Hydro Acoustic Noise Emission of Hubless Propellers

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Outline

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

**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

Hubless propeller (RIM – drive)
Outline

1. Introduction
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CFD Setup and Methods
meshing for URANS and DES - SBES

**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

<table>
<thead>
<tr>
<th></th>
<th>cells [M]</th>
<th>angle [°]</th>
<th>aspect ratio</th>
<th>volume change</th>
<th>y+</th>
<th>°/TS [s]</th>
<th>revolutions</th>
<th>n [s⁻¹]</th>
<th>J</th>
</tr>
</thead>
<tbody>
<tr>
<td>URANS</td>
<td>20</td>
<td>&lt; 18</td>
<td>&lt; 60 (95%)</td>
<td>&lt; 10</td>
<td>&lt; 30</td>
<td>1</td>
<td>10</td>
<td>variable</td>
<td>0, 0.43-0.7</td>
</tr>
<tr>
<td>DES-SBES</td>
<td>33 - 95</td>
<td>&lt; 27</td>
<td>&lt; 60 (95%)</td>
<td>&lt; 8</td>
<td>2 - 0.5</td>
<td>0.5 - 0.25</td>
<td>5</td>
<td>16.9</td>
<td>0</td>
</tr>
</tbody>
</table>
CFD Setup and Methods

general workflow for noise prediction

Hybrid approach:
1\textsuperscript{st} step: CFD for incompressible flow
2\textsuperscript{nd} step: Computation of acoustics

Splitting of the variable
\( p = p^\text{ic} + p^\text{a}, \quad u = u^\text{ic} + u^\text{a}, \quad \rho = \rho^0 + \rho^\text{a} \)
\( \square^\text{ic} = \text{incompressible flow part}, \)
\( \square^\text{a} = \text{compressible, propagable acoustical part} \)

Perturbed Convective Wave Equation (PCWE)
\[
\frac{D^2 \psi^a}{Dt^2} - c_0^2 \Delta \psi^a = -\frac{1}{\rho_0} \frac{D p^\text{ic}}{D t} \quad \text{with} \quad \frac{D}{D t} = \frac{\partial}{\partial t} + (u^\text{ic} \cdot \nabla)
\]
Acoustic potential \( \psi^a \) with \( u^a = -\nabla \psi^a \)
Sound pressure \( p^a = \rho_0 \frac{D \psi^a}{D t} \)
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 $\varphi$ is known at K time instances $t_i$

\[
\varphi = \bar{\varphi} + \varphi' = \bar{\varphi} + \tilde{\varphi} + \varphi''
\]

Galerkin approximation:

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

Eigenvalue problem:

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

Correlation matrix:

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

POD time coefficient:

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

POD modes:

\[
M_k = \frac{1}{\sqrt{K \cdot \lambda_k}} \sum_{i=1}^{K} b_k(t_i) \cdot \varphi'(x, t_i) \quad i = 1, 2, \ldots, K
\]
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MVDR Beamformer: frequency = 9865 Hz; $f_{\text{Rotation}} = 13.1$ Hz
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

$$n \cdot I_s - I_{probe} \rightarrow \text{min}$$

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

- Wave front

- **Advantage AVS:** separation of coherent sources is possible up to approximately $D = \lambda$

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

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

\[ R_{\text{Ref},\text{Hydro}} = S_{\text{Ref}}(\omega)^* \cdot S_{\text{Hydro}}(\omega) \]

phase angle

\[ \alpha(\omega) = \text{atan}(\frac{\text{Im}g(R_{\text{Ref},\text{Hydro}}))}{\text{Re}a l(R_{\text{Ref},\text{Hydro}}))} \]

- 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
Measurement Setup – preliminary tests for field measurement campaign of Topic 2 \(\rightarrow\) acoustic source localization
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
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Results Topic 1
narrow band order spectrum

top row: wall pressure fluctuations
bottom: hydro sound pressure level

\[ p_{d,\text{ref}} = (\omega R)^2 \cdot \frac{\rho}{2} \]

reference acoustic pressure
\[ \tilde{p}_{\text{ref}} = 10^{-6} \text{Pa} \]

\[ p_{d,\text{ref}} = 10^{-6} \text{Pa} \]
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
Results Topic 1
wake flow structures
iso-surfaces: $Q/n^2 = 35$ color: vorticity $X$
Results Topic 1

wake flow structures – clip r/R = 0.9

iso-surfaces: Q/n² = 35 color: vorticity X
Results SBES 93Mio
wake flow structures
iso-surfaces: $Q/n^2 = 35$ color: vorticity $X$
Results Topic 1
POD wall pressure mode (top)
recombined POD wall pressure modes (bottom)
Results Topic 1
recombined POD wall pressure modes

\[ \frac{p'}{p_{ref}} \]

\[ f/n = 8; 2^{\text{th}} \text{ BPF order} \]

\[ f/n = 10.5 \]

\[ f/n = 12; 3^{\text{th}} \text{ BPF order} \]

\[ \frac{p'}{p_{ref}} \]

feedback loop

leading edge duct

Separation Region
Blade

leading edge separation

\[ U_x \]

\[ \frac{\alpha_x}{n} \]
Results Topic 1
POD-pressuremode 2 - clip r/R = 0.9
f/n = 4
Results Topic 1
POD-pressure mode 44 - clip r/R = 0.9
f/n = 12
Results Topic 2
narrow band order spectrum
hydro sound pressure level in dB re(1\cdot10^{-6} \text{ Pa})
n = 787 \text{ 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} \text{ Pa})
n = 787 \text{ min}^{-1}

related to components of the electrical drive

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

- 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; \( f_{\text{Rotation}} = 13.1 \) Hz
Results Topic 2
Beamforming result
“acoustic cavitation signature”

Inline thruster during operation

MVDR Beamformer: frequency = 6915 Hz; \( f_{\text{rotation}} \) = 13.1 Hz
Results Topic 2
Beamforming results

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

MVDR Beamformer: frequency = 9856 Hz; $f_{\text{Rotation}} = 13.1$ 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 separate different coherent flow structures → identification of wall pressure oscillations patterns 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

• **Menter, F. R.:** Best Practice: Scale-Resolving Simulations in ANSYS CFD. ANSYS GERMANY GmbH, Nov. 2015.


Thank you for your attention!