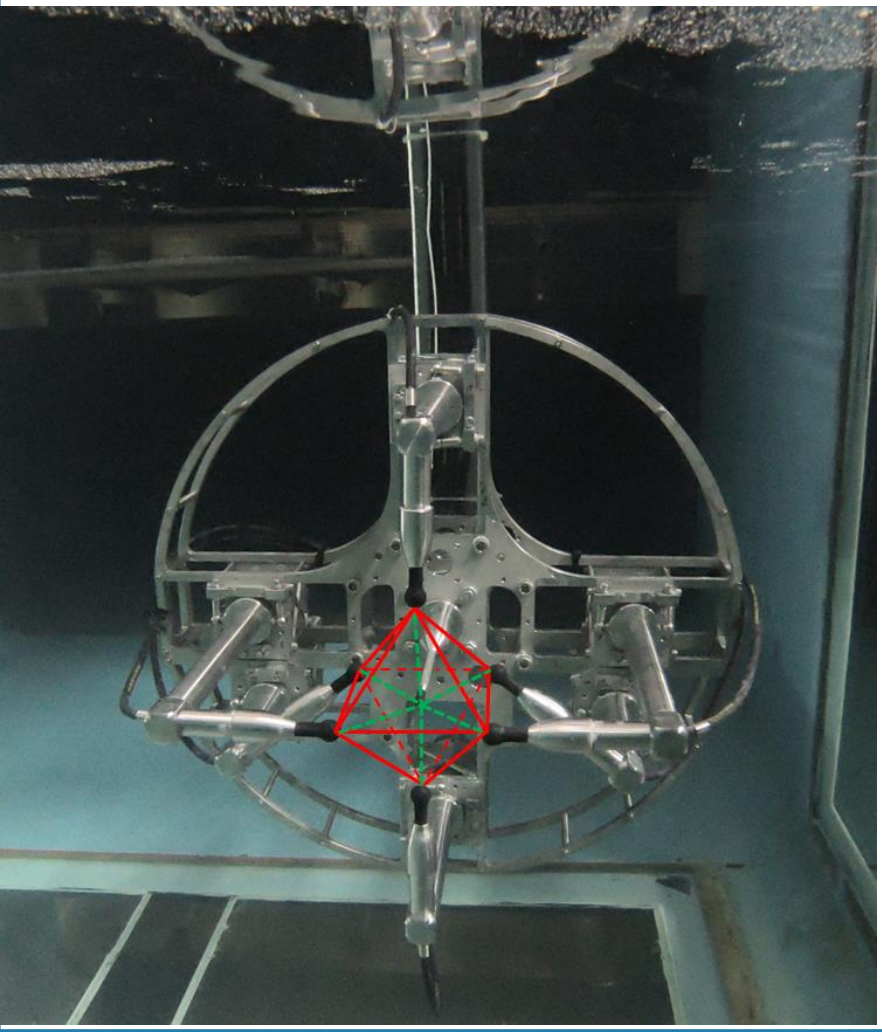


	symbol	value
blades	z	4
diameter in mm	D	100
max. rotation speed in min^{-1}	n	1600
pitch/diameter (r/R = 0.7)	P/D	1.94
skew/rake	-	no/no
max. power supply in kW	P_{el}	1.2

- Experiments were done in the towing tank facility at Voith in Heidenheim

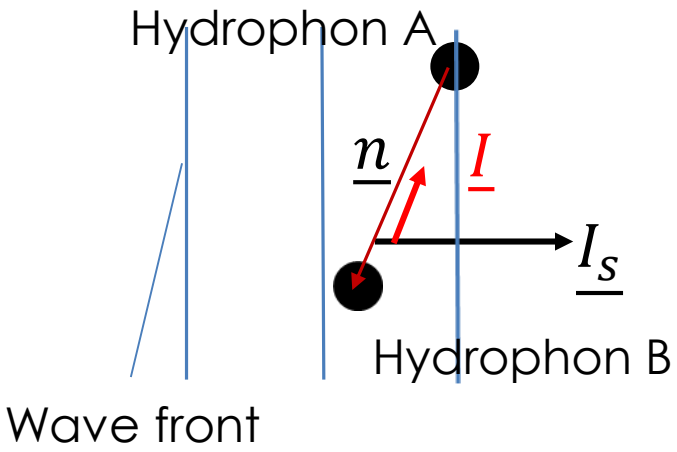
Measurement Setup – preliminary tests for field measurement campaign of Topic 2 → acoustic source localization

sound intensity based beamforming (AVS):



3D intensity probe

- I_S is the projected intensity along the axis between Hydrophone A and B
- least square approach for reconstruction of the 3D intensity vector



$$\left\| \underline{\underline{n}} \cdot \underline{I_s} - \underline{I_{probe}} \right\|_2 \rightarrow min$$

$$\underline{I_s} = \left(\underline{\underline{n^T}} \cdot \underline{\underline{n}} \right)^{-1} \cdot \underline{\underline{n^T}} \cdot \underline{I_{probe}}$$

derivation from Euler equation

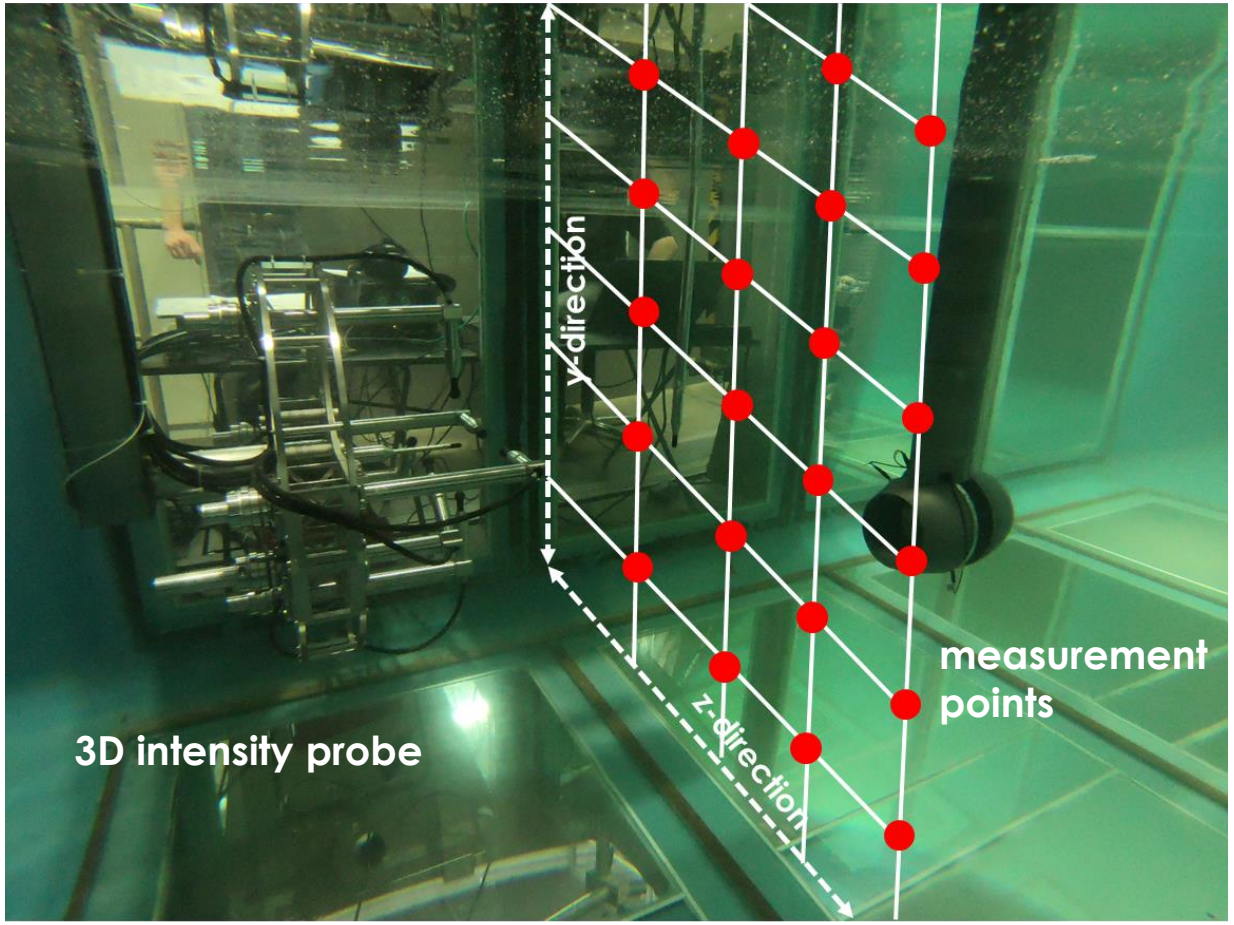
$$\frac{p_A(t)+p_B(t)}{2\rho_0 \Delta r} \int p_B(t) - p_A(t)\, dt = |I_s|$$

$$|Is| = \frac{1}{2\pi\rho_0 \Delta r} \sum_{n=1}^{N/2} \frac{Im(G_{AB})}{n\, \Delta f}$$

Advantage AVS:
separation of coherent sources is possible up to approximately D = λ

Measurement Setup – preliminary tests for field measurement campaign of Topic 2 → acoustic source localization

sound intensity based beamforming (AVS):



phase reconstruction of individual measurements:

- problem: uncorrelated single measurements → no beamforming possible
- reconstruction of the phase by usage of reference sensors fixed in space → dynamic pressure sensors, hydrophon, acceleration sensor

cross power spectrum

$$R_{Ref,Hydro} = S_{Ref}(\omega)^* \cdot S_{Hydro}(\omega)$$

phase angle

$$\alpha(\omega) = \mathrm{atan}\left(\frac{Imag(R_{Ref,Hydro})}{Real(R_{Ref,Hydro})}\right)$$

- Different uncorrelated single measurements can be treated as one single dataset which has been measured with all sensors synchronously at the same time when the relative phase angle has been recovered using the reference sensors → only valid for stationary processes
- application of various beamforming approaches after phase reconstruction possible

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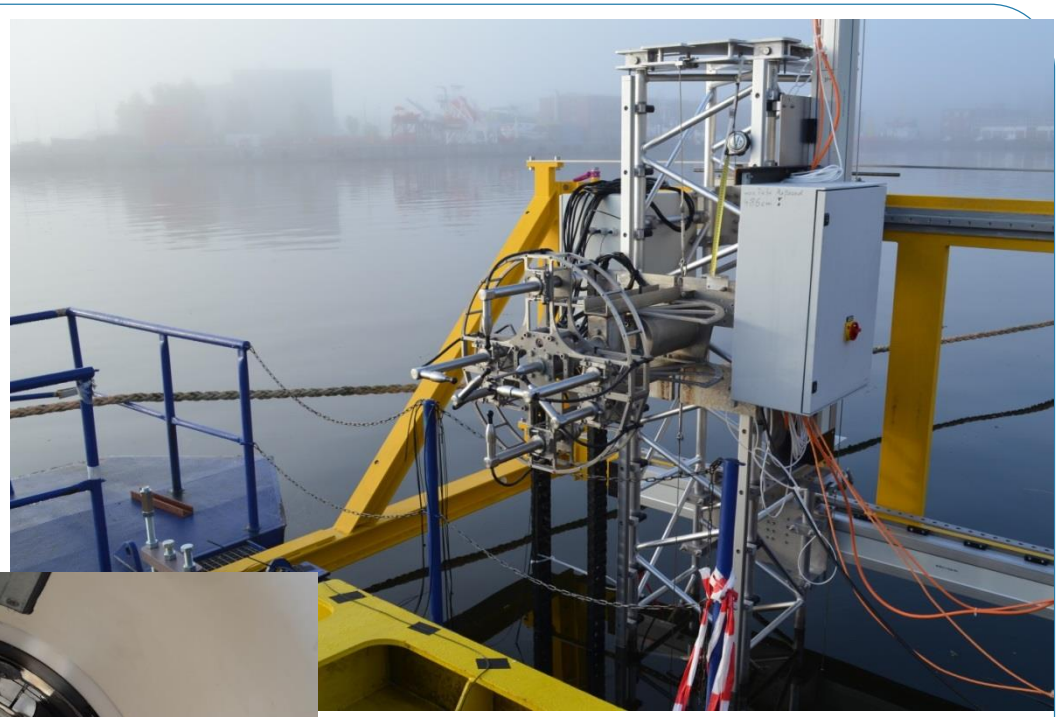
Measurement Setup – preliminary tests for field measurement campaign of Topic 2 → acoustic source localization



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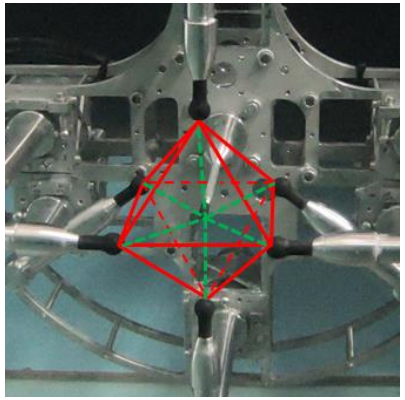
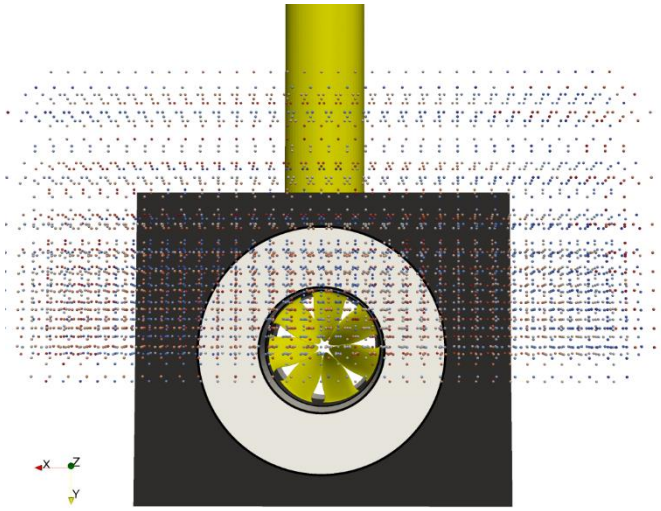
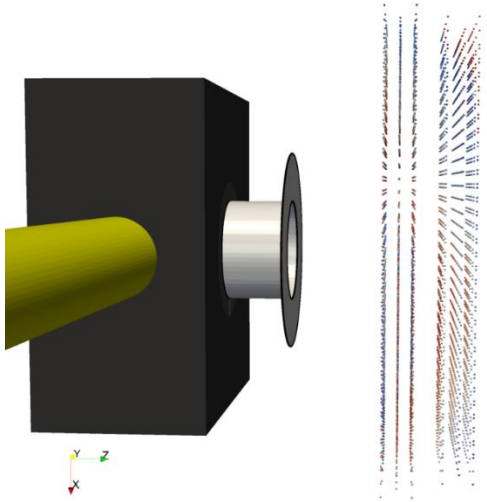
Measurement Setup – preliminary tests for field measurement campaign of Topic 2 → acoustic source localization







- **637 3D intensity probe positions → 4459 hydrophone positions (BKSV 8103,8105)**
- **intensity or pressure based beamforming evaluation possible depending on the frequency**
- **acquisition time 30s, 65 kHz sample rate → 13 channels**
- **propeller speed 787 min^{-1}**

Outline

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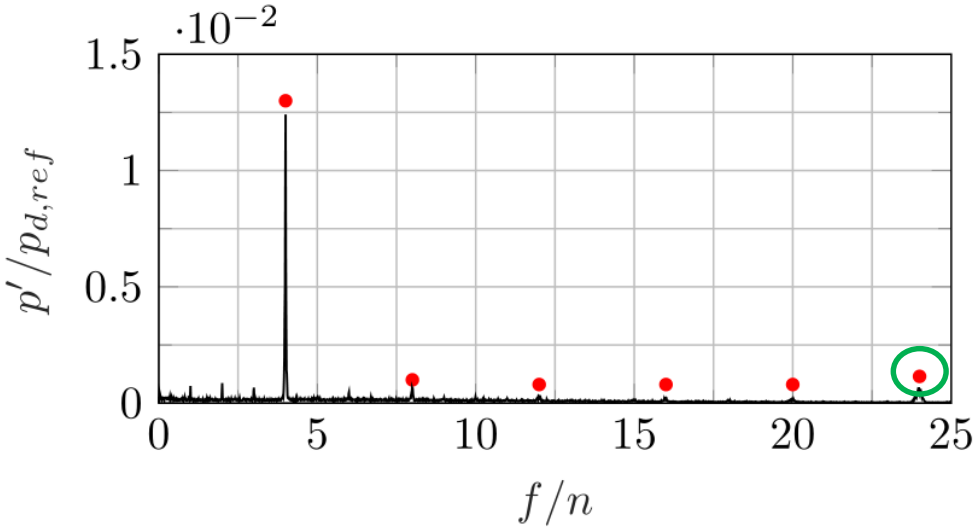
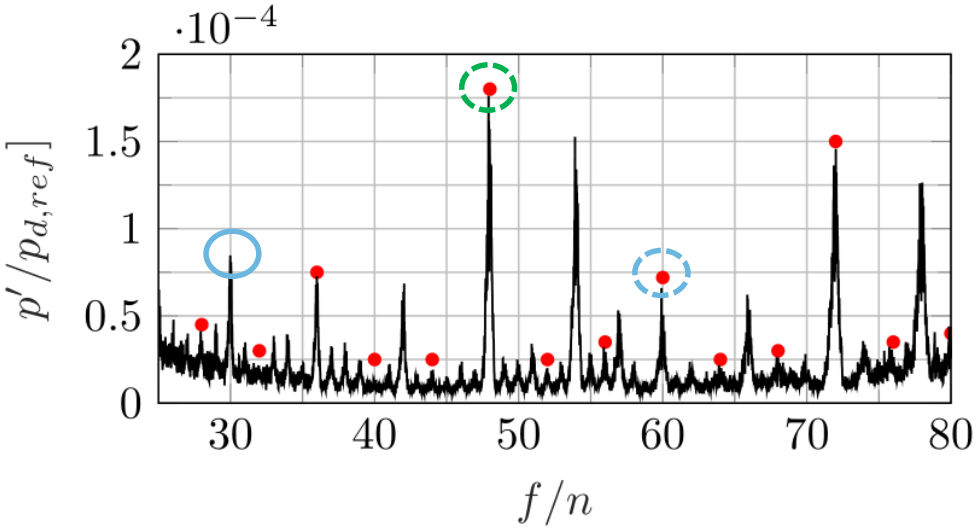
Results Topic 1

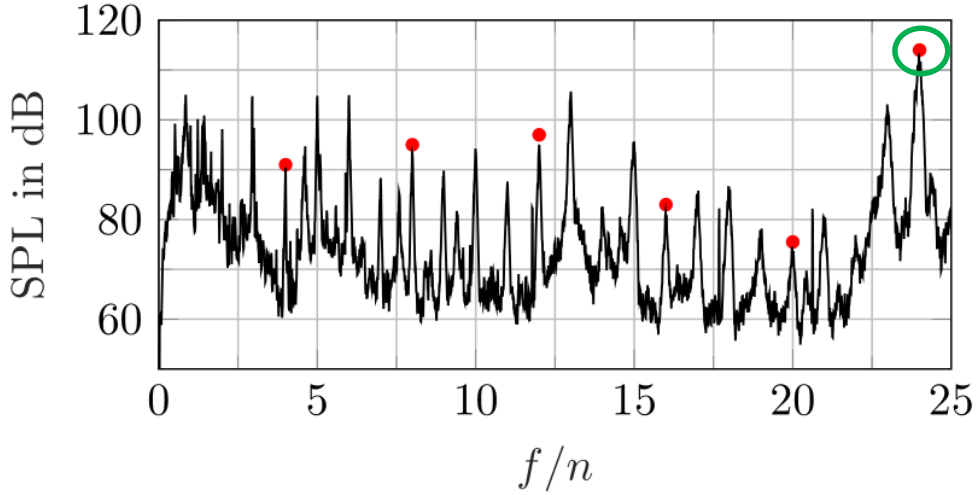
narrow band order spectrum
top row: wall pressure fluctuations
bottom: hydro sound pressure level

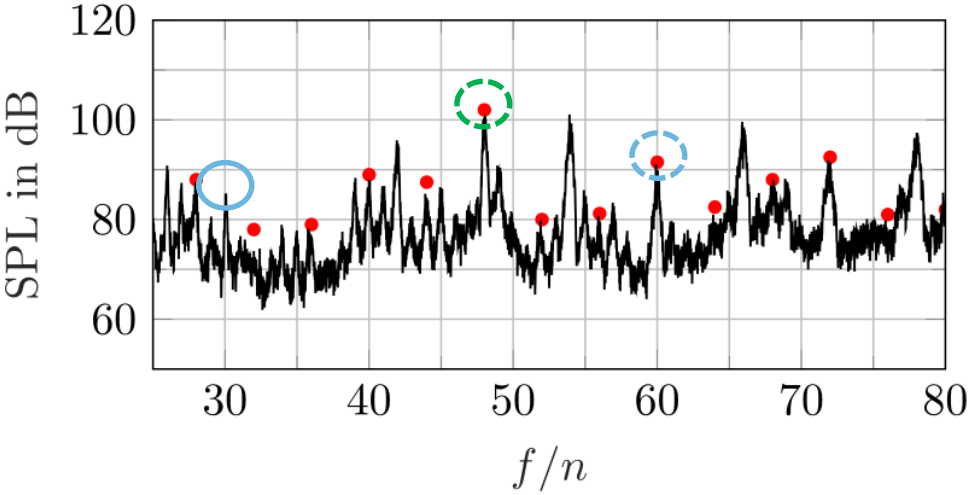




reference pressure

$p_{d,ref} = (\omega R)^2 \cdot \rho/2$





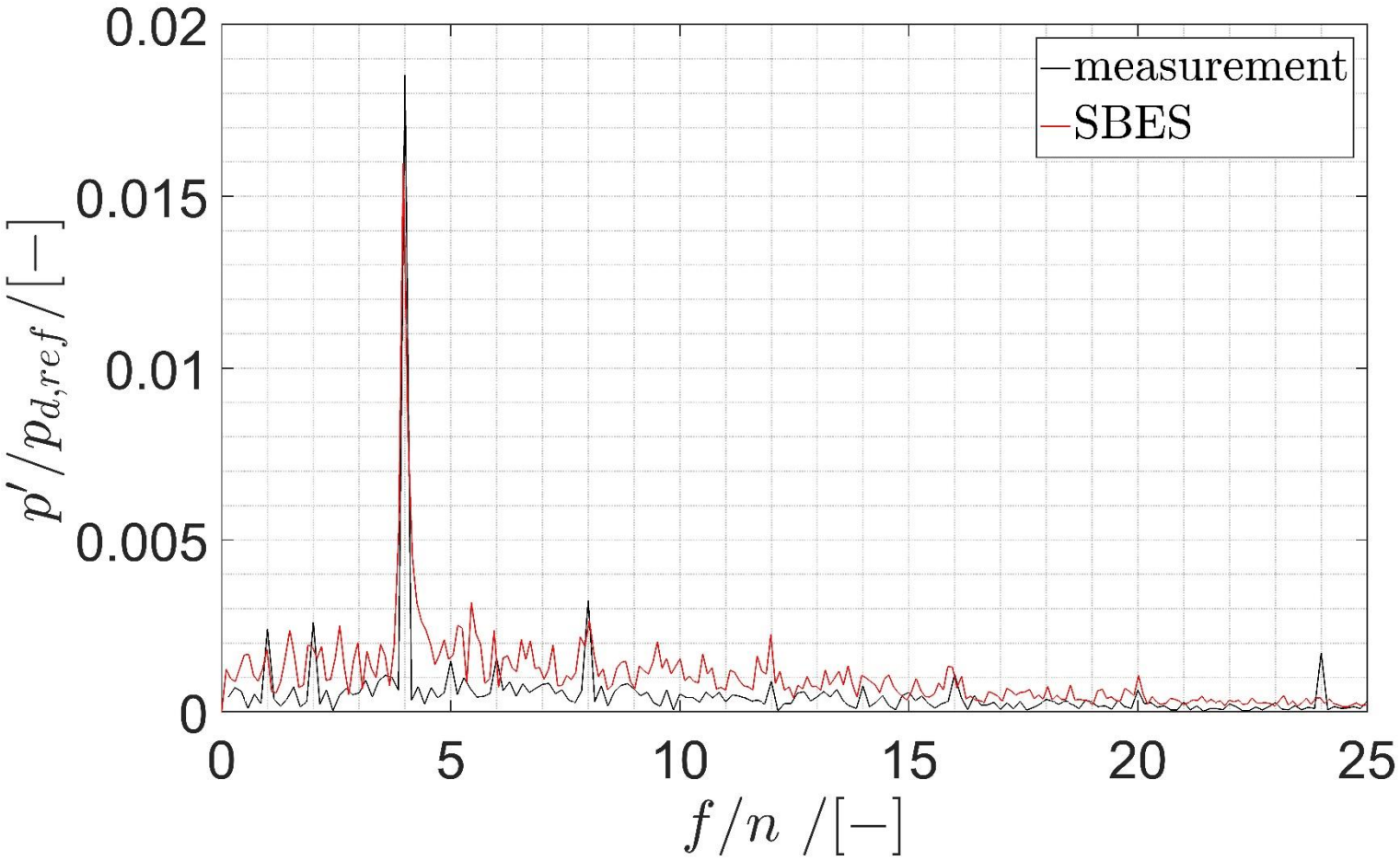
reference acoustic pressure

$\tilde{p}_{ref} = 10^{-6} Pa$

Results Topic 1

Orderspectra

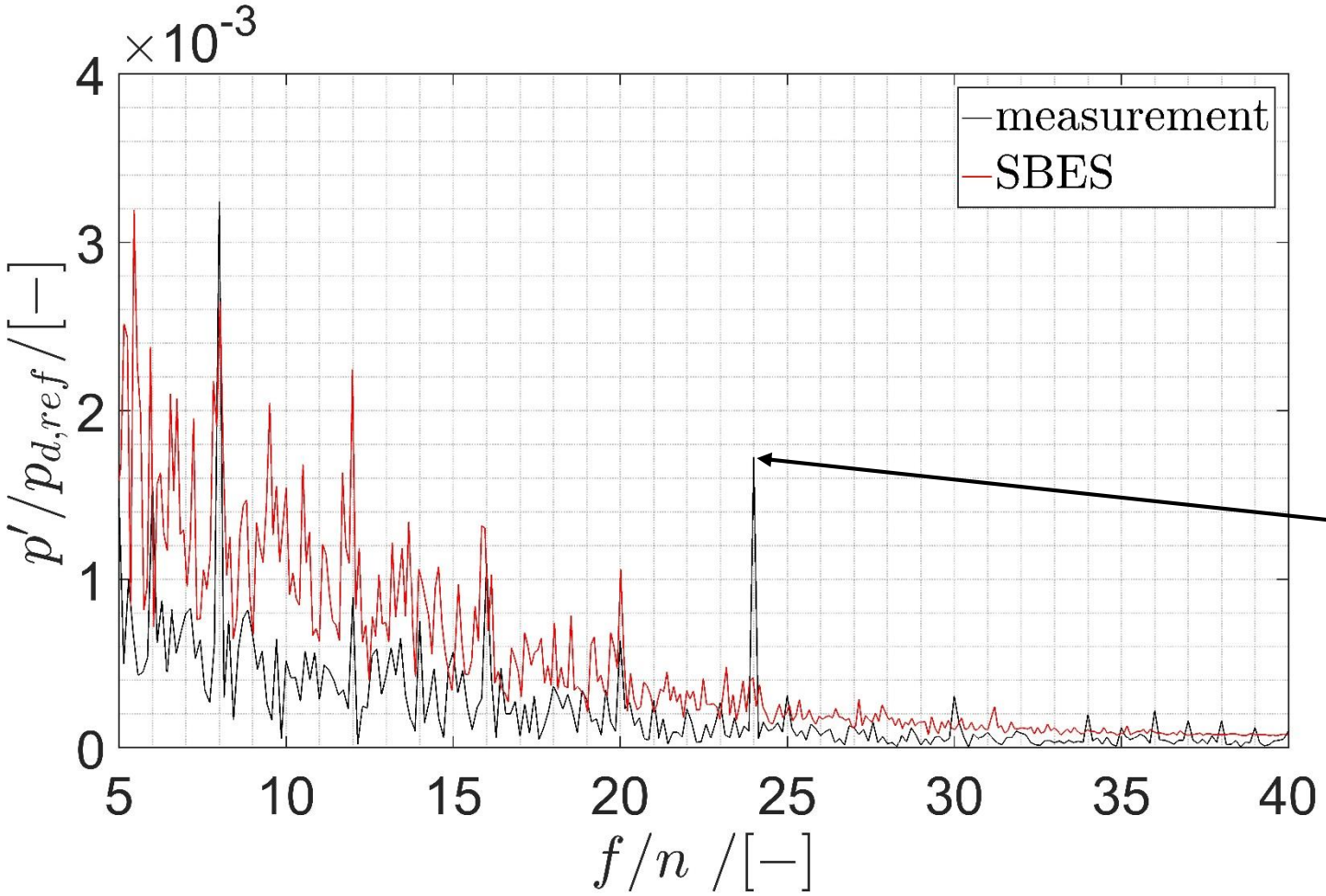
Wallpressure-fluktuations of the SBES and the measurement



Results Topic 1

Orderspectra

Wallpressure-fluktuations of the SBES and the measurement



Higher Amplitude due to the order of used magnets(12) and coils (8) of the DC motor

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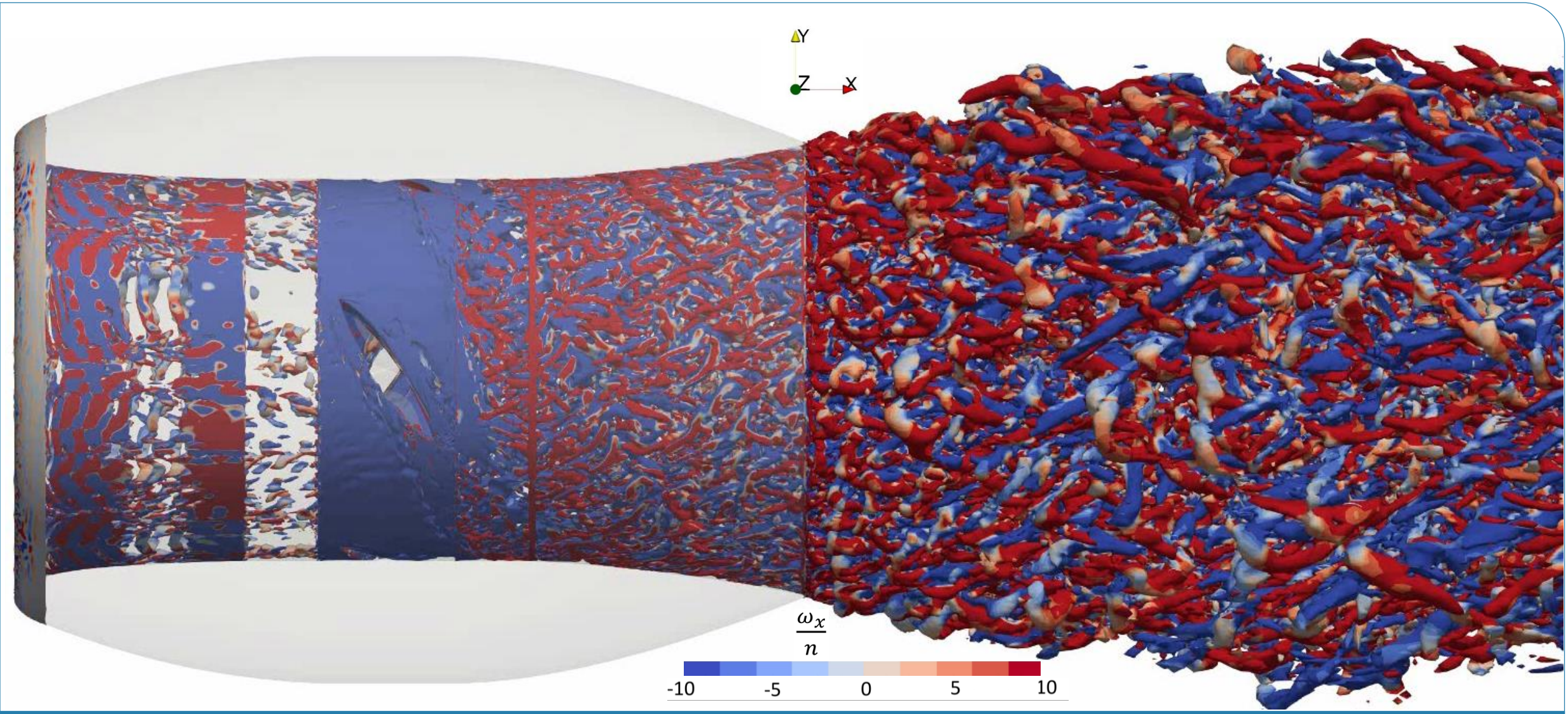
Results Topic 1

wake flow structures

iso-surfaces: $Q/n^2 = 35$ color: vorticitiy X



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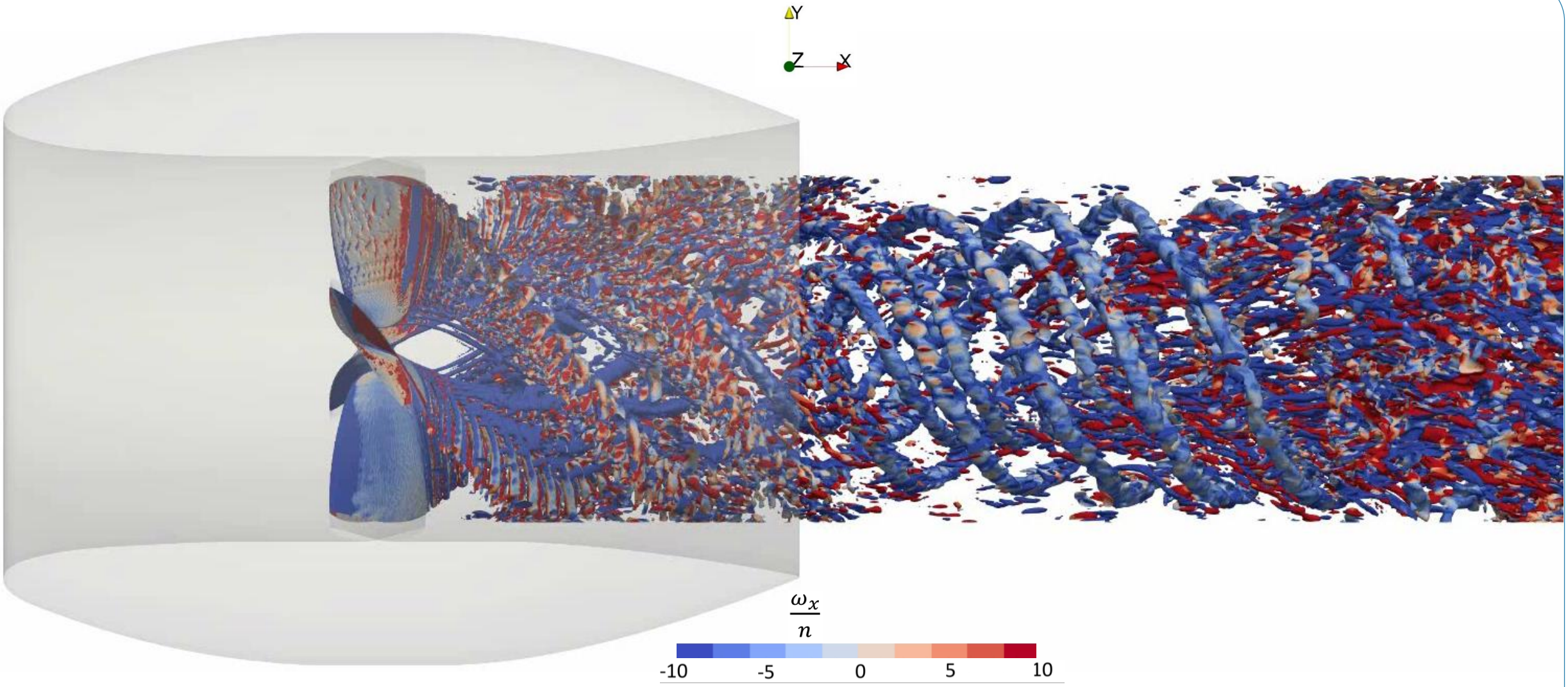
Results Topic 1

wake flow structures – clip r/R = 0.9
iso-surfaces: $Q/n^2 = 35$ color: vorticitiy X



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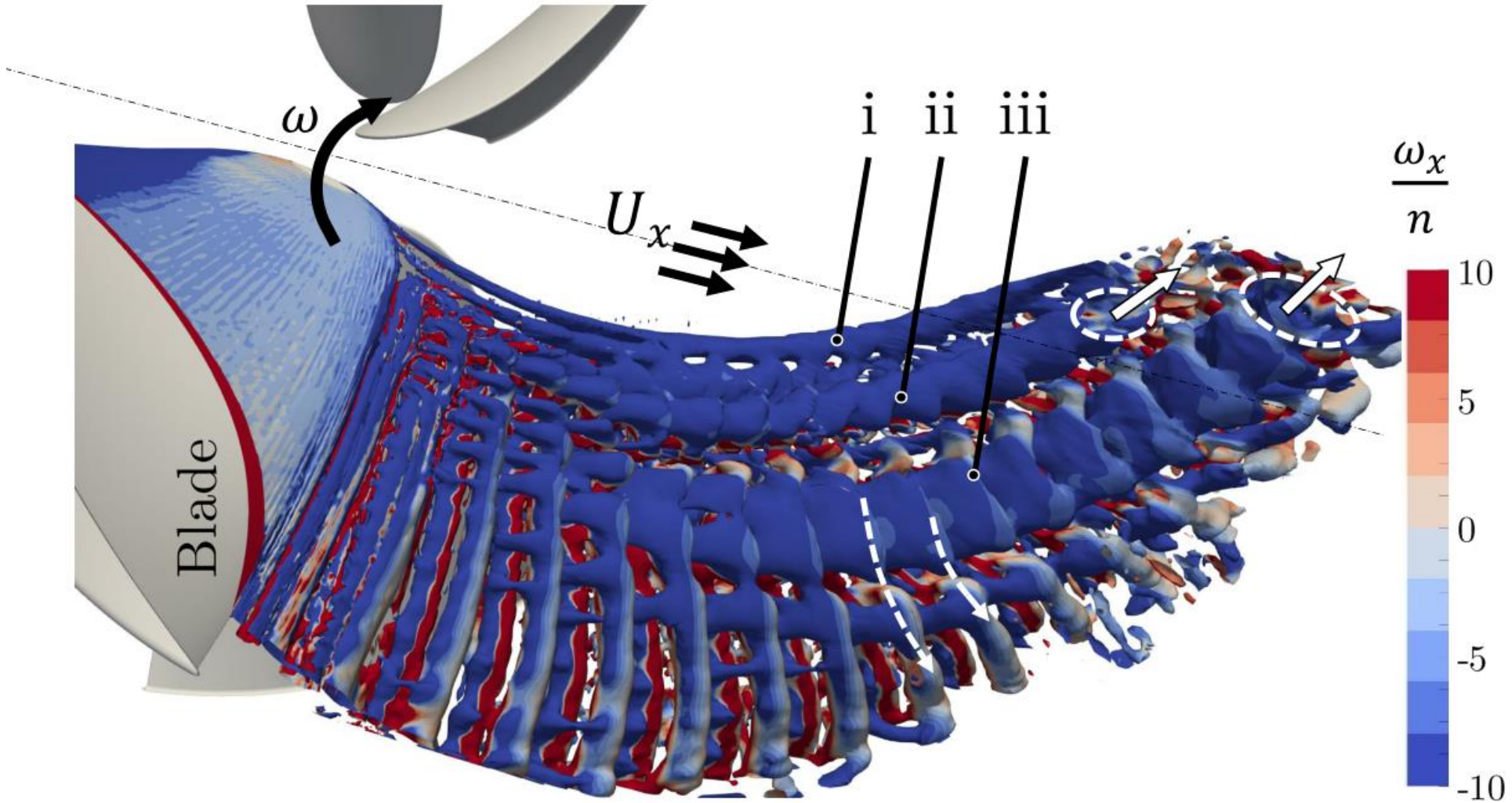
Results SBES 93Mio

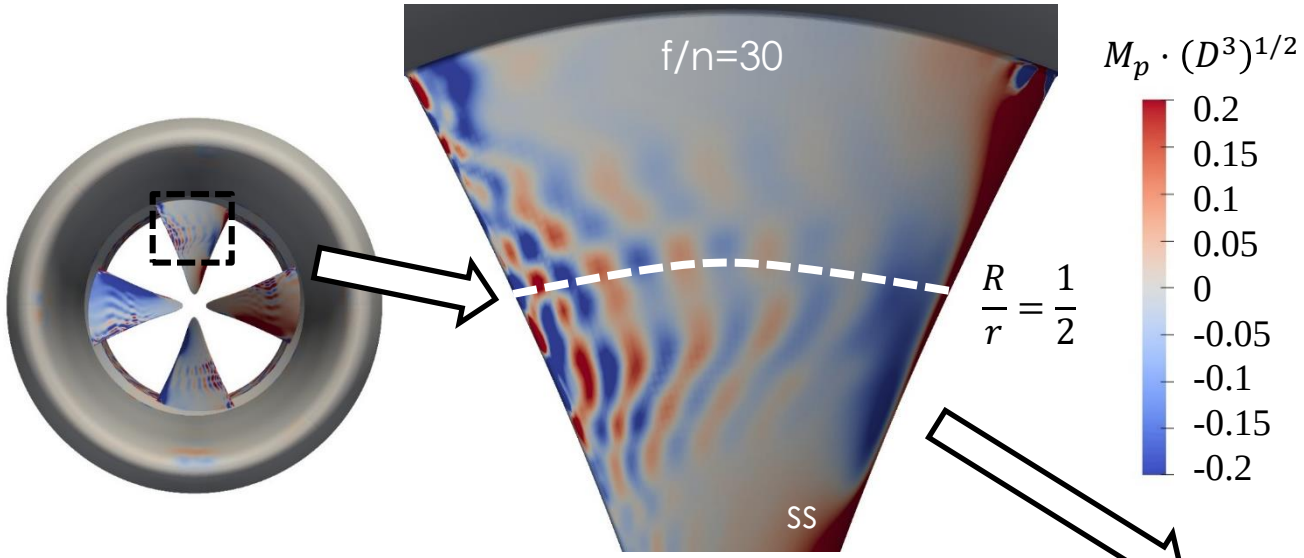
wake flow structures

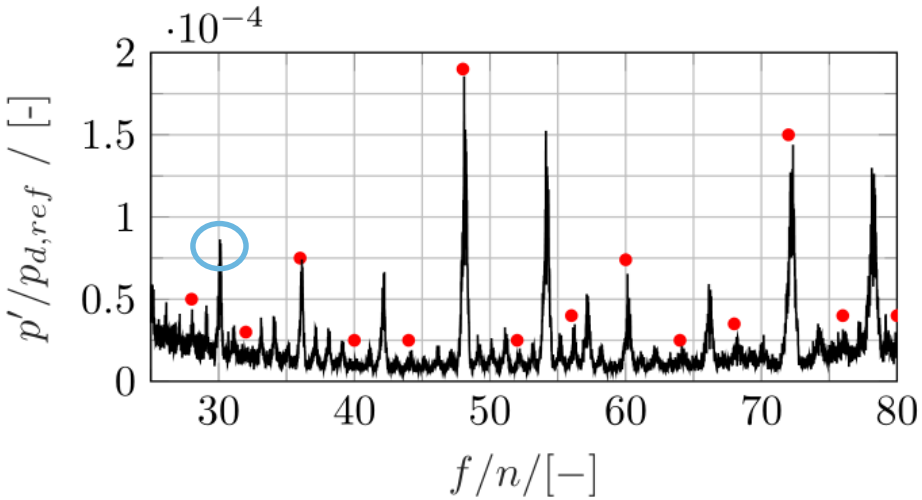
iso-surfaces: $Q/n^2 = 35$ color: vorticitiy X

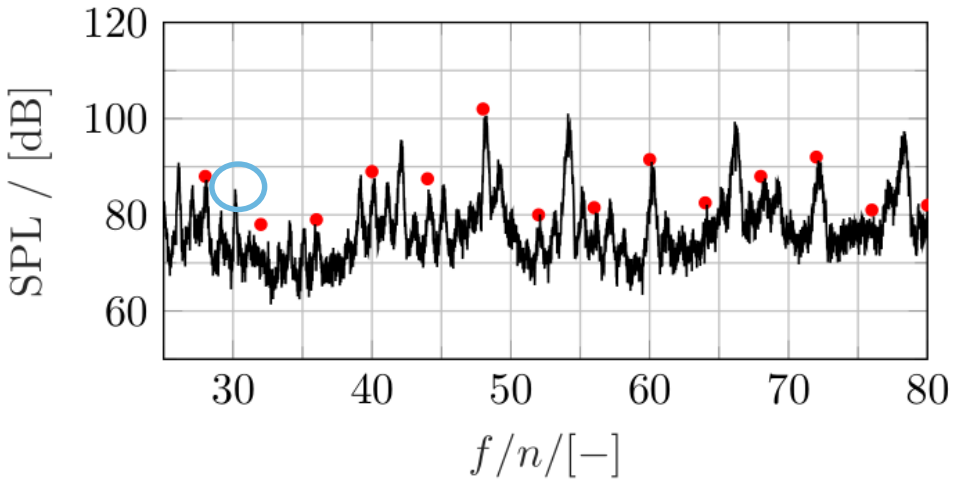


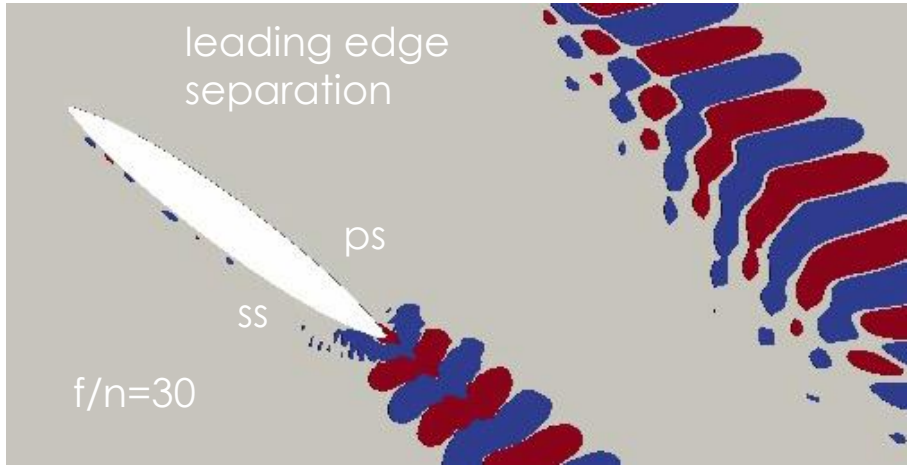
Results Topic 1

POD wall pressure mode (top)
recombined POD wall pressure modes (bottom)

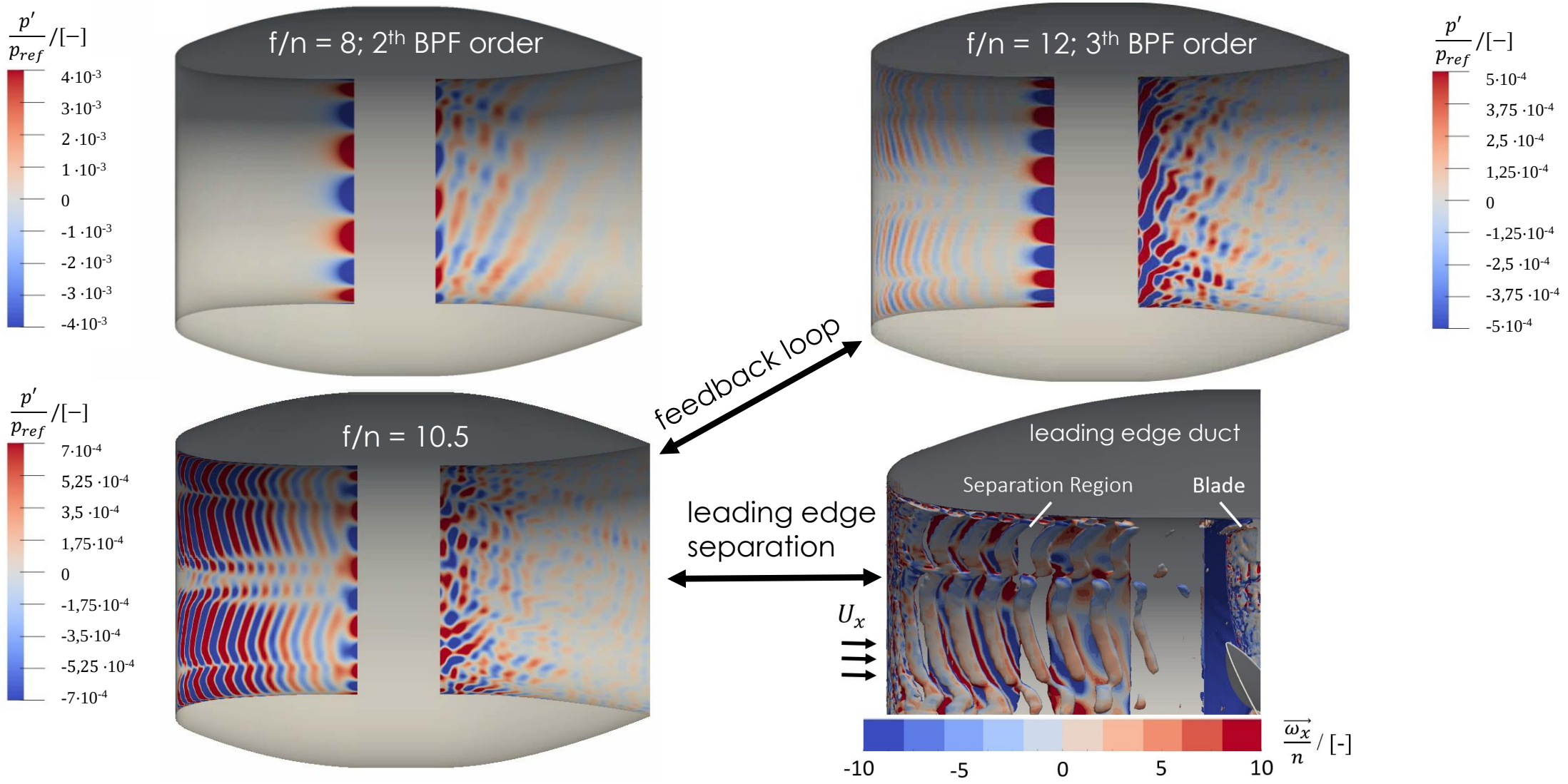








Results Topic 1
recombined POD wall pressure modes



Results Topic 1

POD-pressuremode 2 - clip r/R = 0.9
f/n = 4

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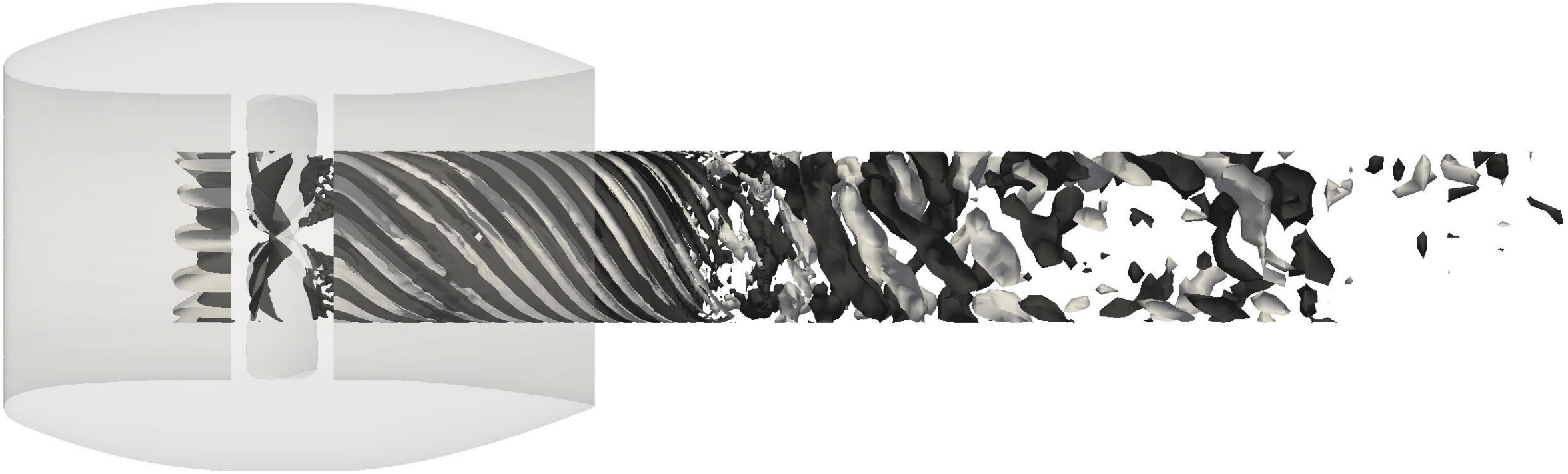
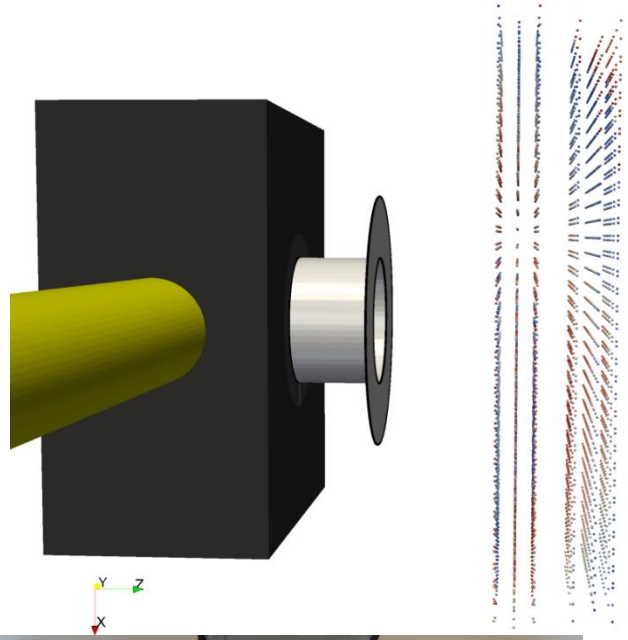
Results Topic 1

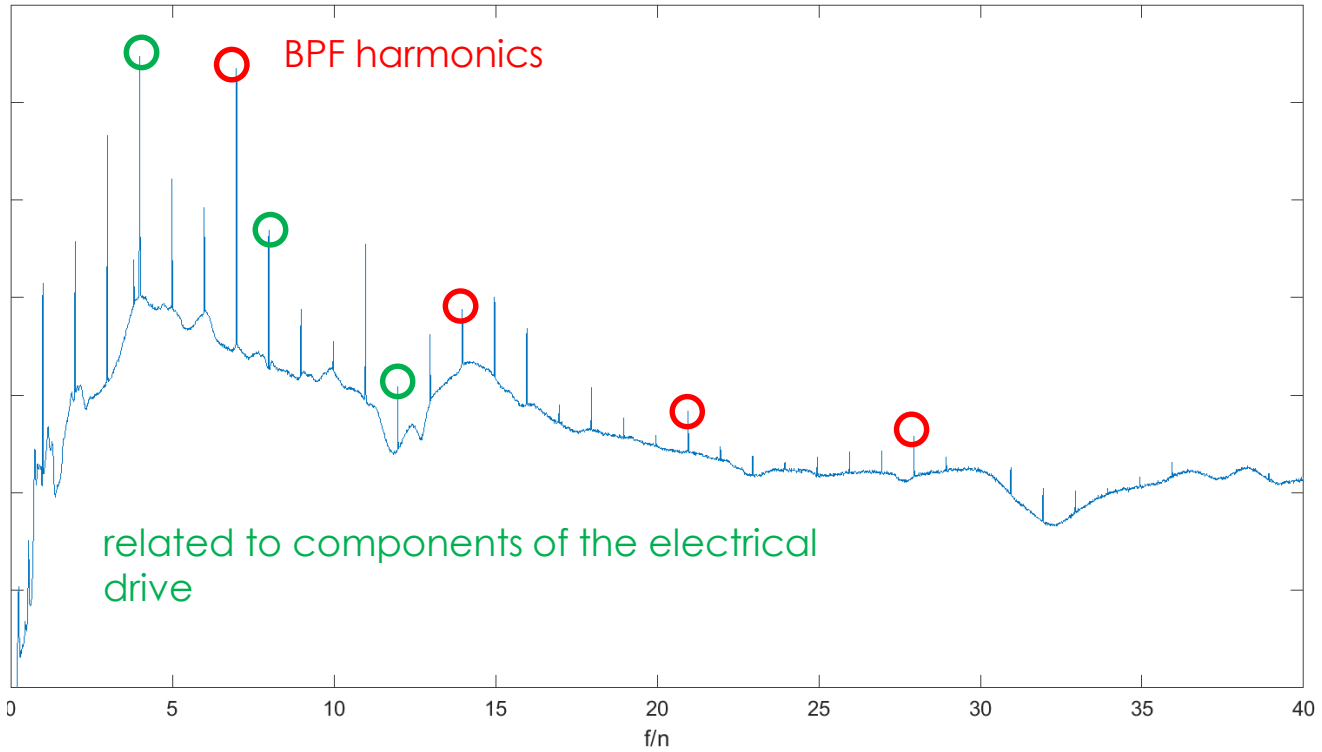
POD-pressuremode 44 - clip r/R = 0.9
f/n = 12



Results Topic 2

narrow band order spectrum
hydro sound pressure level in dB re($1 \cdot 10^{-6}$ Pa)
n = 787 min^{-1}

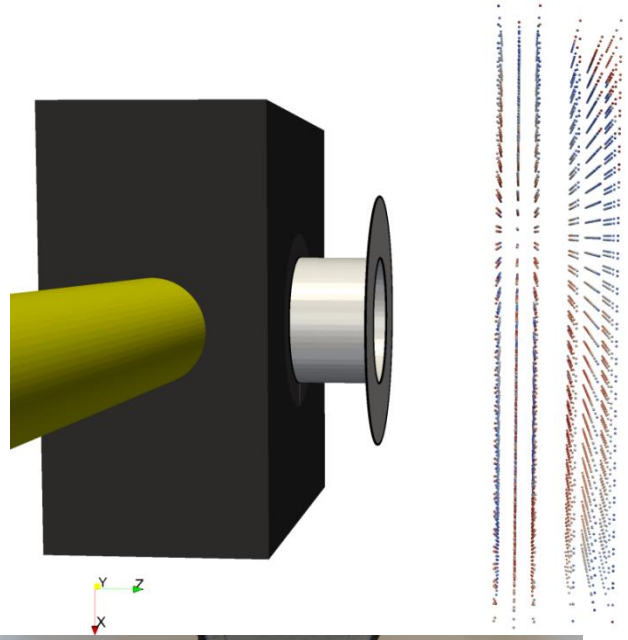


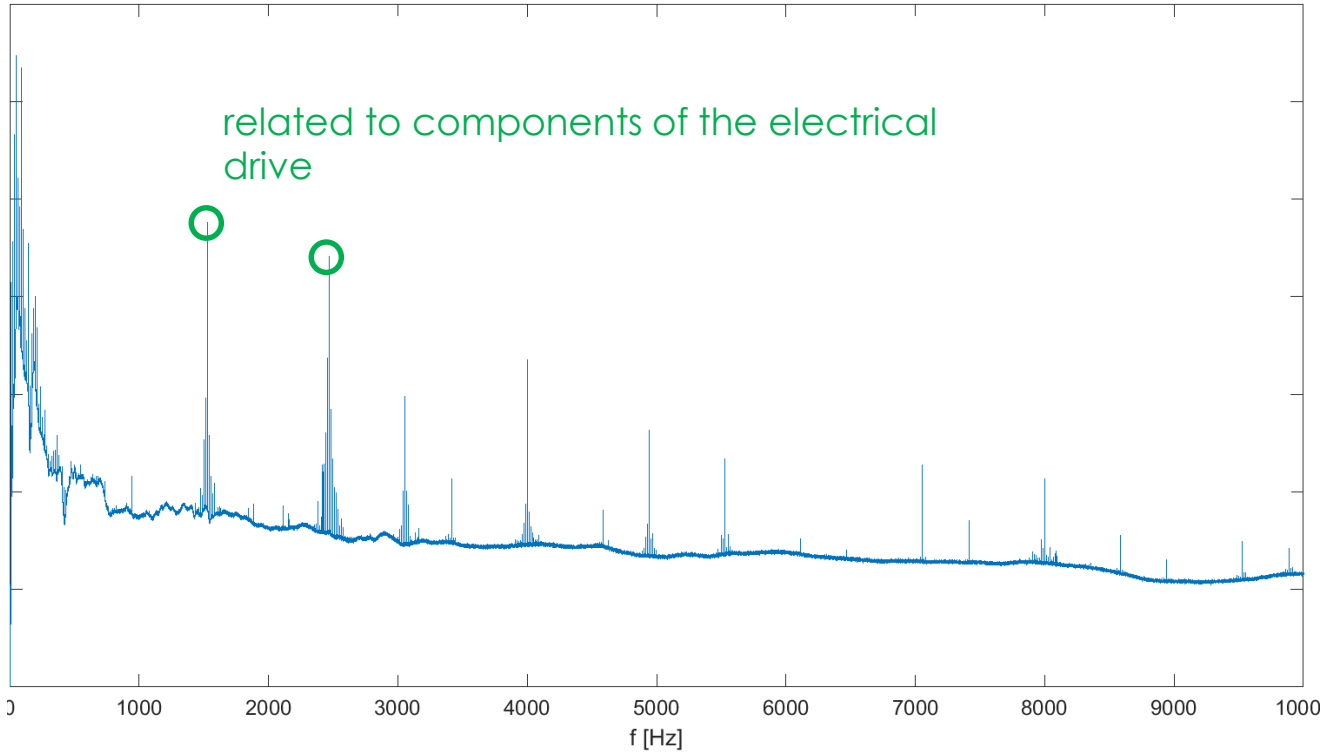


averaged narrow band order spectra
from all single measurement

Results Topic 2

narrow band order spectrum
hydro sound pressure level in dB re($1 \cdot 10^{-6}$ Pa)
n = 787 min^{-1}



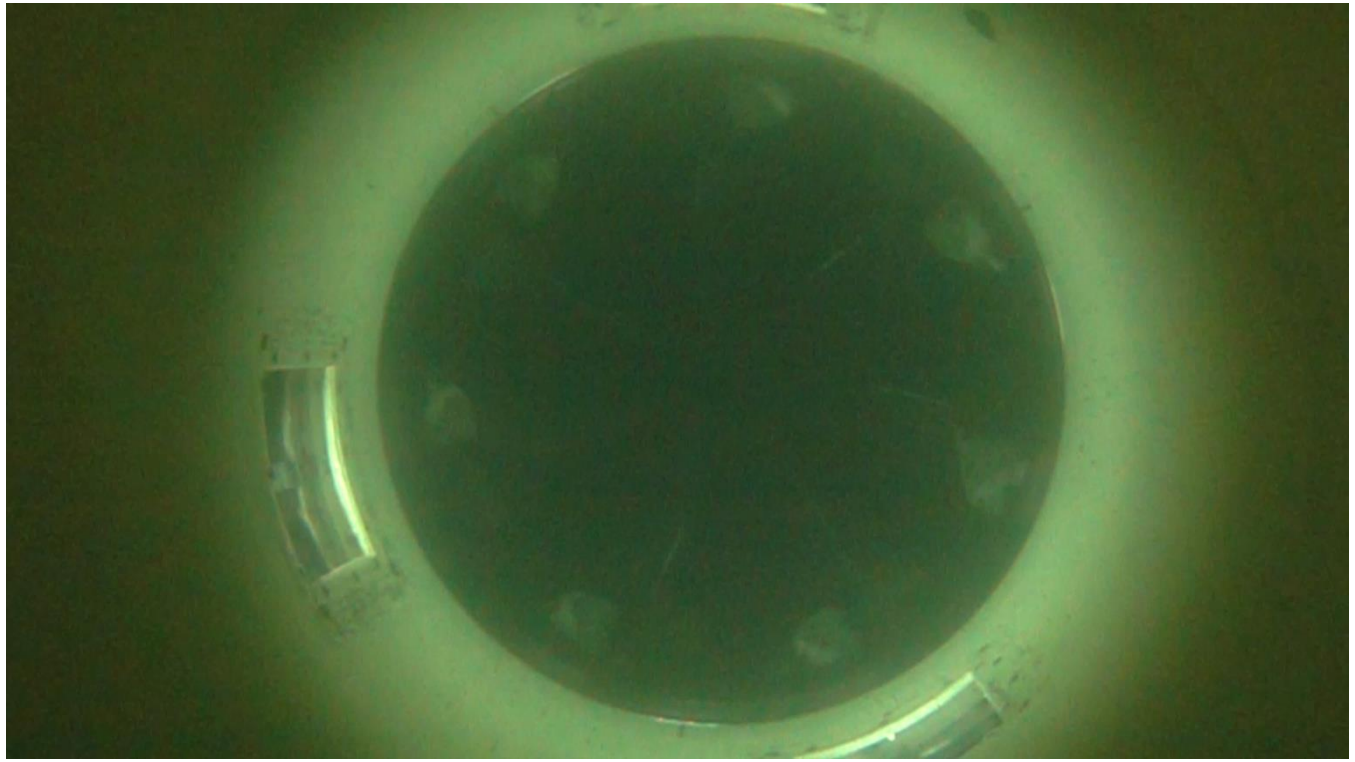


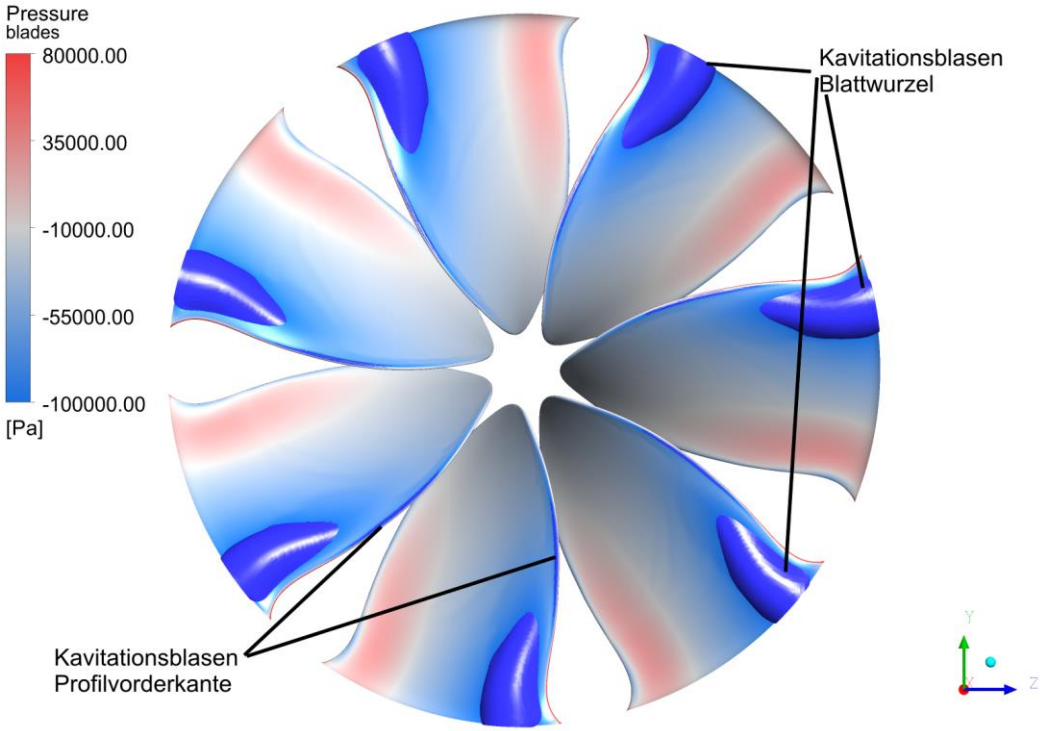
averaged narrow band order spectra
from all single measurement

Results Topic 2

CFD result
iso-surfaces where the local pressure drops below the vapor pressure

Inline thruster during operation

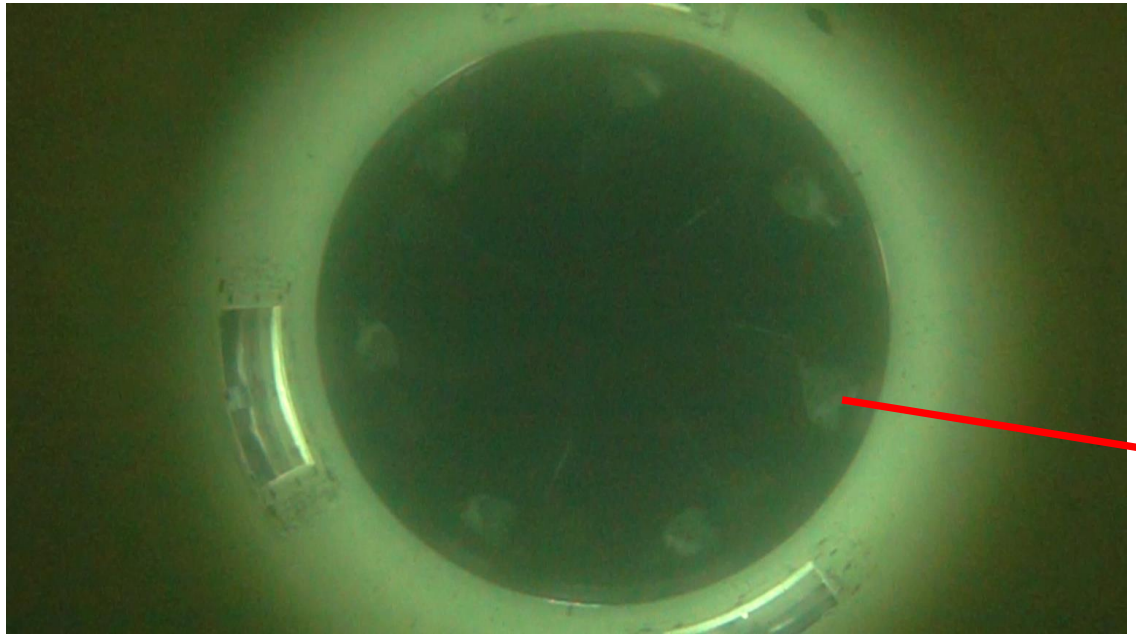


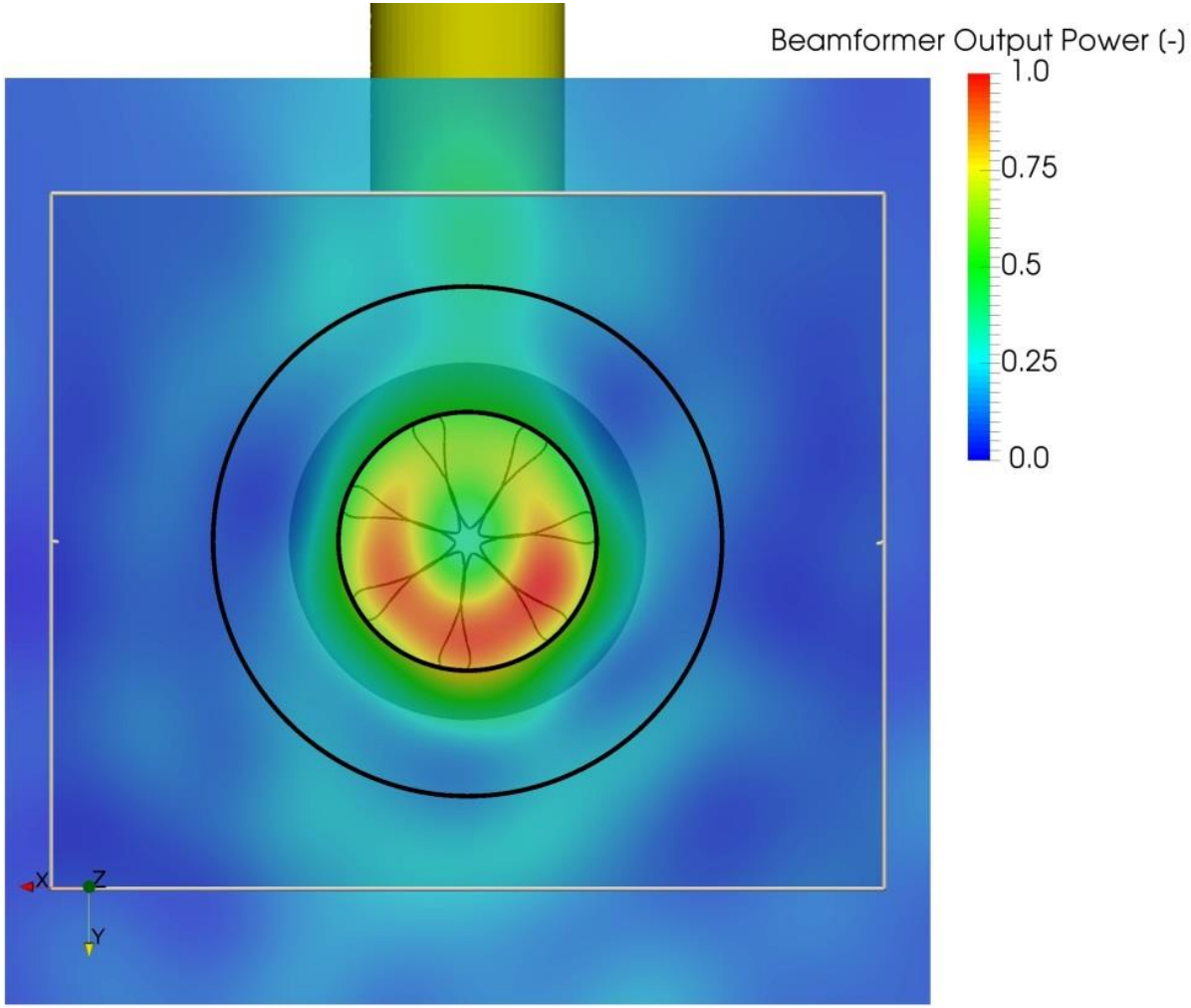


- cavitation in the profile root region
- cavitation at the blade leading edge

Results Topic 2
Beamforming results
"acoustic cavitation signature"

Inline thruster during operation

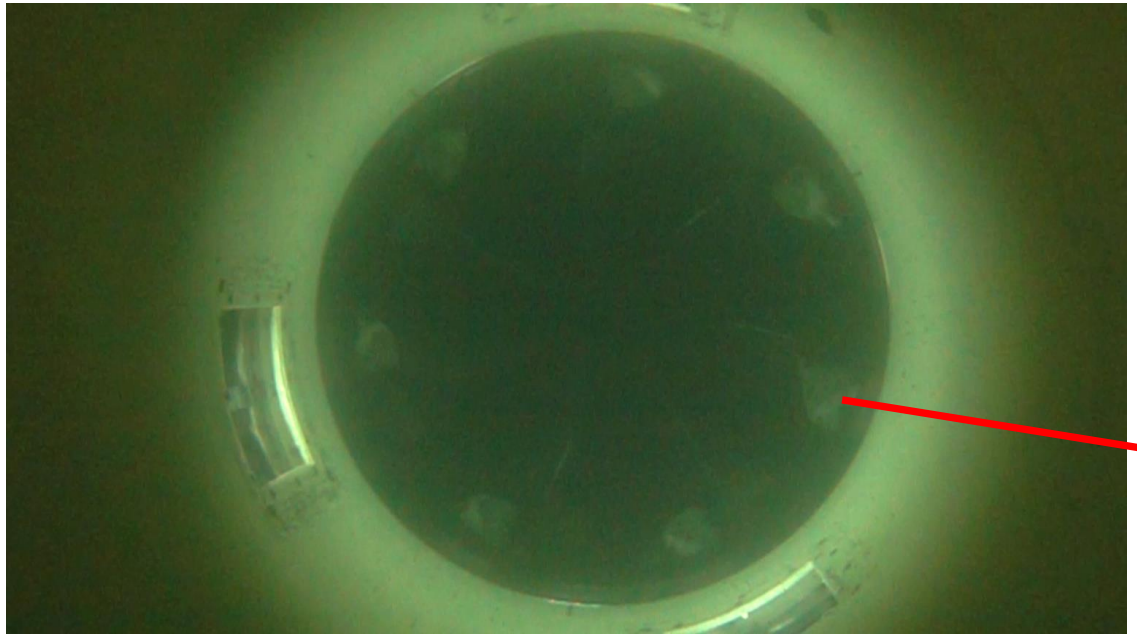


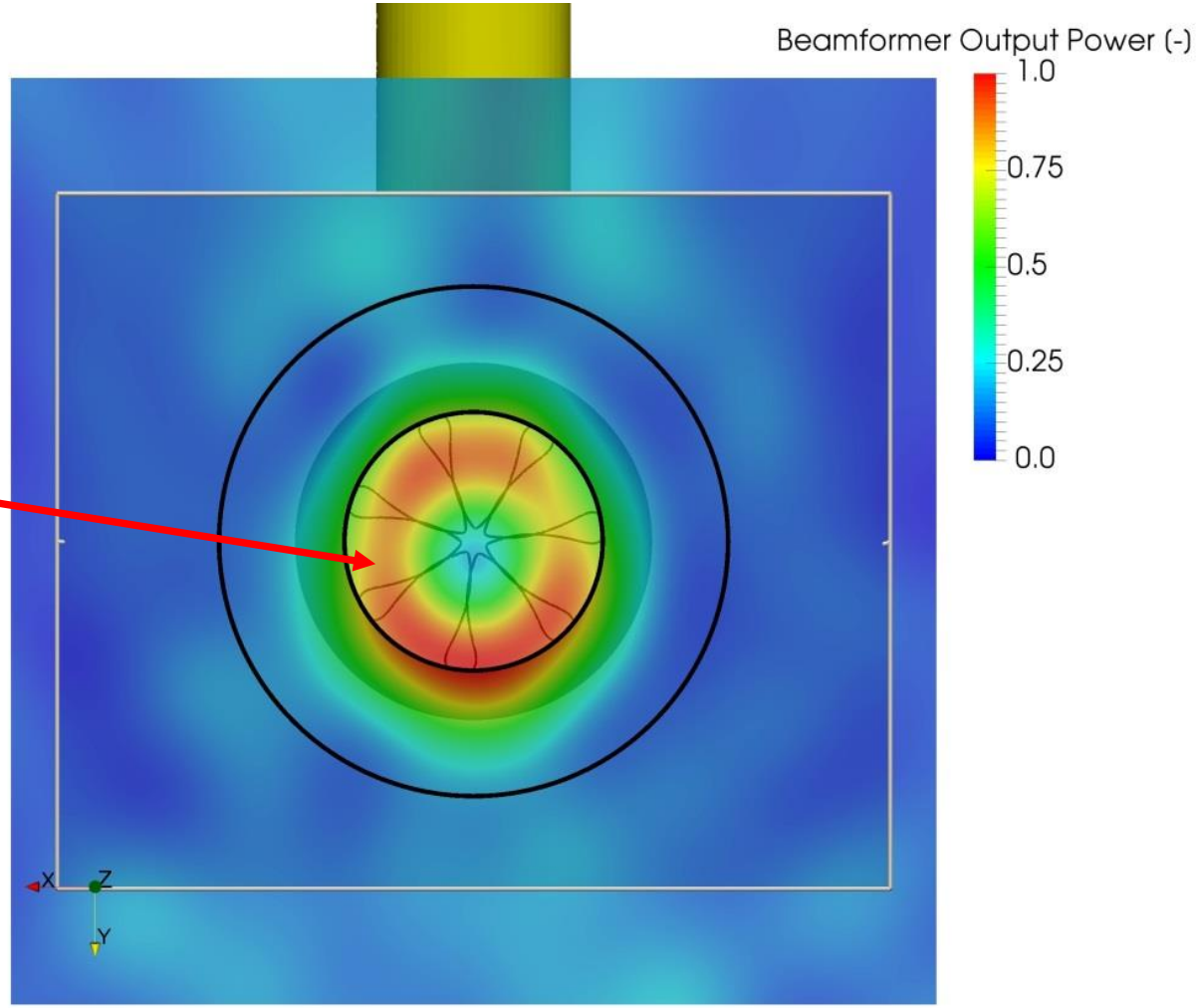


MVDR Beamformer: frequency = 6840 Hz; $f_{Rotation}$= 13.1 Hz

Results Topic 2
Beamforming result
"acoustic cavitation signature"

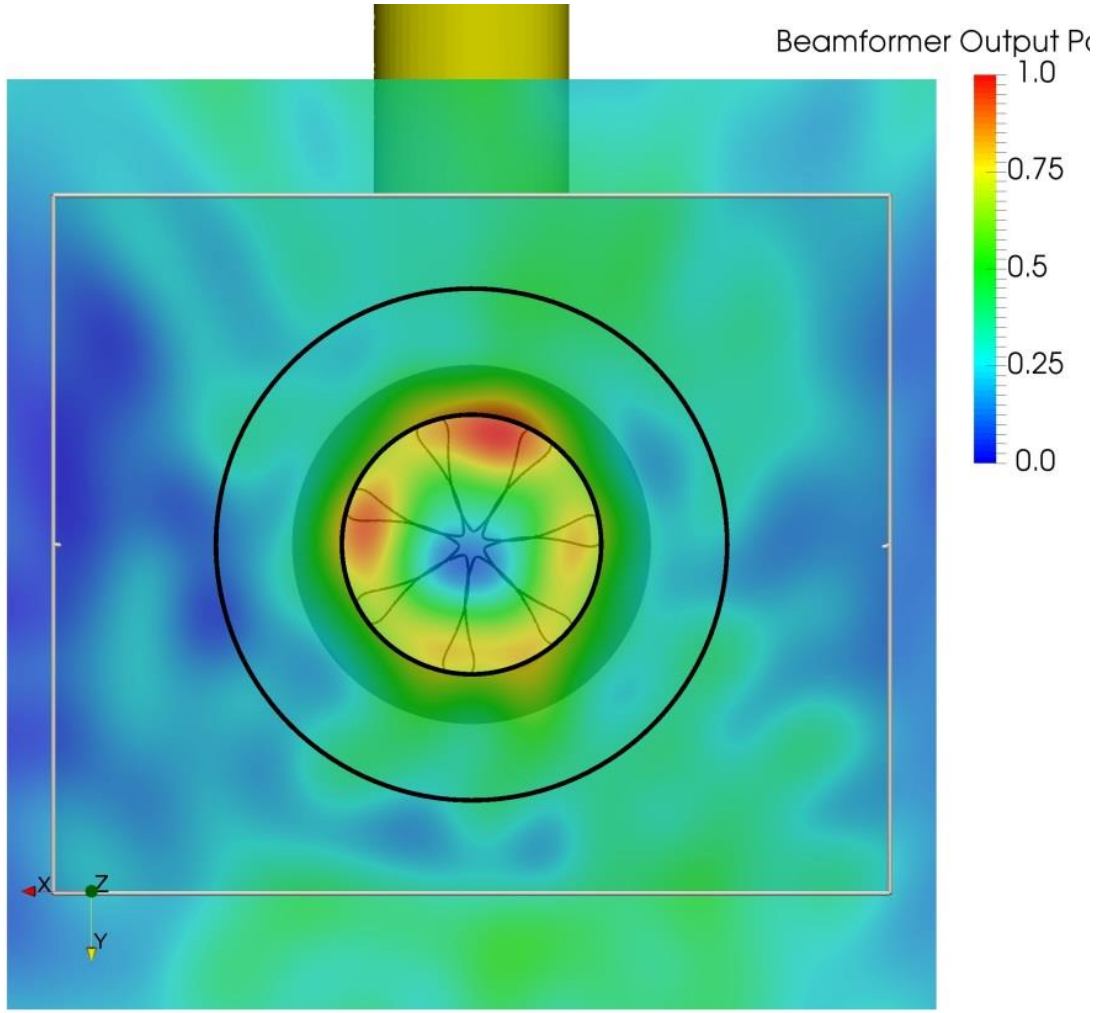
Inline thruster during operation



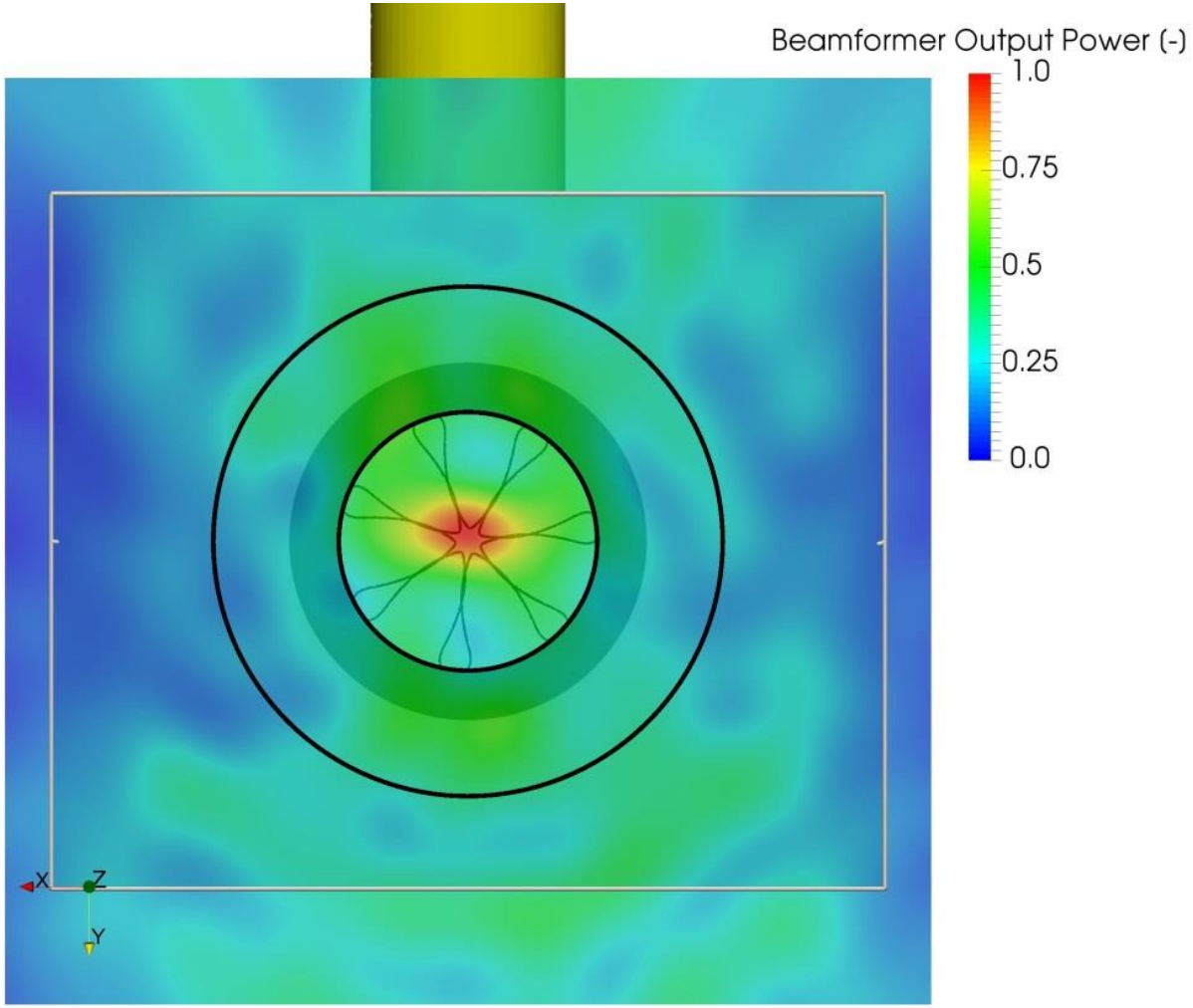


MVDR Beamformer: frequency = 6915 Hz; $f_{Rotation}$= 13.1 Hz

Results Topic 2
Beamforming results



MVDR Beamformer: frequency = 8943 Hz; $f_{Rotation}$= 13.1 Hz



MVDR Beamformer: frequency = 9856 Hz; $f_{Rotation}$= 13.1 Hz

Conclusions

Summary

- DES-SBES simulation of the hubless propeller was done for J=0
- hydrodynamic wall pressure fluctuations of the SBES were validated by experimental data and showed an acceptable accordance
- good correlation between the hydro acoustic spectrum and the wall pressure spectrum
- POD analysis was applied to the wall pressure field and the entire 3D flow field to seperate different coherent flow structures → identification of wall pressure oscillations patters on the rotor blade caused by flow separation at the leading edge (f/n = 30, 60 and 154)
- development of a measurement procedure to analyze rotating noise sources on a hubless propeller system → further development steps are still needed

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Thank you for your attention!