PARAMETRIC NUMERICAL STUDY ON THE IMPACT OF STEADY COSINE INFLOW DISTORTIONS ON TONAL ROTOR-STATOR INTERACTION NOISE

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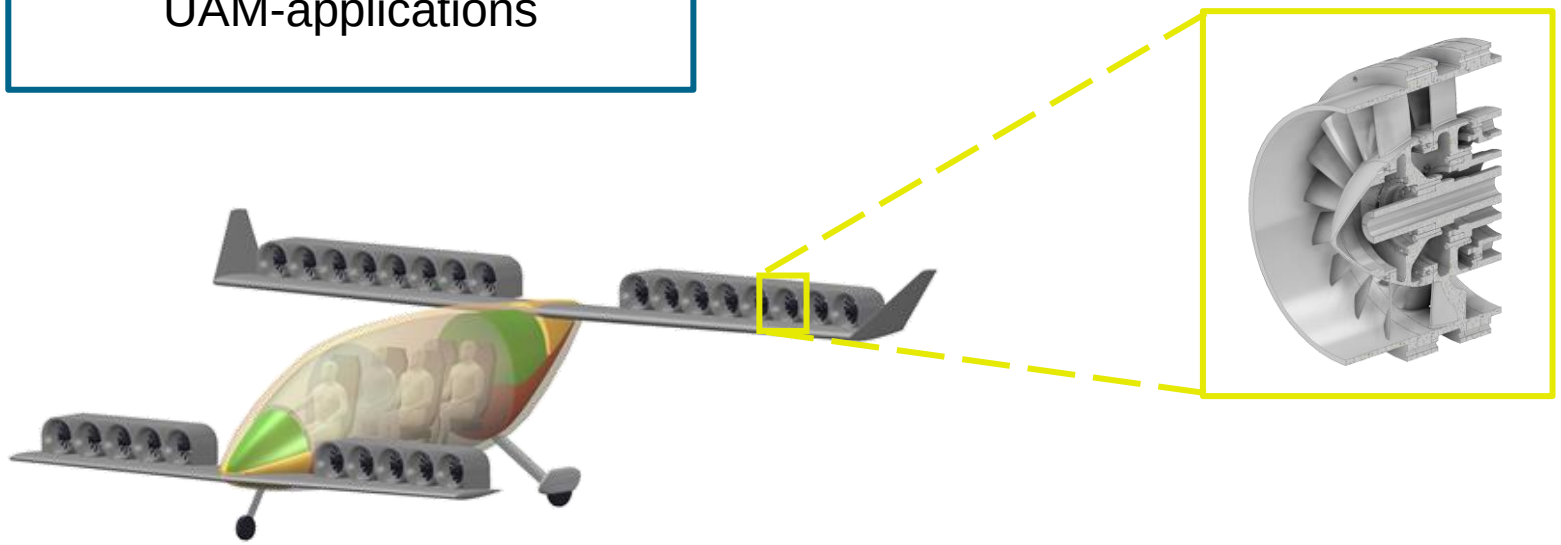
DLR

Air Mobility Context

shrouded low-speed fans for UAM-applications

low speed fan stage



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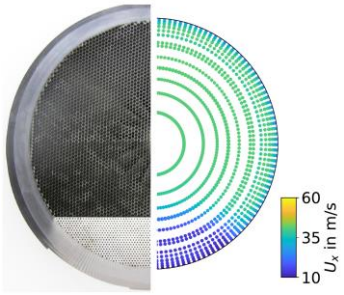
sketch of tilt duct vehicle configuration with simplified fan housings contour
(Credits: P. Ratei, SL-AES)

variable	value (DP)
Ma_{tip}	0.31
$Ma_{x,outlet}$	0.17
$\phi = \frac{U_x}{U_{tip}}$	0.33
Q_c	6.98 kg/s
PR	1.038
N_c	4500 rpm

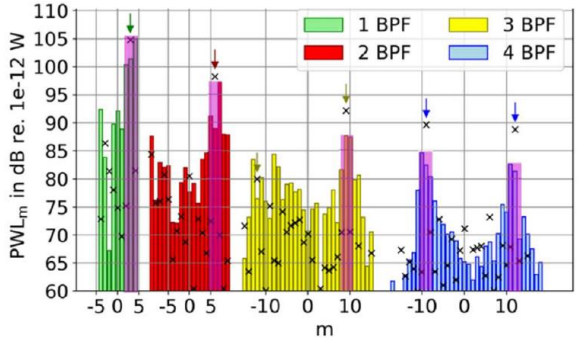
CRAFT: Co/Counter Rotating Acoustic Fan Test-Rig

CRAFT-Rig:

experimental data

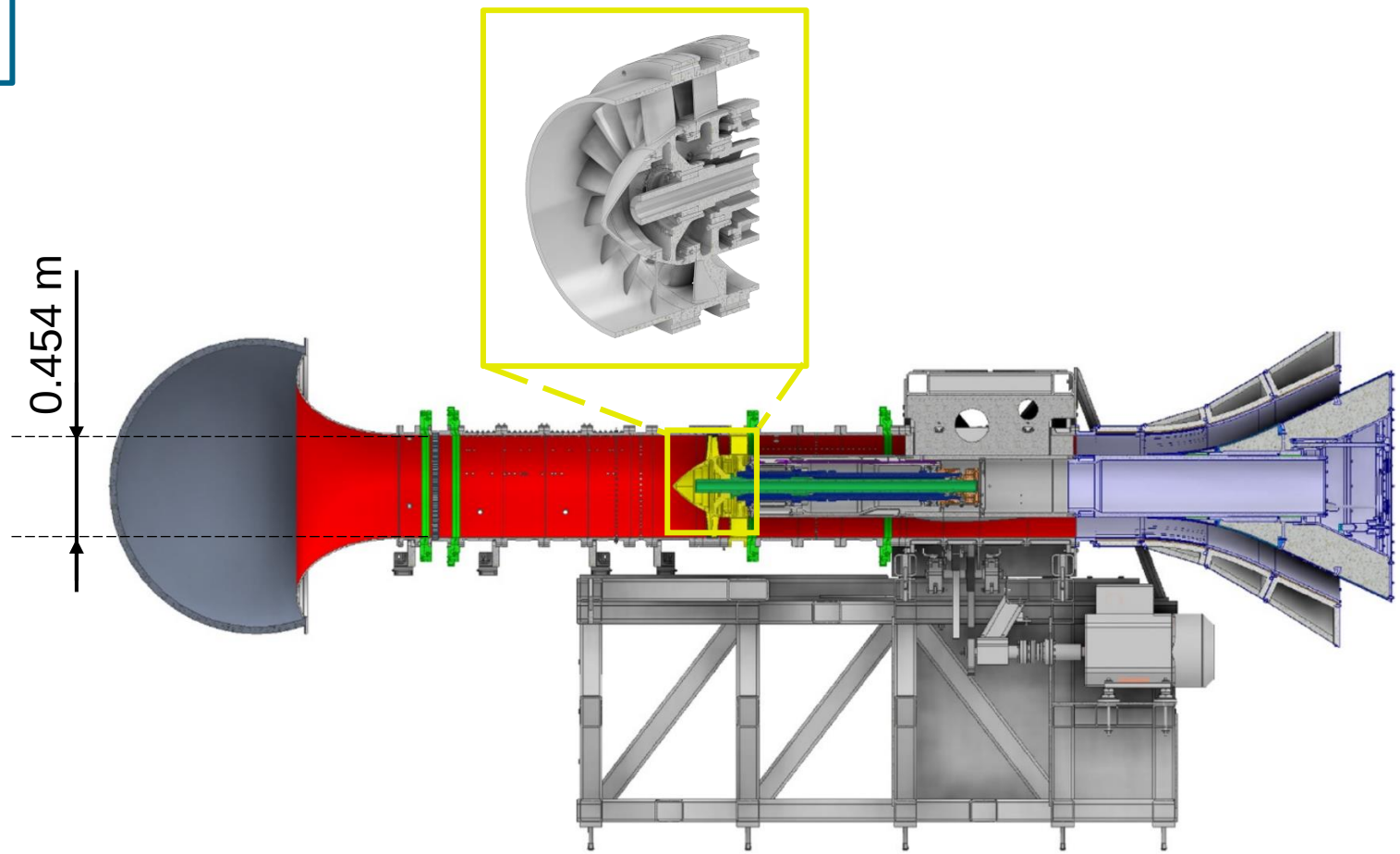


Aerodynamic measurements [1]



Acoustic measurements [2]

low speed fan stage

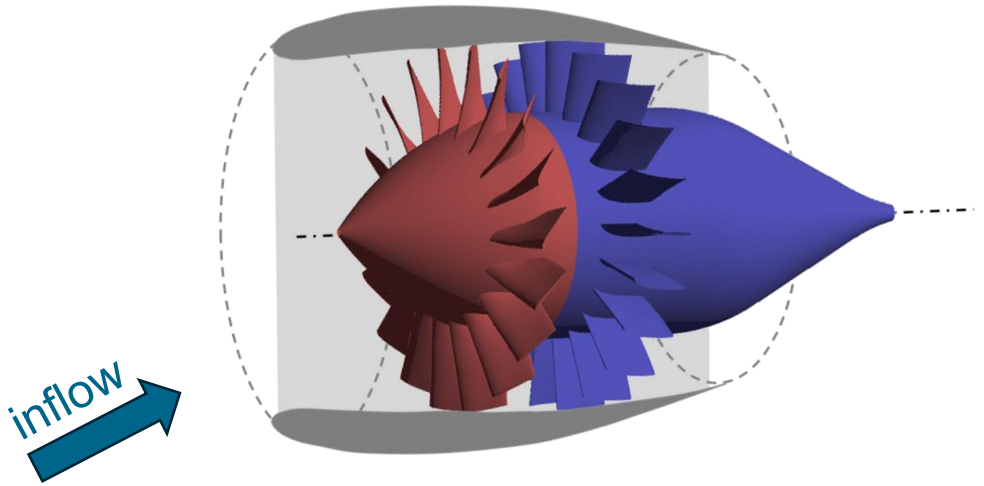


CRAFT-rig of the DLR Institute of Propulsion Technology [3]

Problem Description

„What is the influence of inflow distortion on tonal fan noise for a low-speed fan?“

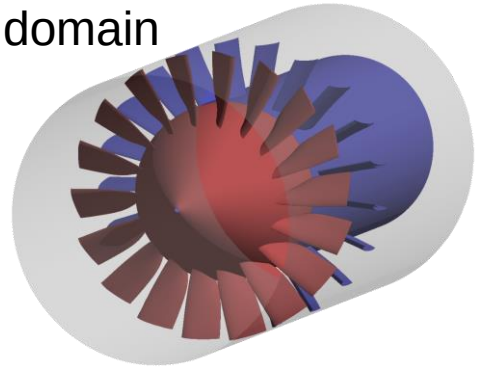
→ future aim: unsteady 3D simulations

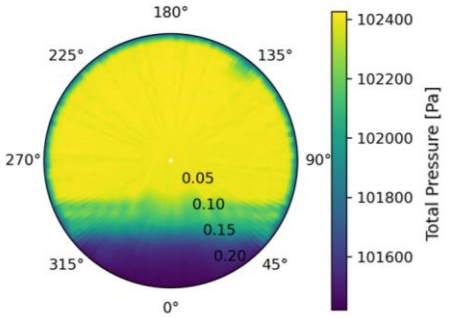


→ in this study: simplified problem for physical understanding

Methodology

3D
domain





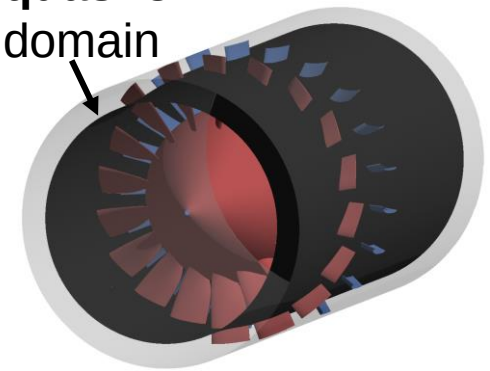
measured inflow distortion

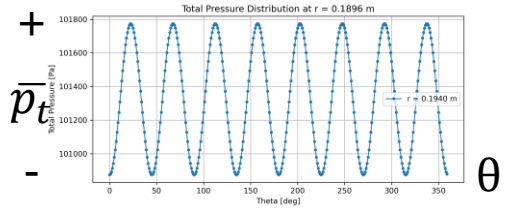
representative problem

reduction of complexity

numerical setup / best-practices

quasi-3D
domain

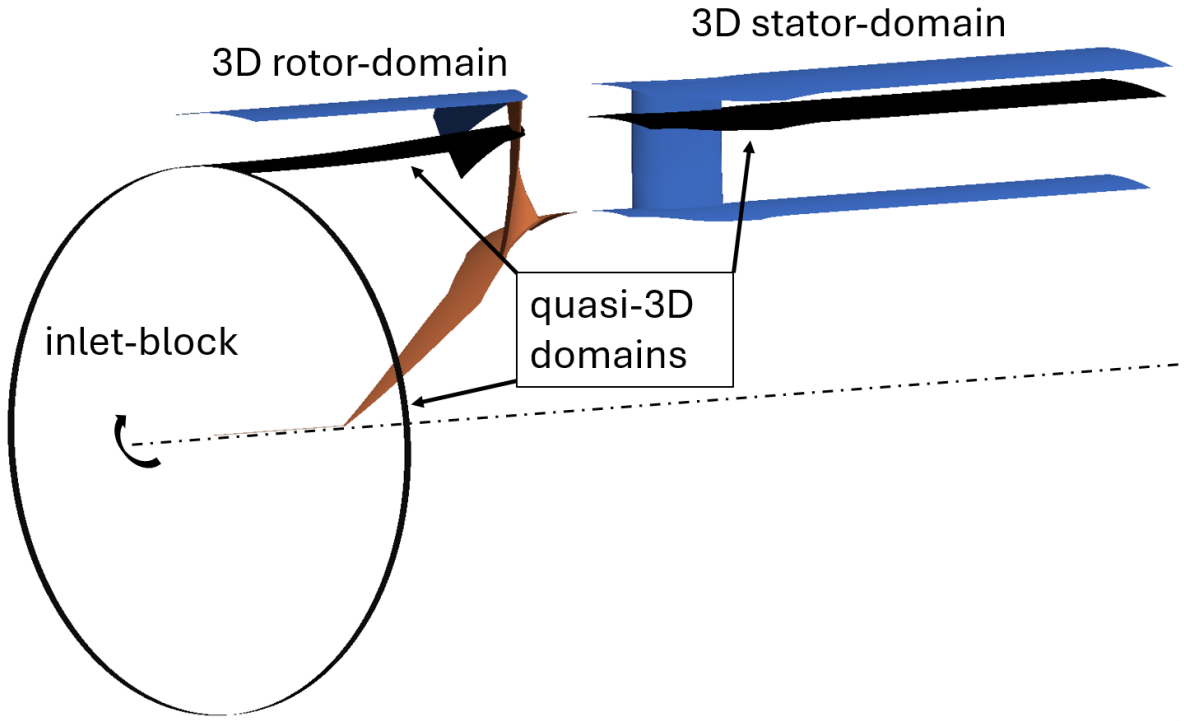




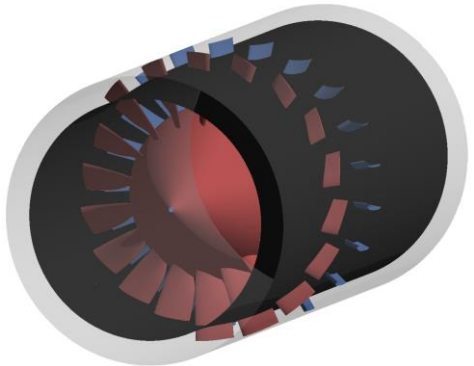
generic cosine inflow distortions

simplified problem

Numerical Setup

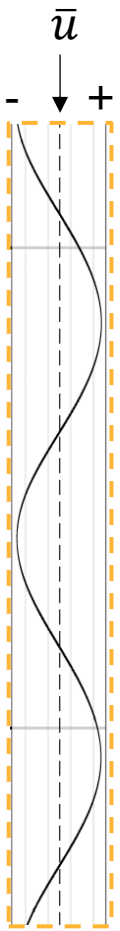


numerical simulations with
TRACE Harmonic Balance (HB):
hybrid frequency domain approach



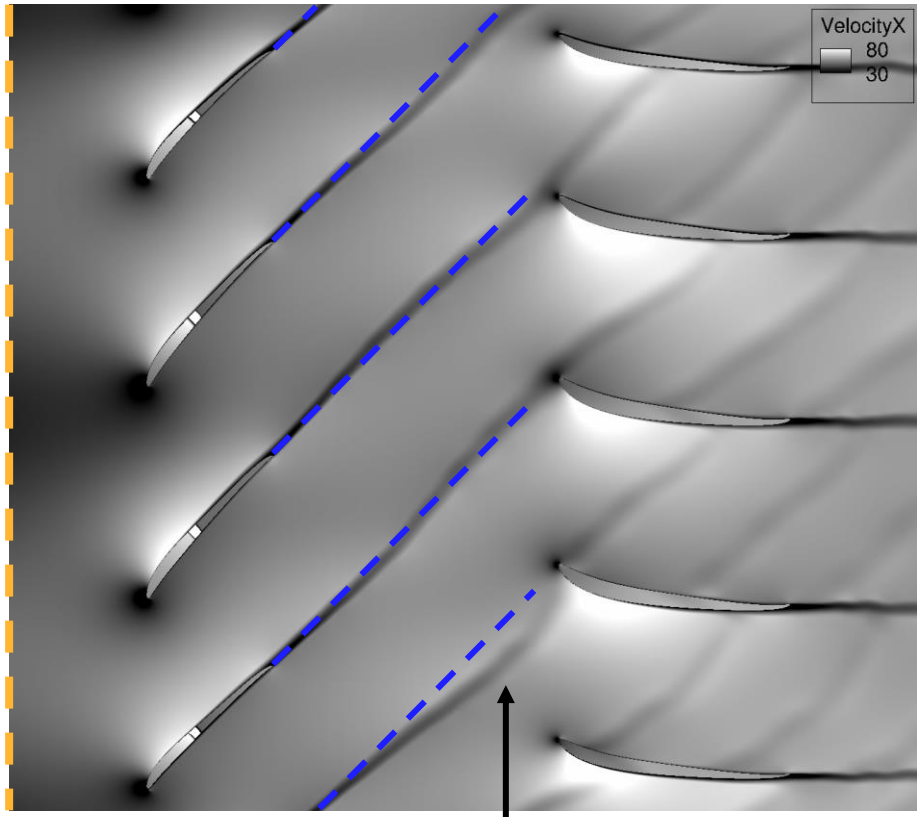
streamtube at
70% rotor height

Rotor-Stator Interaction



rotor
with B blades

stator
with V vanes



inflow velocity
with modal
content m_0

modulated
rotor wakes

aerodynamic excitation:
rotor wakes

acoustic response
at stator

undisturbed spectral
wake content

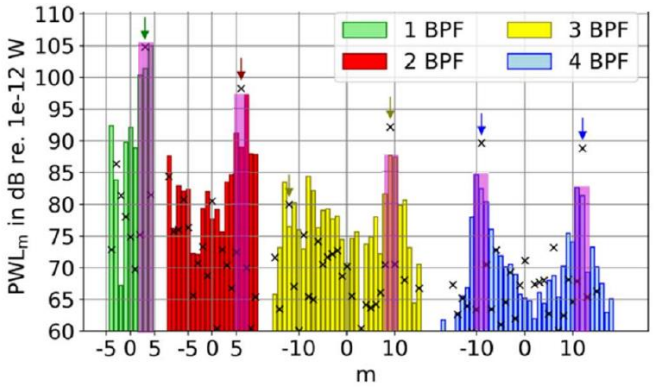
$m_1 = hB$

RSI Tyler-Sofrin
modes

$m = m_1 + kV$
with $m_1 = hB$

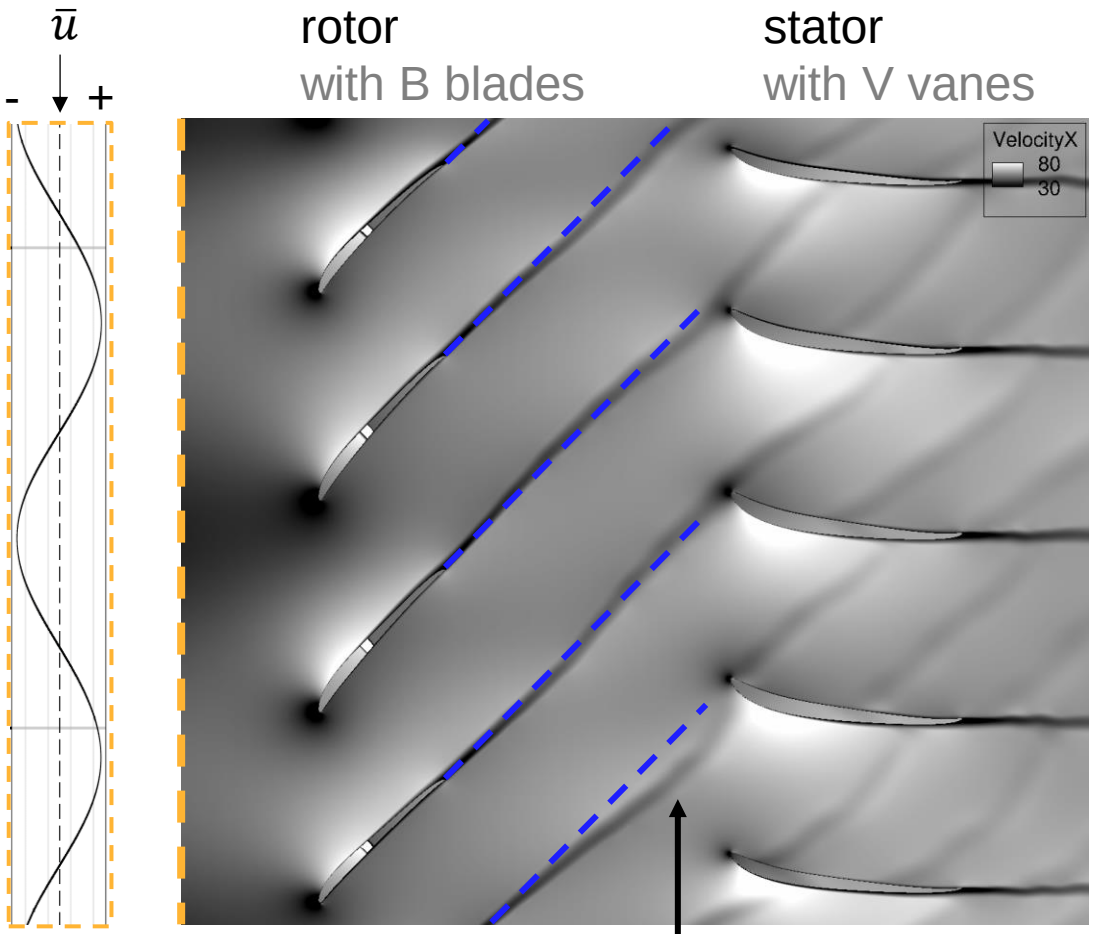
additional spectral wake
content due to interaction

additional
RSI-modes



Acoustic measurements [2]

Rotor-Stator Interaction



aerodynamic excitation:
rotor wakes

acoustic response
at stator

undisturbed spectral
wake content

$m_1 = hB$

RSI Tyler-Sofrin
modes

$m = m_1 + kV$
with $m_1 = hB$

additional spectral wake
content due to interaction

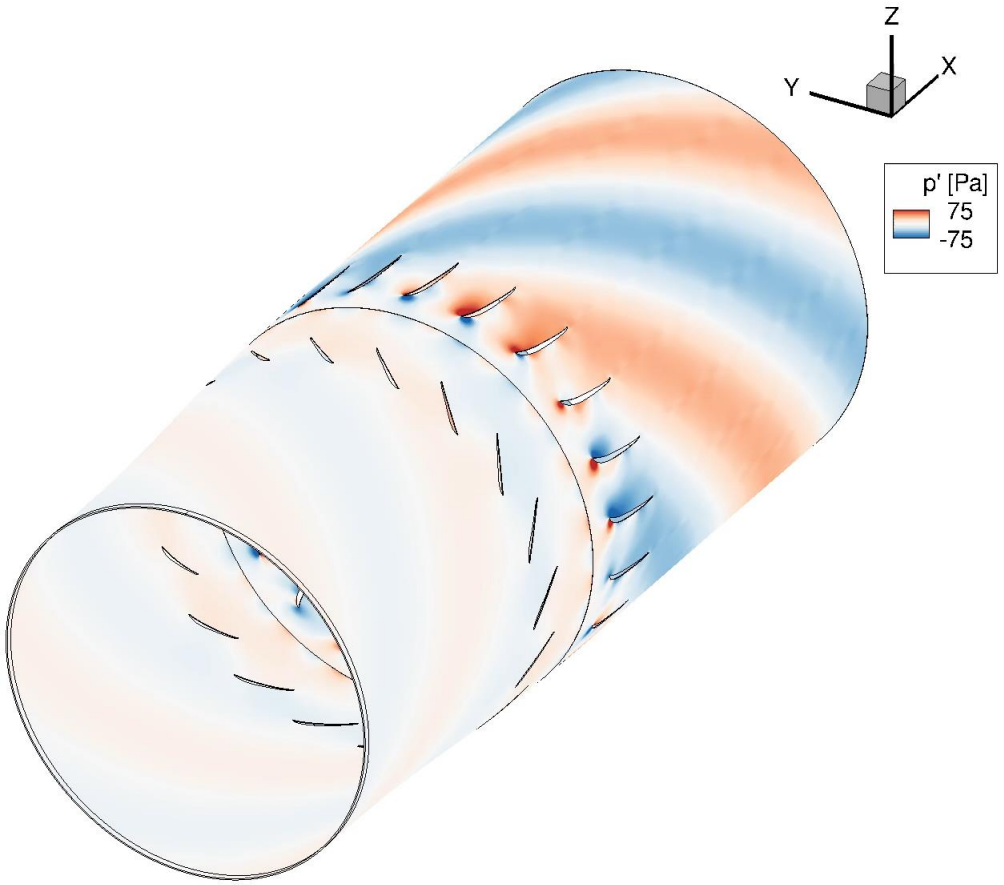
$m_1 = -|m_0| + hB$

$m_1 = |m_0| + hB$

additional
RSI-modes

$m = m_1 + kV$
with $m_1 = \pm|m_0| + hB$

Rotor-Stator Interaction



pressure fluctuations at BPF,
clean inflow

aerodynamic excitation:
rotor wakes

acoustic response
at stator

undisturbed spectral
wake content

$m_1 = hB$

RSI Tyler-Sofrin
modes

$m = m_1 + kV$
with $m_1 = hB$

e.g.: fan stage with 18 blades (B)
and 21 vanes (V) at BPF:

$m_1 = 18$

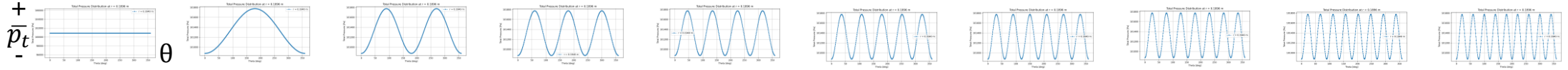
$m = 18 - 21 = -3$

Modal Variation Study Setup

- numerical inlet: generic steady inflow distortion:

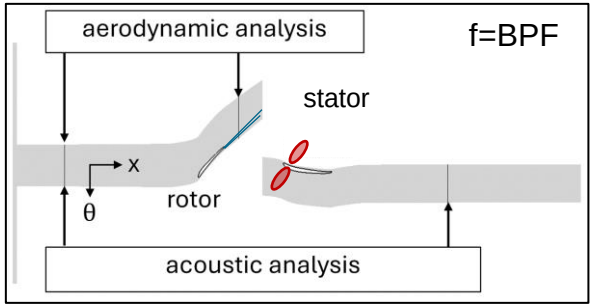
  →pure cosine variation: $p_t'(\theta) = A\cos(m_0\theta)$ with $m_0 \in [0, 9]$

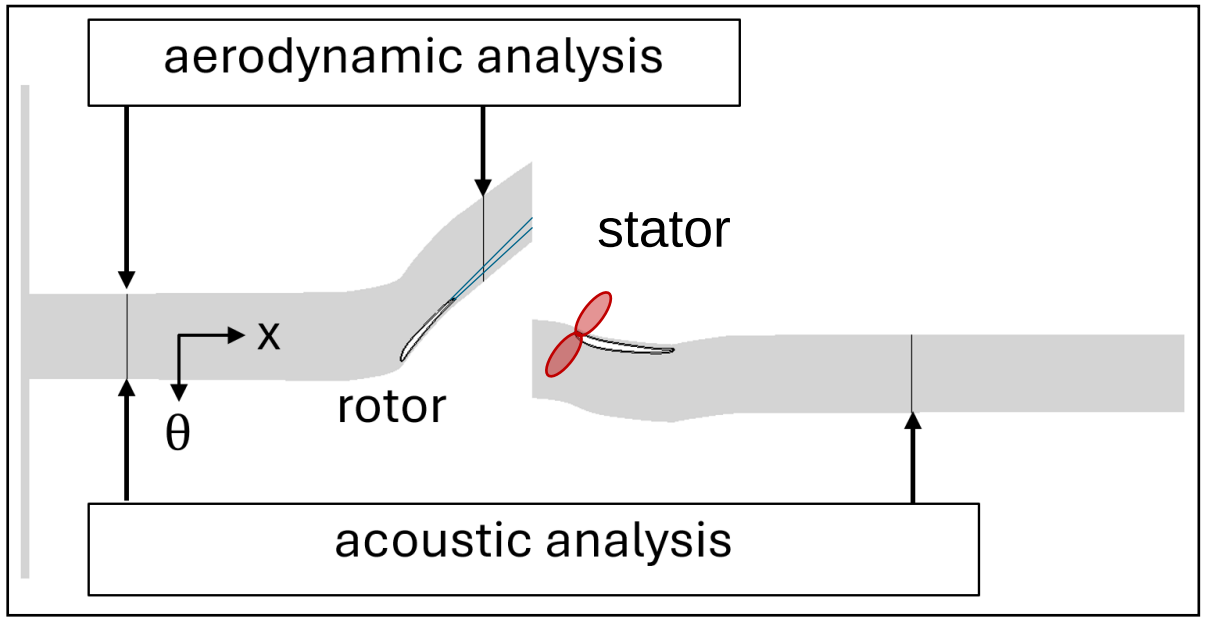
m_0 = 0 (clean) 1 2 3 4 5 6 7 8 9



→ 10 HB simulations

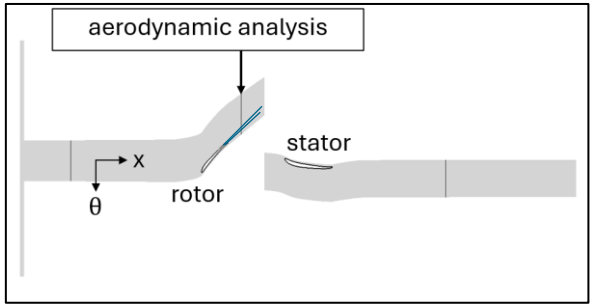
Methodology – Evaluation

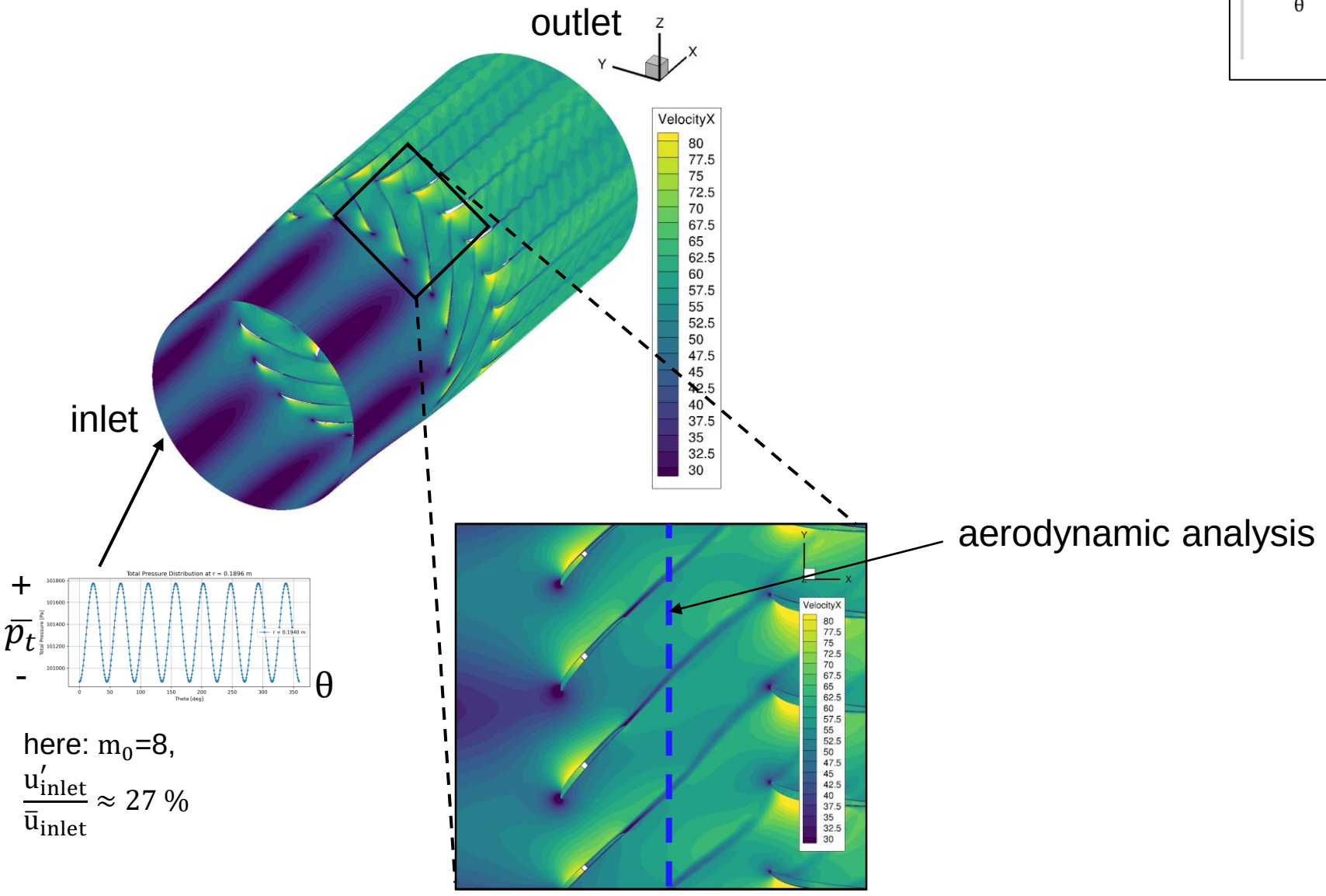




evaluation of results:
information for
current slide

Results – Case Study for m_0=8

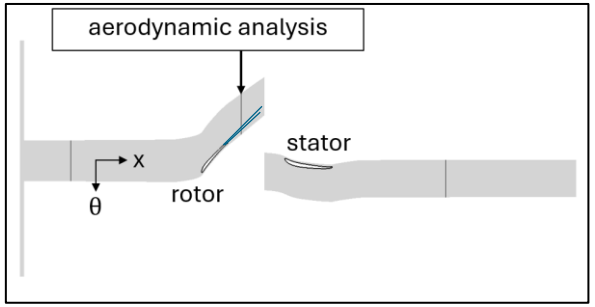




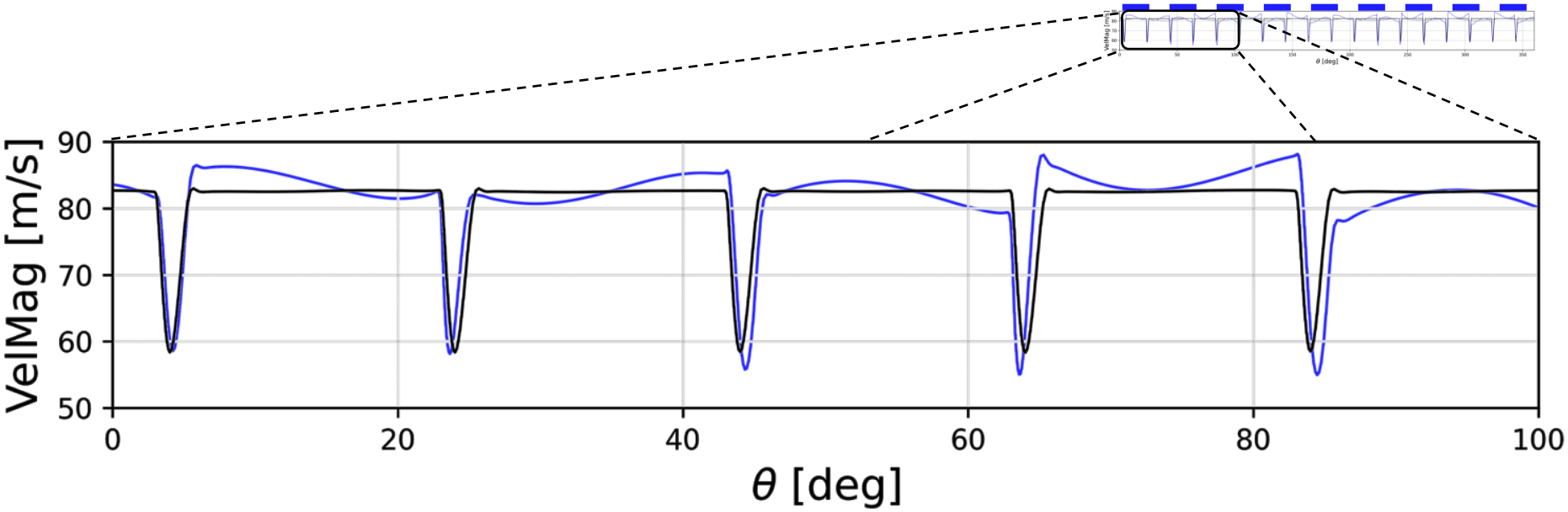
here: m_0=8,

$\frac{u'_{inlet}}{\bar{u}_{inlet}} \approx 27\ \%$

Results – Case Study for m_0=8

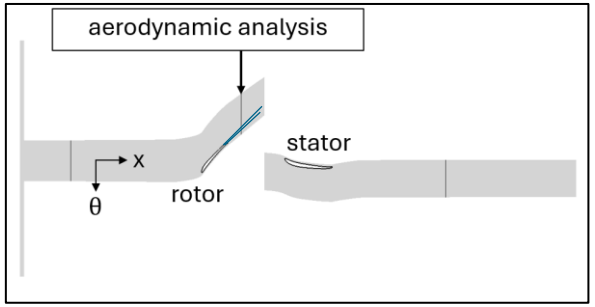


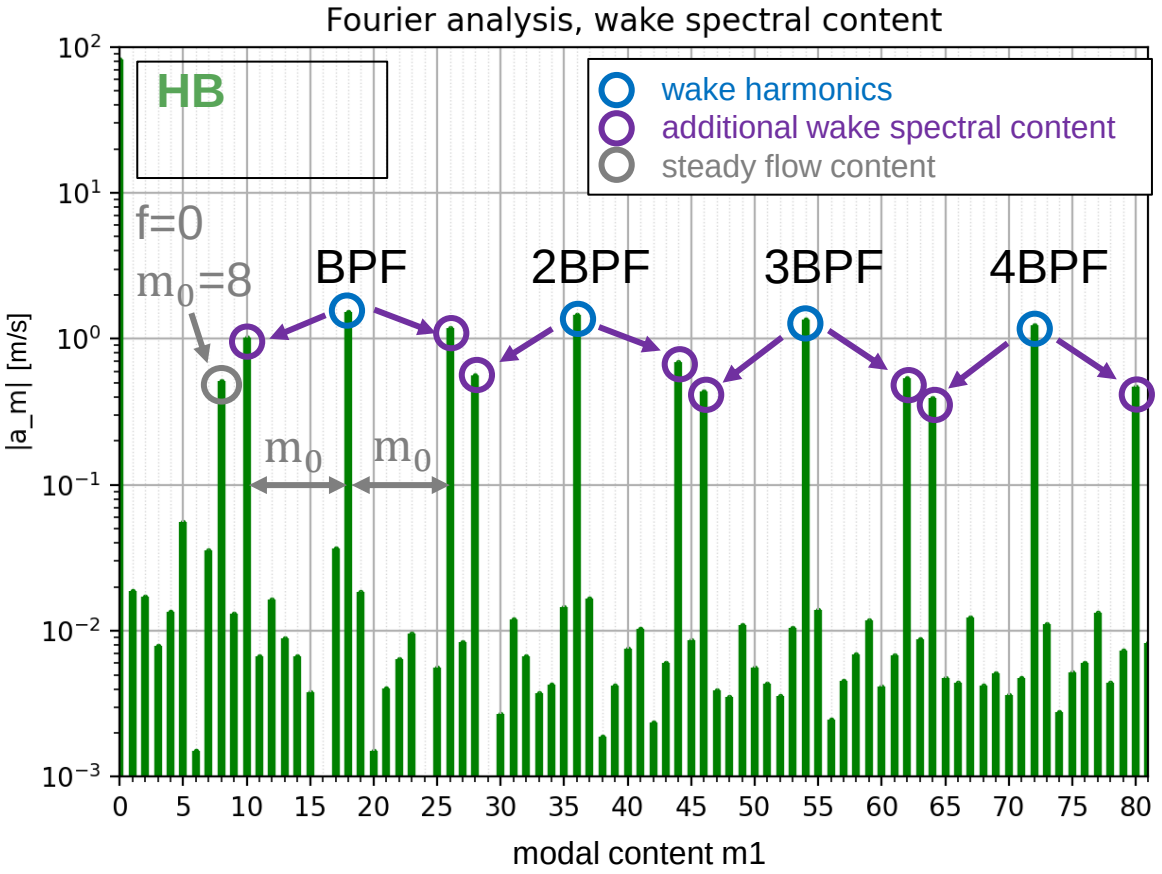
— modulated wakes due to inflow distortion with m_0=8
— rotor wakes with clean inflow



Fourier analysis
→ spatial spectral rotor wake content

Results – Case Study for m_0=8





Inflow distortion

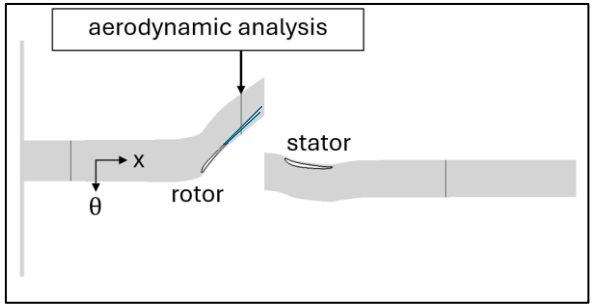
↑

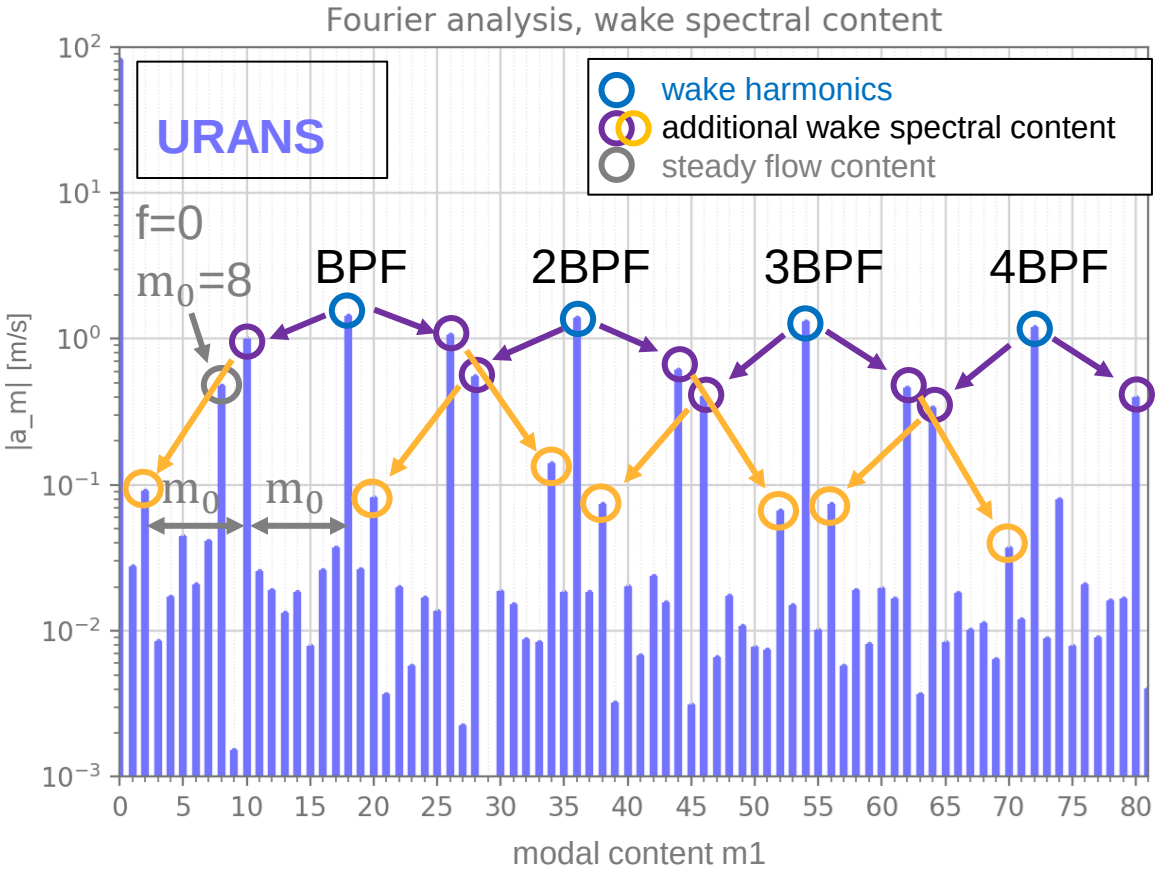
↓

rotor interaction:

- first order

Results – Case Study for m_0=8





Inflow distortion

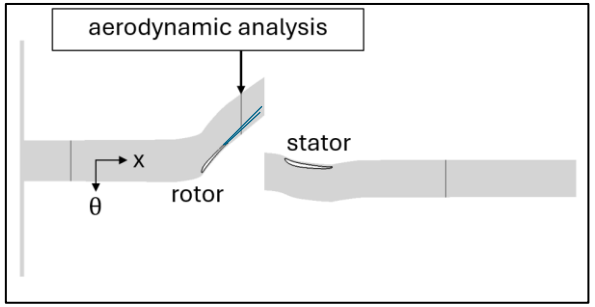
↑

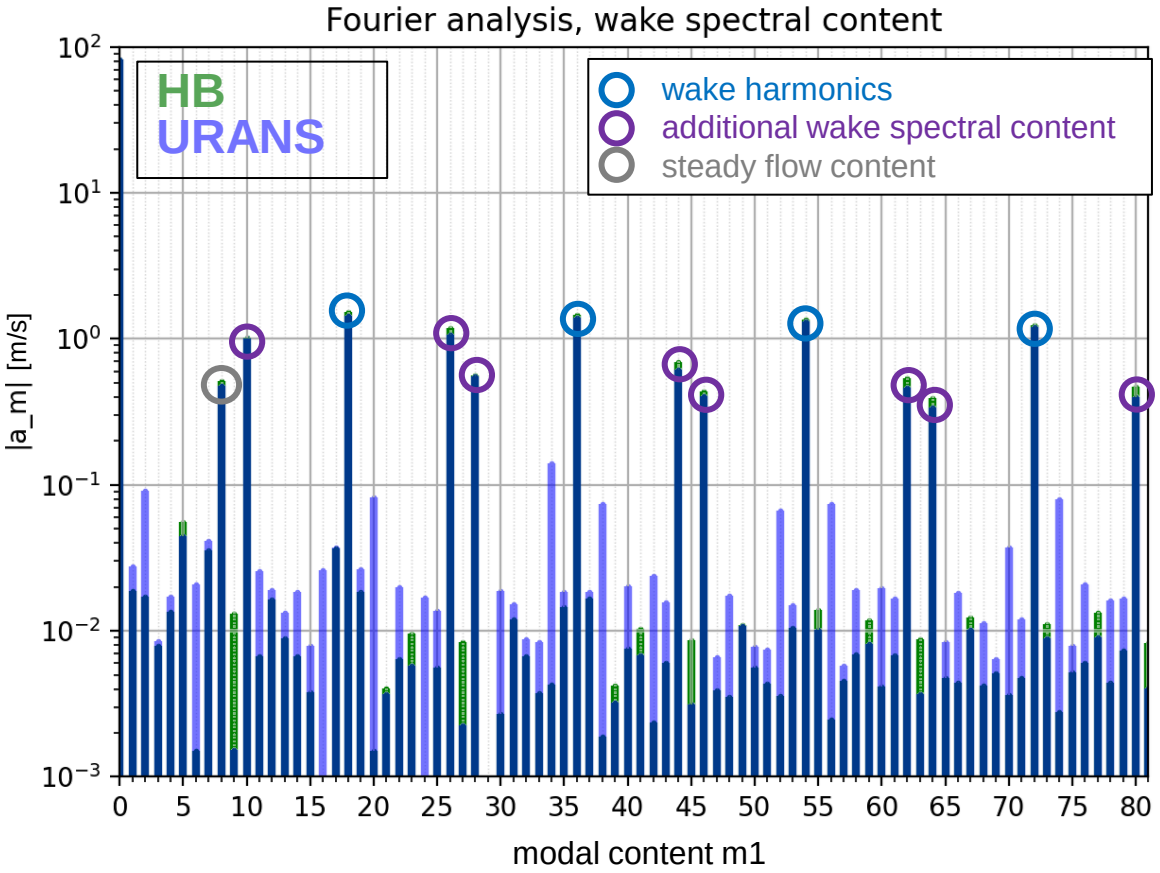
↓

rotor interaction:

- first order
- second order

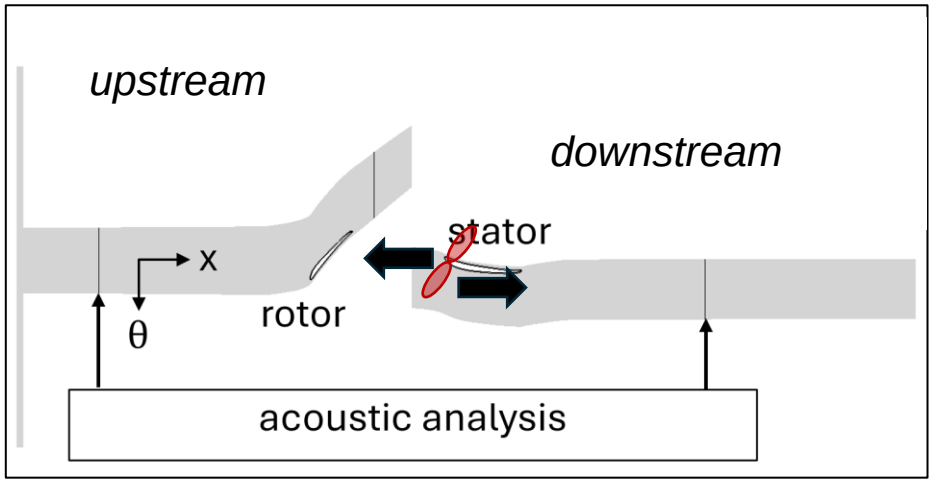
Results – Case Study for m_0=8



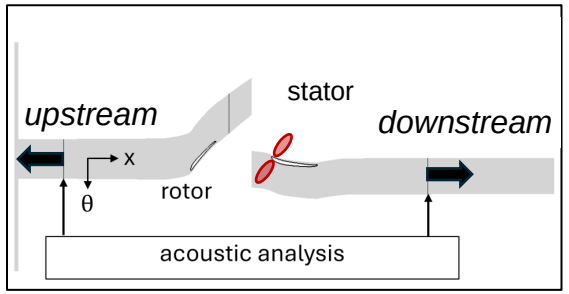


Inflow distortion
↑
↓
rotor interaction:
in this study: limitation to
first order interactions

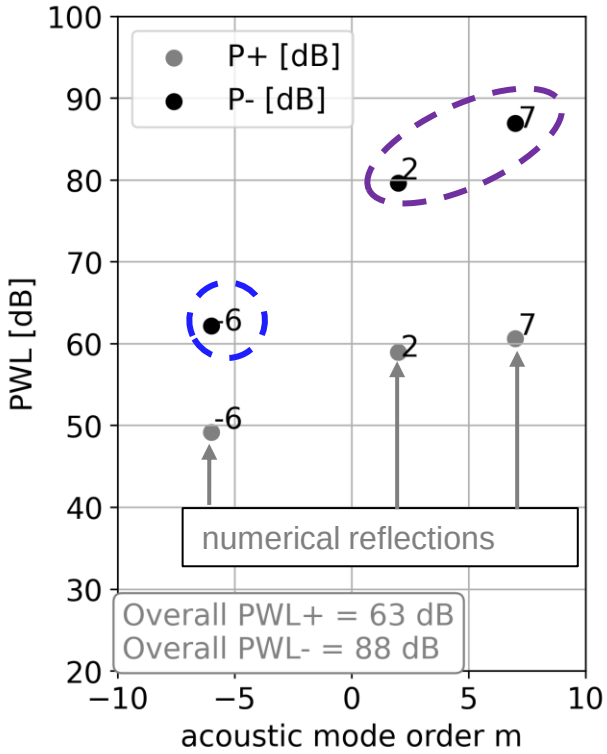
Results – Case Study for m_0=8



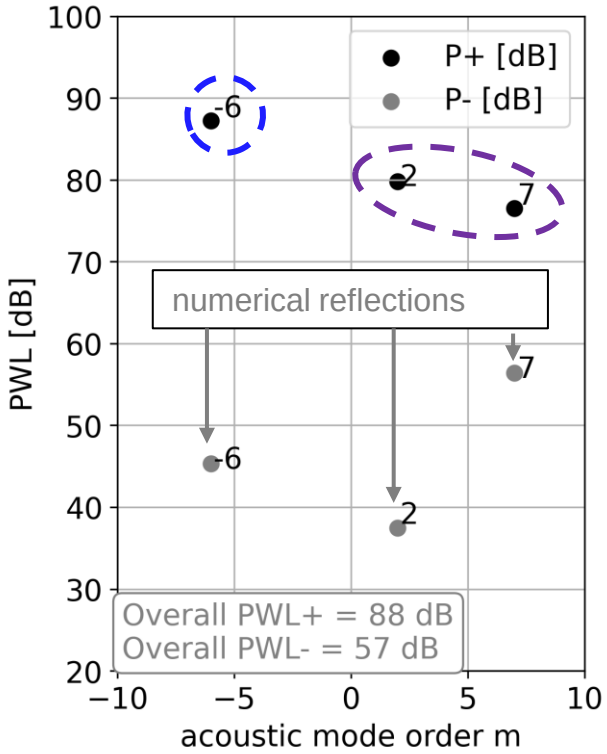
Results – Case Study for m_0=8



2BPF upstream



2BPF downstream



RSI Tyler-Sofrin modes

$m = m_1 + kV$
with $m_1 = hB$

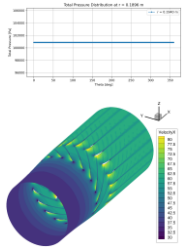
additional RSI-modes

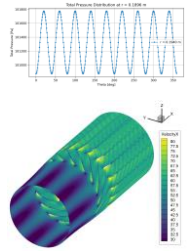
$m = m_1 + kV$
with $m_1 = \pm|m_0| + hB$

Results – Modal Variation Study

steady inflow with variation of modal content m_0 along θ

m_0 = 0 (clean) … 9



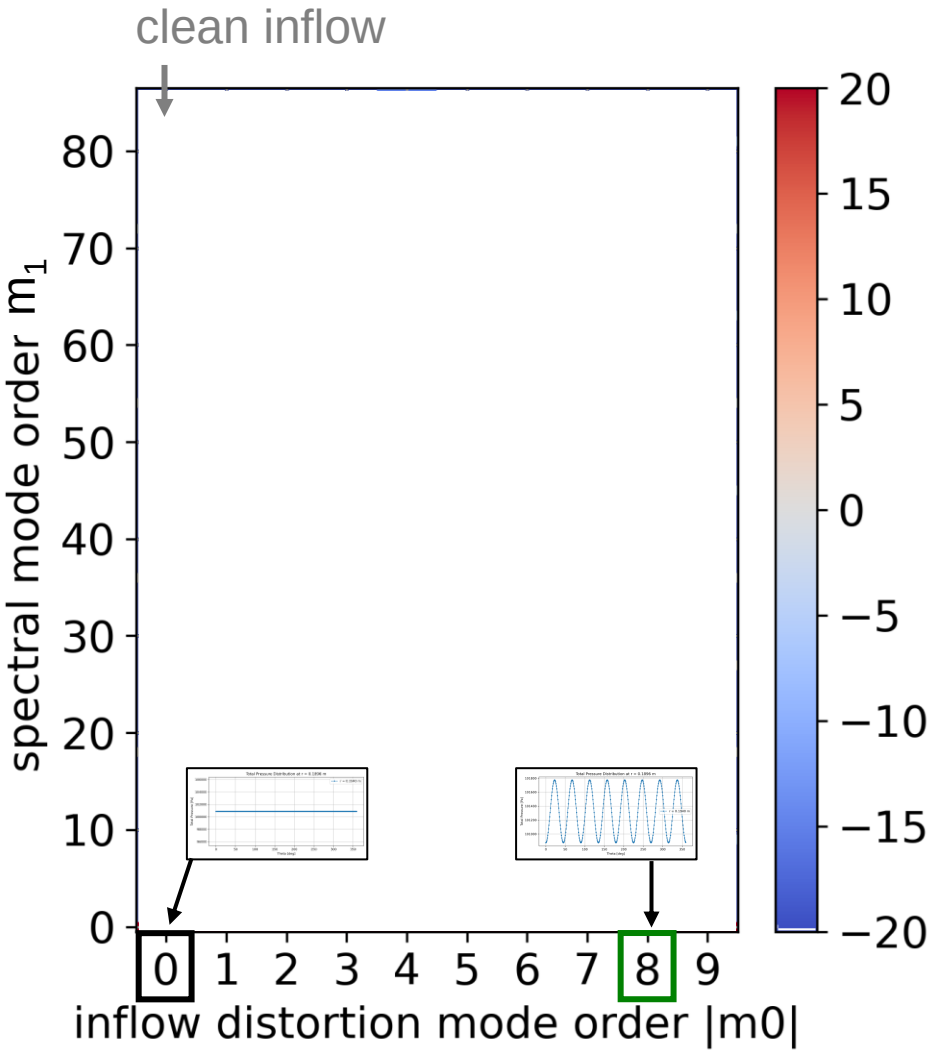


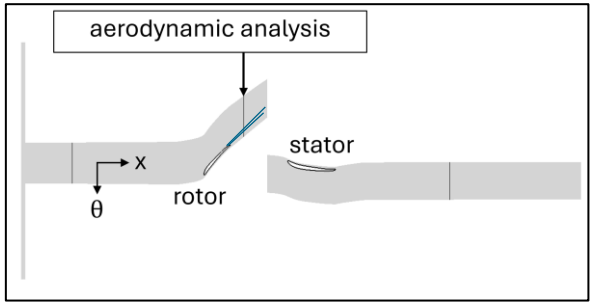
→ 10 HB simulations

Analysis of

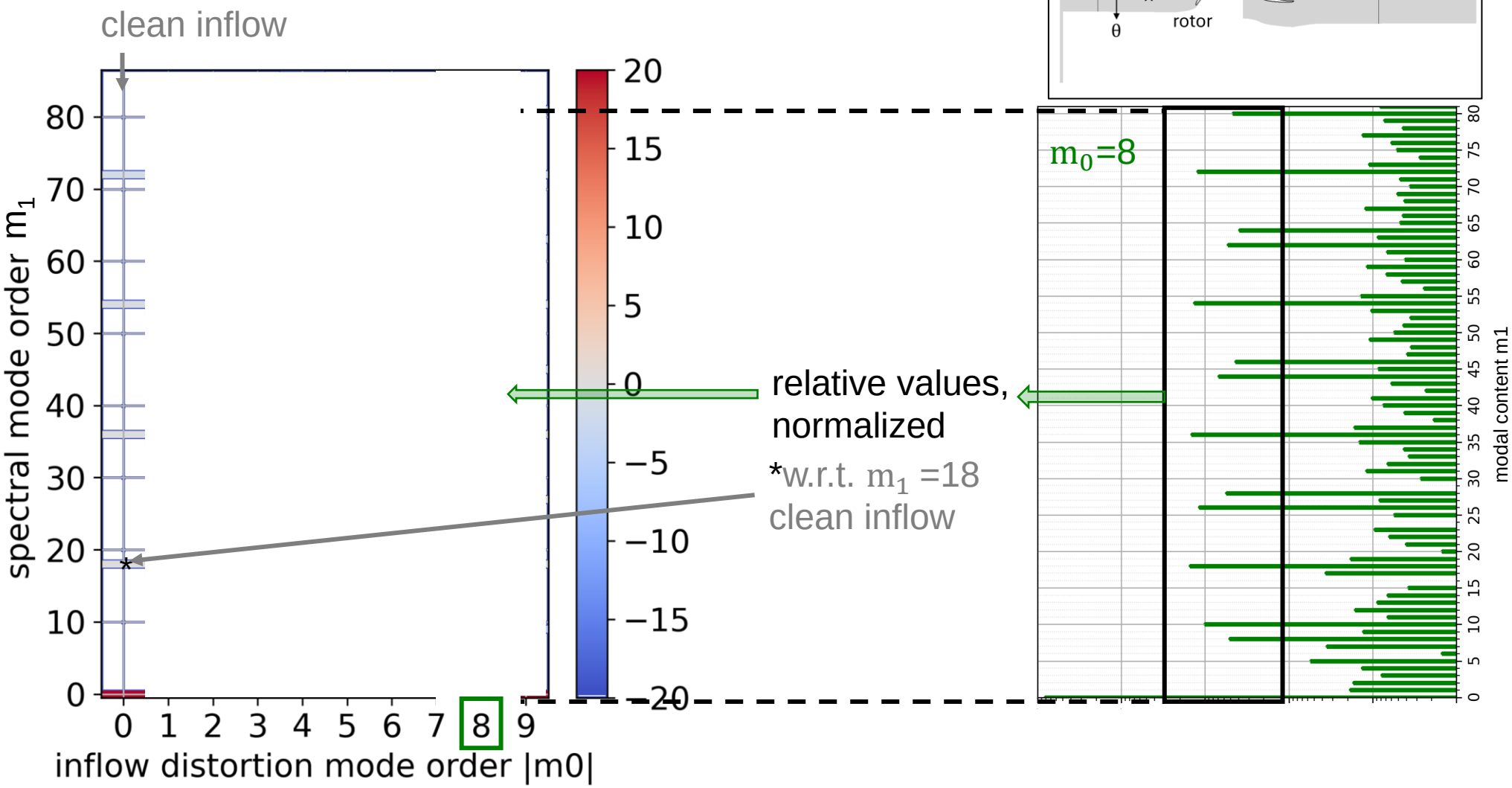
1. aerodynamic exciation: rotor wakes
2. acoustic mode excitation strength

Results – Modal Variation Study





Results – Modal Variation Study



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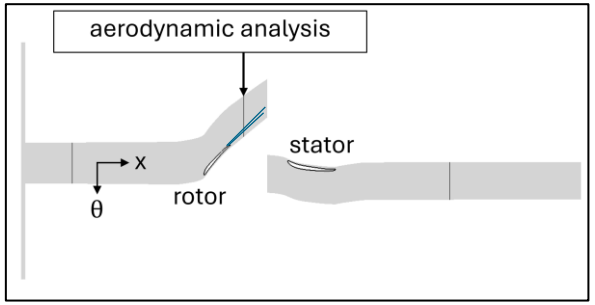

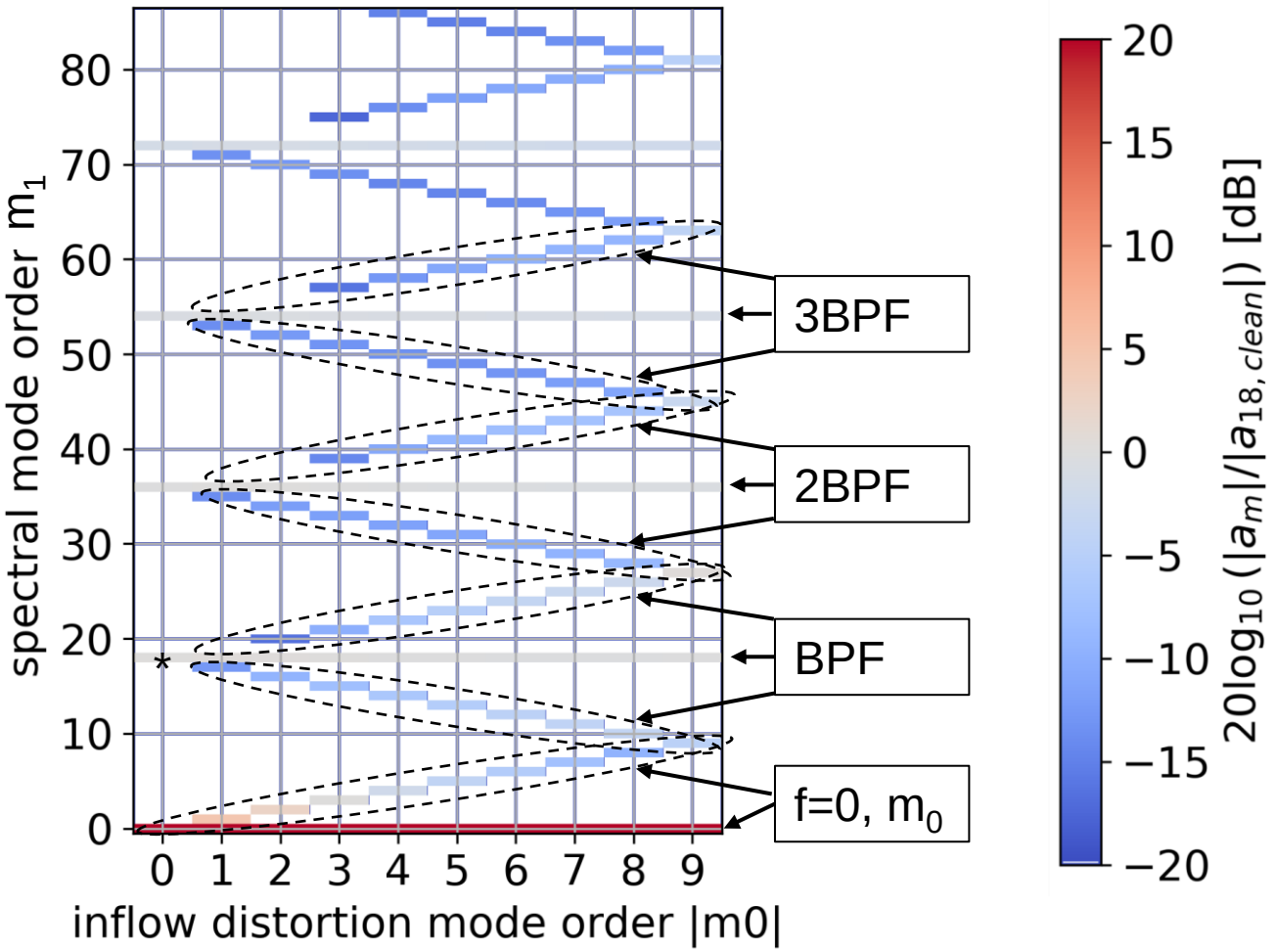

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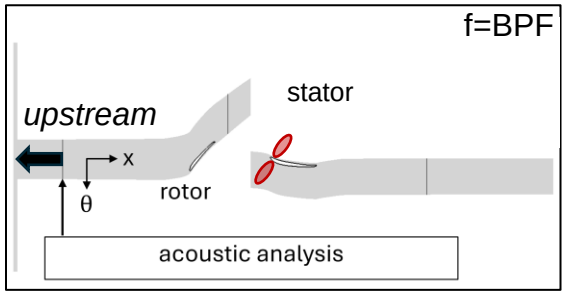
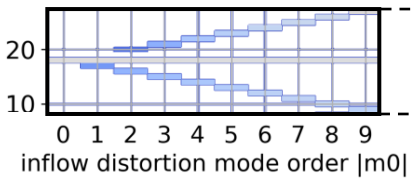
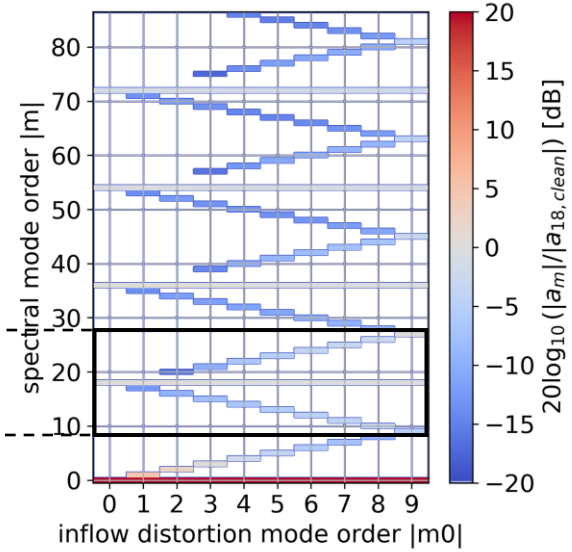


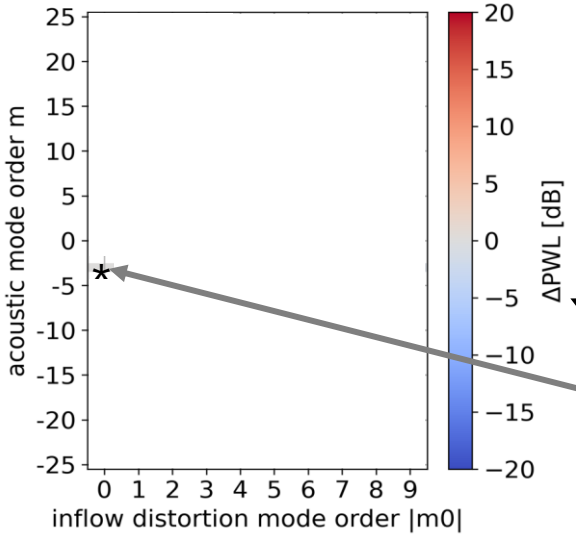
upstream

aerdynamic excitation (BPF)





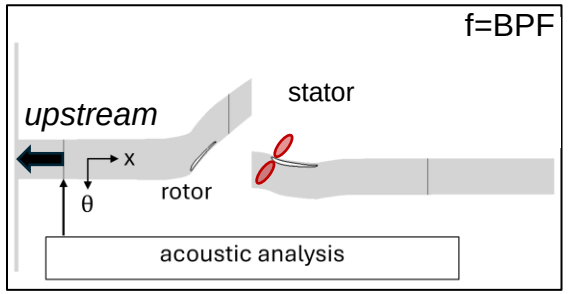
acoustic response (BPF)



relative values,

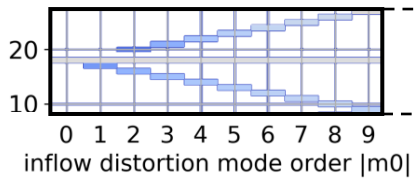
*w.r.t. PWL of TS-mode at clean inflow

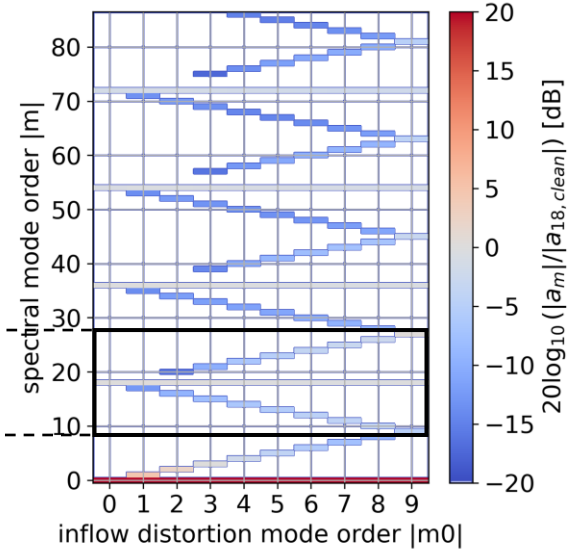
Results – Modal Variation Study



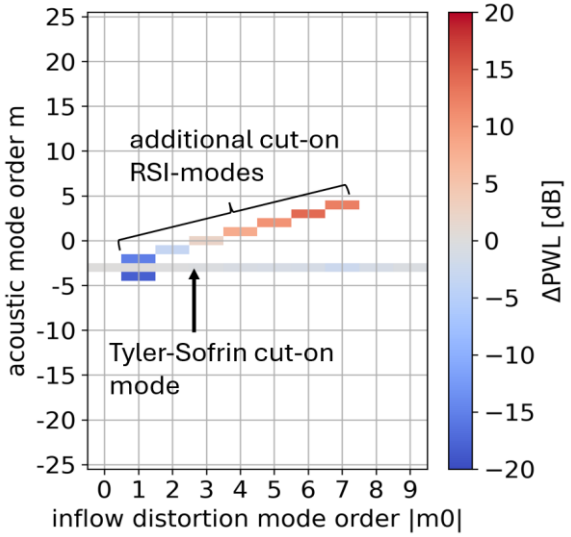
upstream

aerdynamic excitation (BPF)

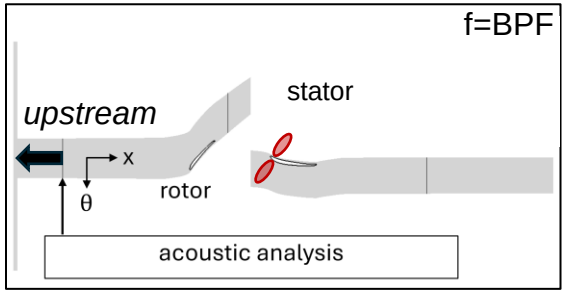




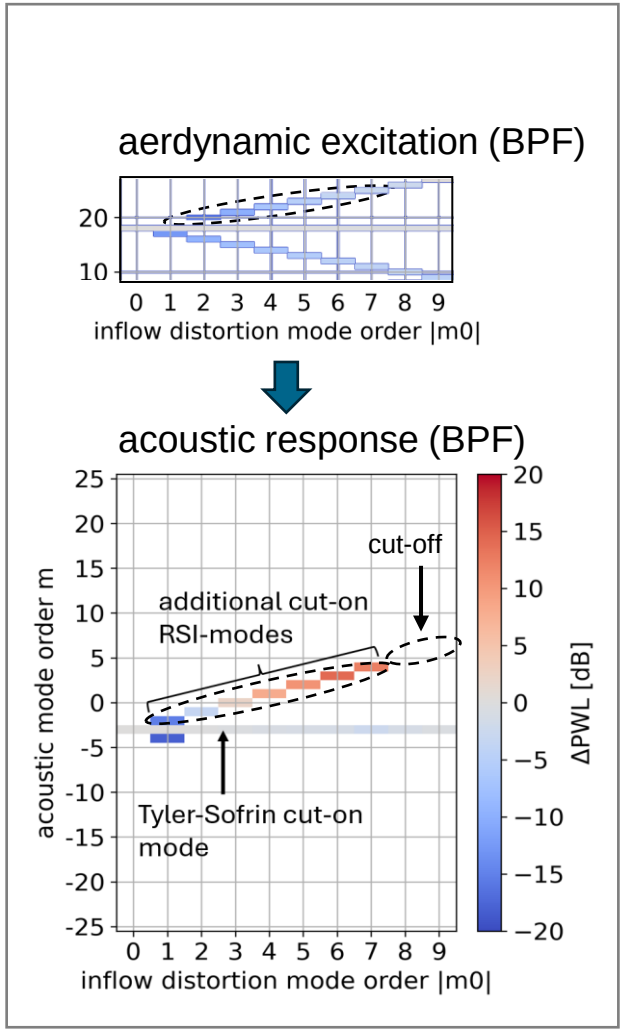
acoustic response (BPF)



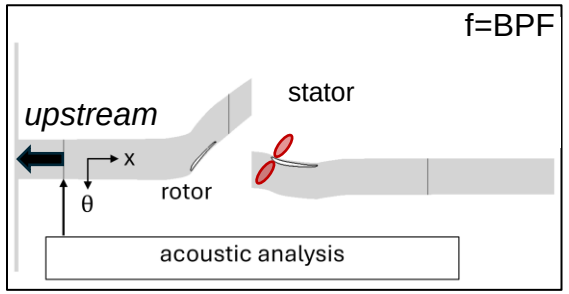
Results – Modal Variation Study



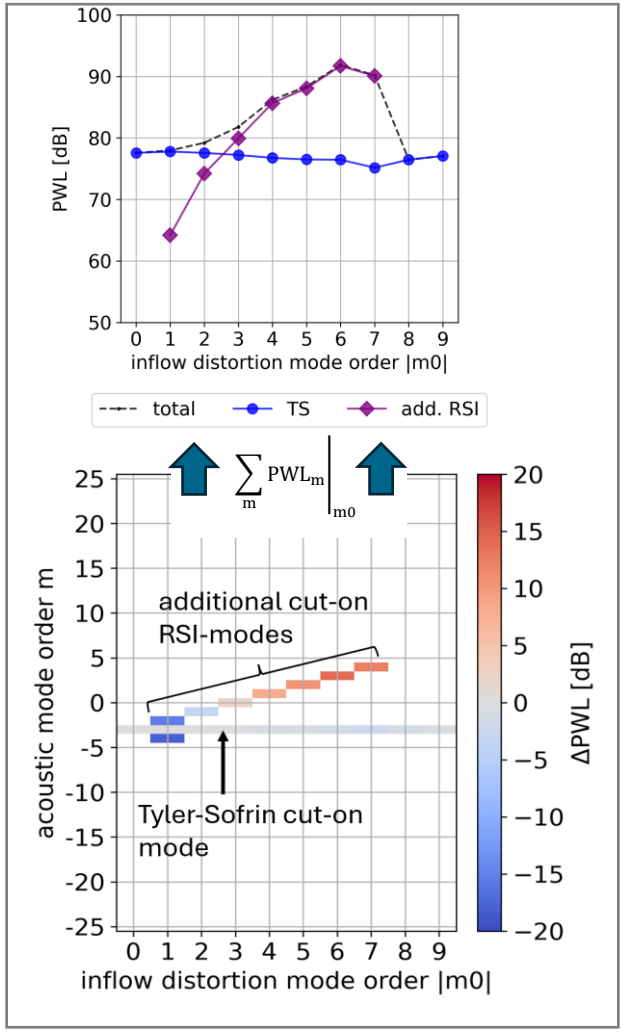
upstream



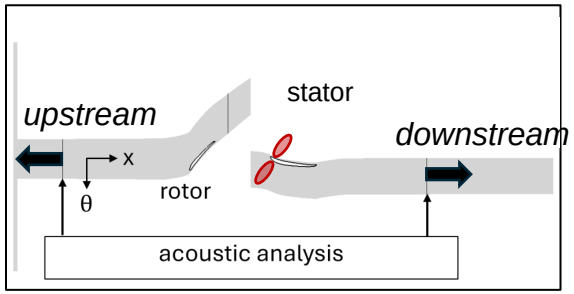
Results – Modal Variation Study



upstream



Results – Modal Variation Study



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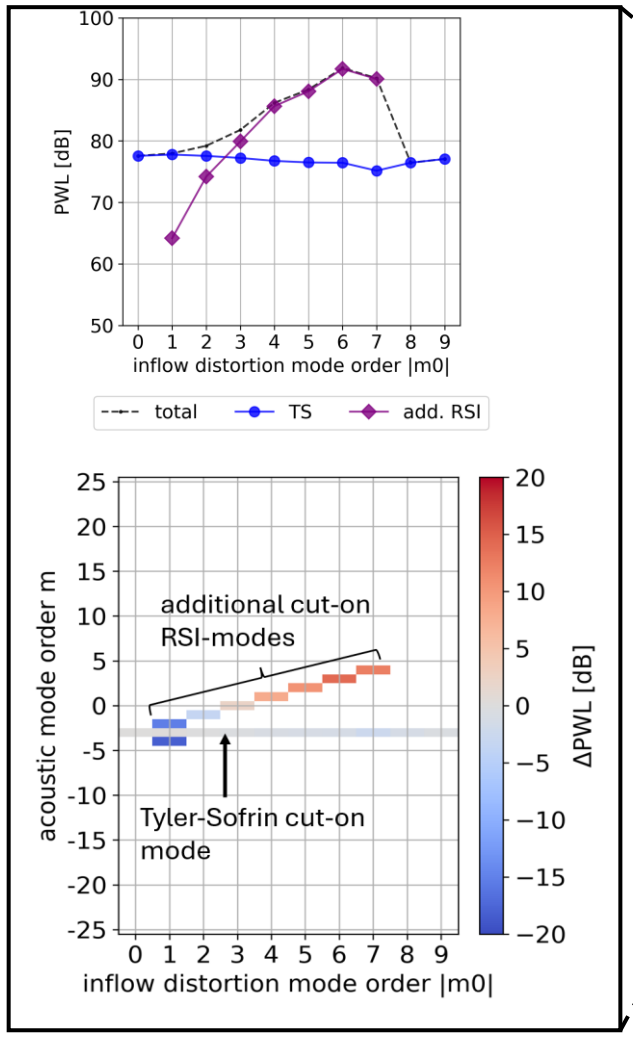
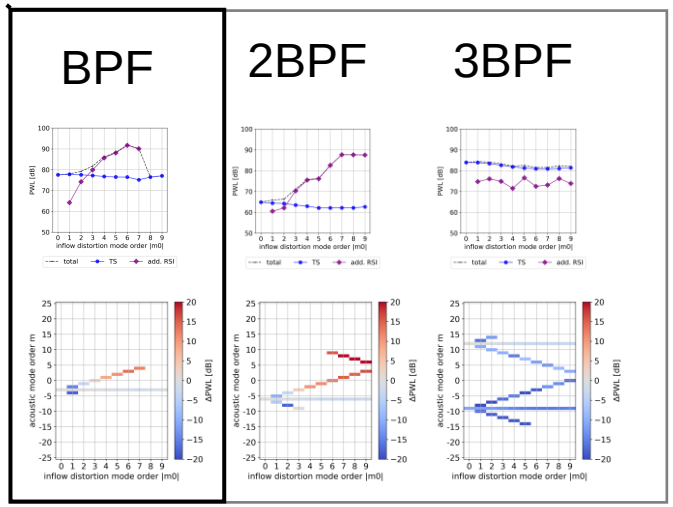
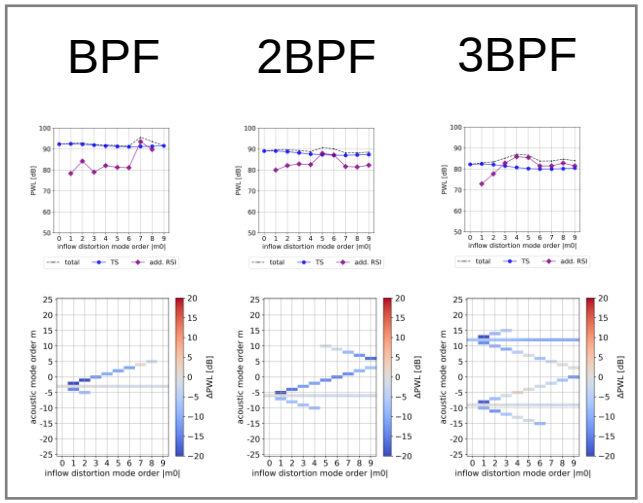


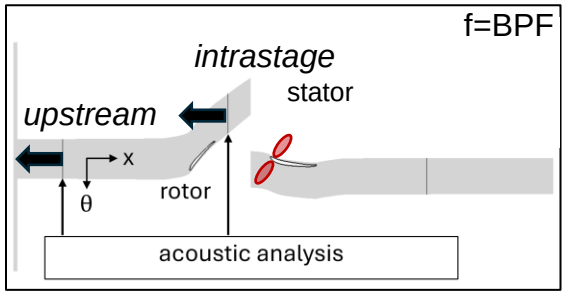
upstream



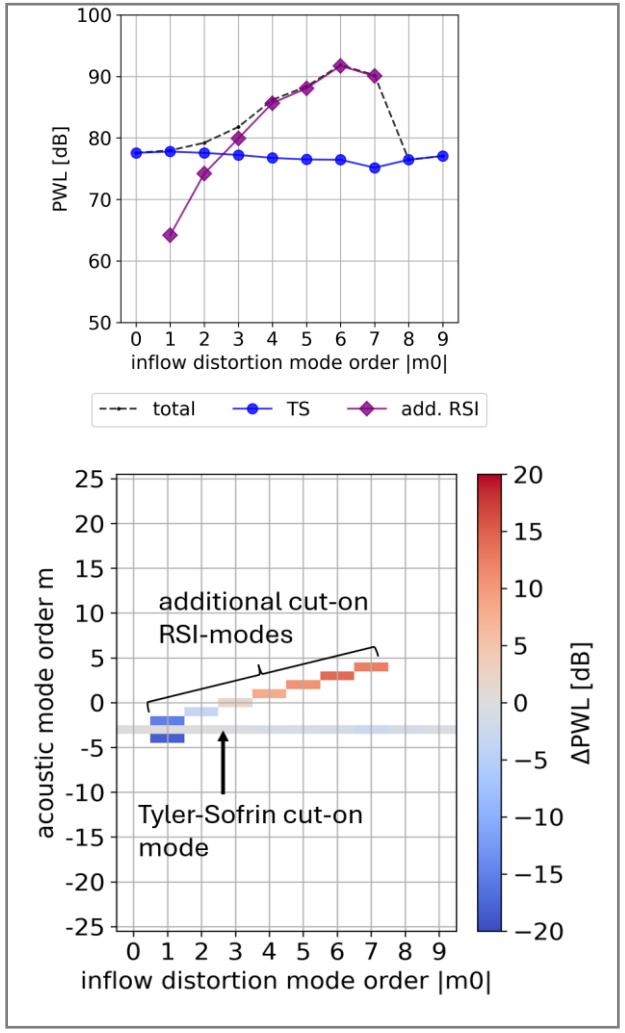
downstream

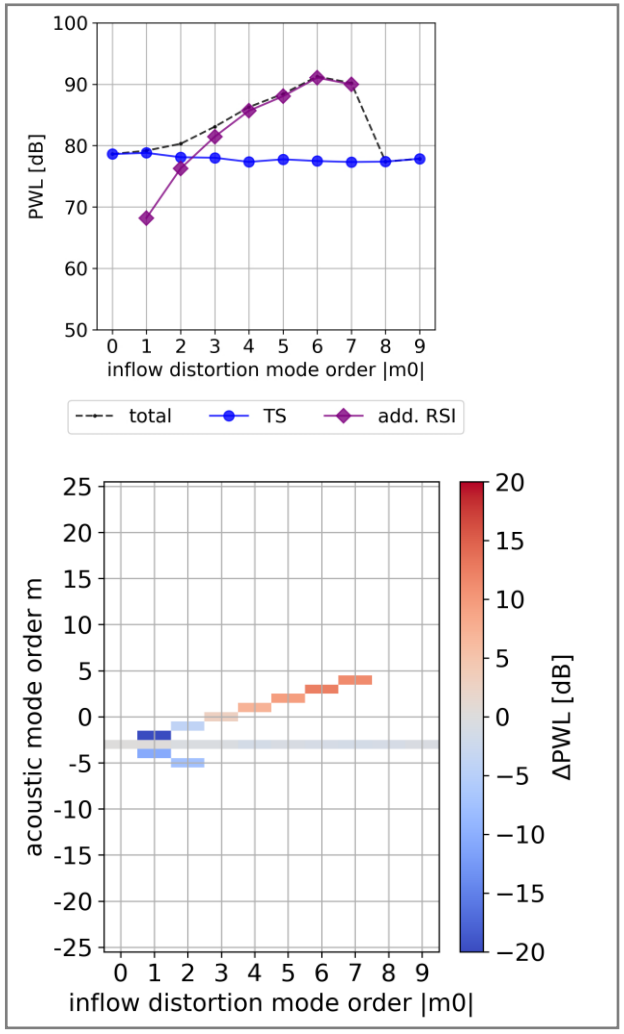


Results – Modal Variation Study



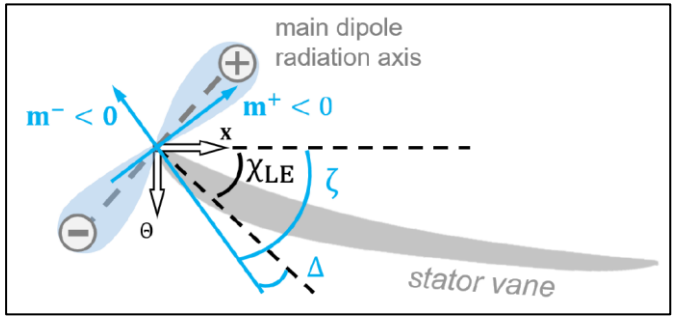
upstream ⟵ intrastage

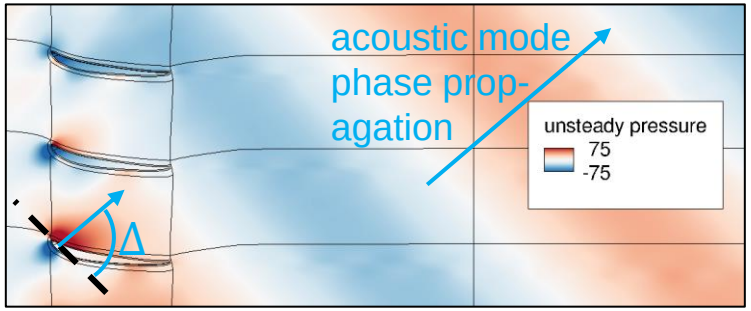


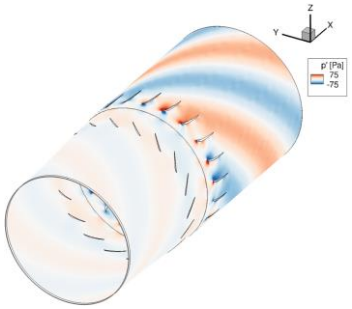


Results – Modal Variation Study

mode phase propagation angles





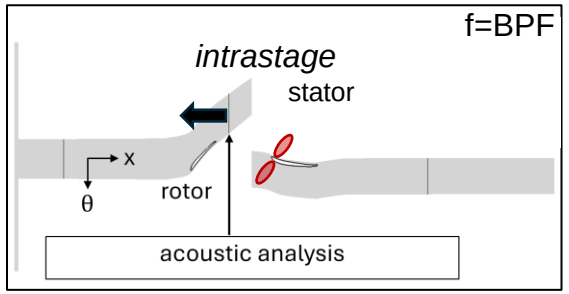


→ analytical description of acoustic mode excitation strength [4]

- strong excitation: Δ→ 90°
- weak excitation : Δ→ 0°

example:
m=-3, BPF,
downstream

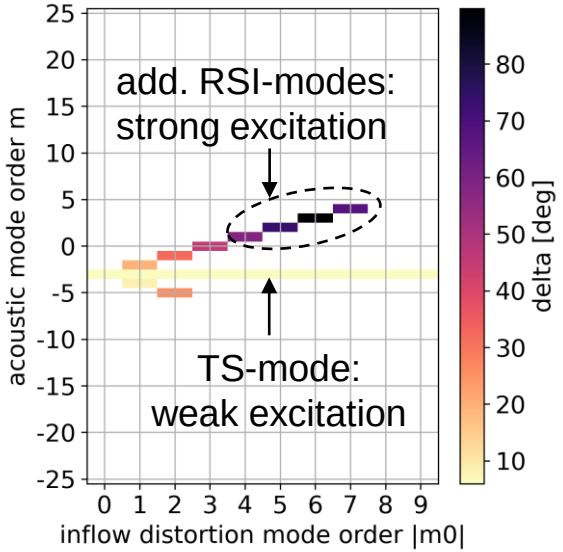
Results – Modal Variation Study

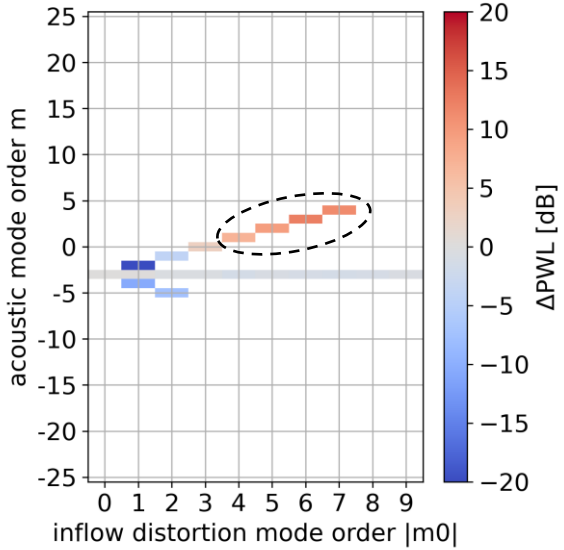


mode phase propagation angles

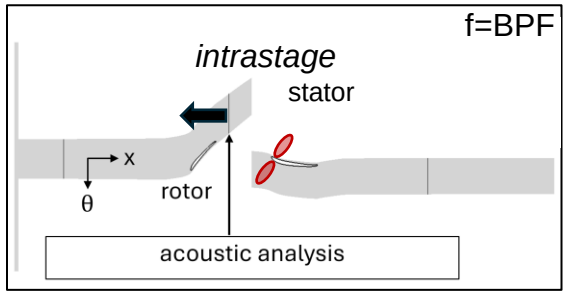
- strong excitation: Δ→ 90°
- weak excitation : Δ→ 0°

mode phase propagation angles





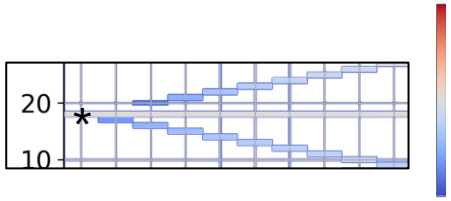
Results – Modal Variation Study



intrastage

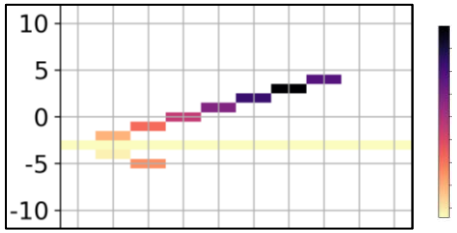
analysis steps

① <u>aerodynamic excitation:</u>
rotor wakes

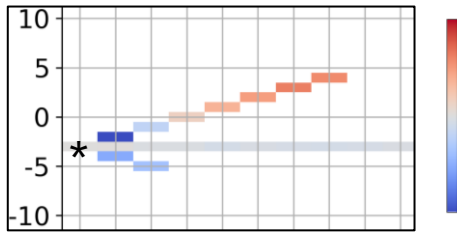


relative values*

② <u>acoustic excitation</u> strength:
mode phase propagation angles

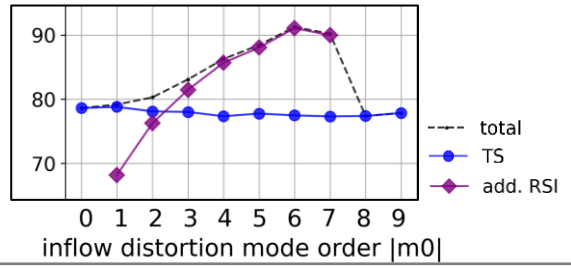


③ acoustic modes



relative values*

④ $$\mathrm{PWL}_{m0} = \sum_{m} \mathrm{PWL}_{m}\Big|_{m0}$$



Summary

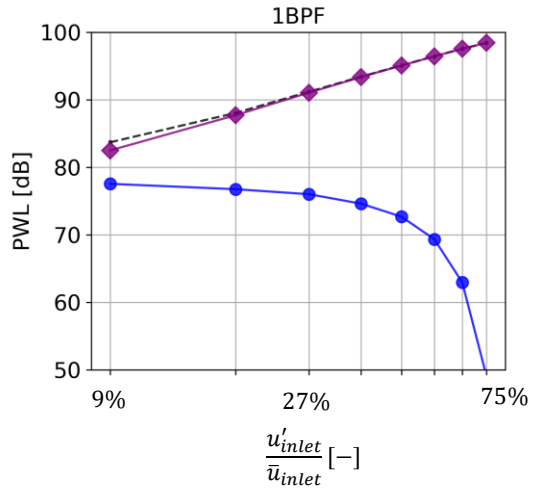
1. quasi-3D CFD study with cosine inflow distortions. Variation of modal content
2. inflow distortion → broader spatial mode specrum of rotor wakes

   → excitation of additional RSI-modes
3. additional RSI-modes can dominante tonal noise (for a given amplitude and high m_0)

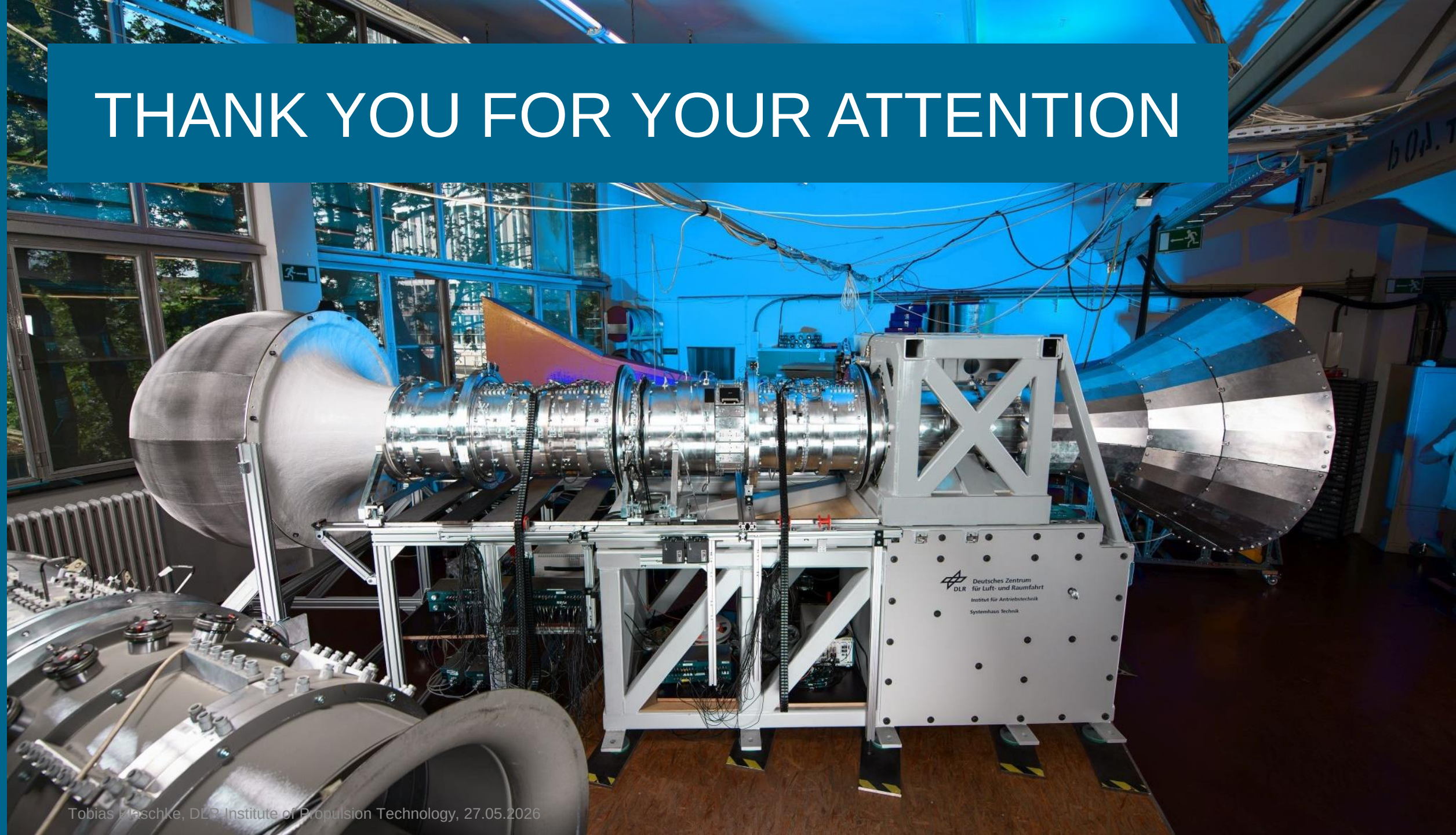
Outlook

- amplitude variation
- more realistic inflow distortions
- 3D CFD simulations

m_0=6 upstream



THANK YOU FOR YOUR ATTENTION



Imprint

Topic:	**Parametric Numerical Study on the Impact of Steady Cosine Inflow Distortions on Tonal Rotor-Stator Interaction Noise**
Date:	2026-05-27
Author:	Tobias Blaschke, Sébastien Guerin, Antoine Moreau, Robert Jaron
Institute:	Propulsion Technology
Image sources:	All images “DLR (CC BY-NC-ND 3.0)” unless otherwise stated

Sources

[1] Klähn, Lukas; Caldas, Luciano; Meyer, Robert; Moreau, Antoine; Tapken, Ulf (2023): Experimental Investigation of Inflow-Distortion-Induced Tonal Noise in a Sub-Sonic Fan Test Rig, 2023. 29th International Congress on Sound and Vibration, ICSV 2023.
[2] Tapken, Ulf; Schade, Stephen; Klähn, Lukas; Rudolphi, Angelo; Behn, Maximilian; Meyer, Robert (2023): CRAFT test rig for assessing the aeroacoustic impact of fans of electrically powered urban/regional aircraft. CEAS-ASC Workshop 12.-13.10.2023, Budapest “Aeroacoustics of Electrically Driven Air Vehicles: Towards a Green and Quiet Aviation”.
[3] Tapken, U., Caldas, L., Meyer, R., Behn, M., Klähn, L., Jaron, R., Moreau, A., Enghardt, L. (2021): New test facility to investigate the noise generated by shrouded fans for small aircraft applications. DICUAM 2021 - Delft International Conference on Urban Air-Mobility, 15.-17. March 2021, Delft, Netherlands.
[4] S. Schade, R. Jaron, L. Klähn, A. Moreau. Smart Blade Count Selection to Align Modal Propagation Angle with Stator Stagger Angle for Low-Noise Ducted Fan Designs. Aerospace 2024, 11, 259. doi:10.3390/aerospace11040259