CFD Analysis of Centrifugal Compressor Aeroacoustics and Sensitivity to Backside Cavity Modeling

UNIVERSITAT POLITÈCNICA DE VALÈNCIA

MÁSTER UNIVERSITARIO EN MECÁNICA DE FLUIDOS COMPUTACIONAL

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MuMFC - Seminar

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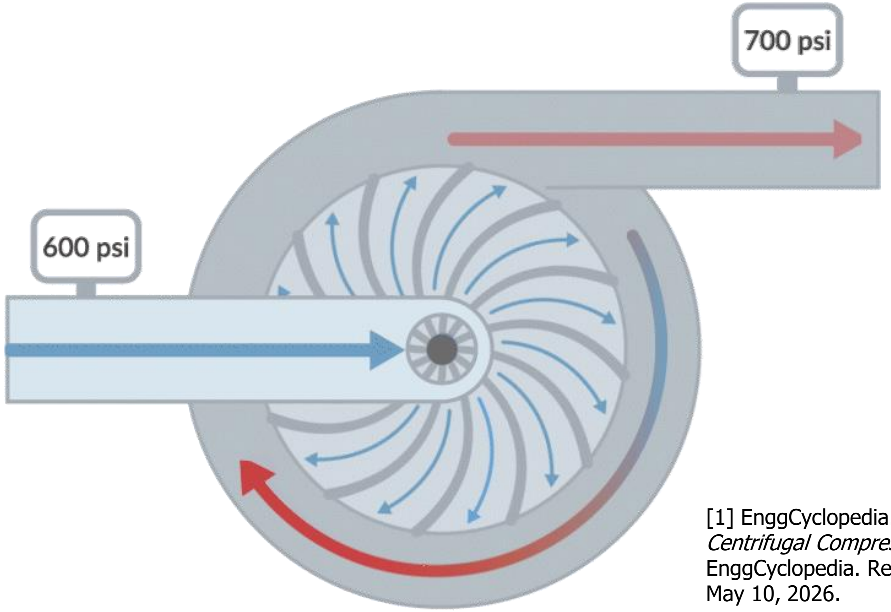
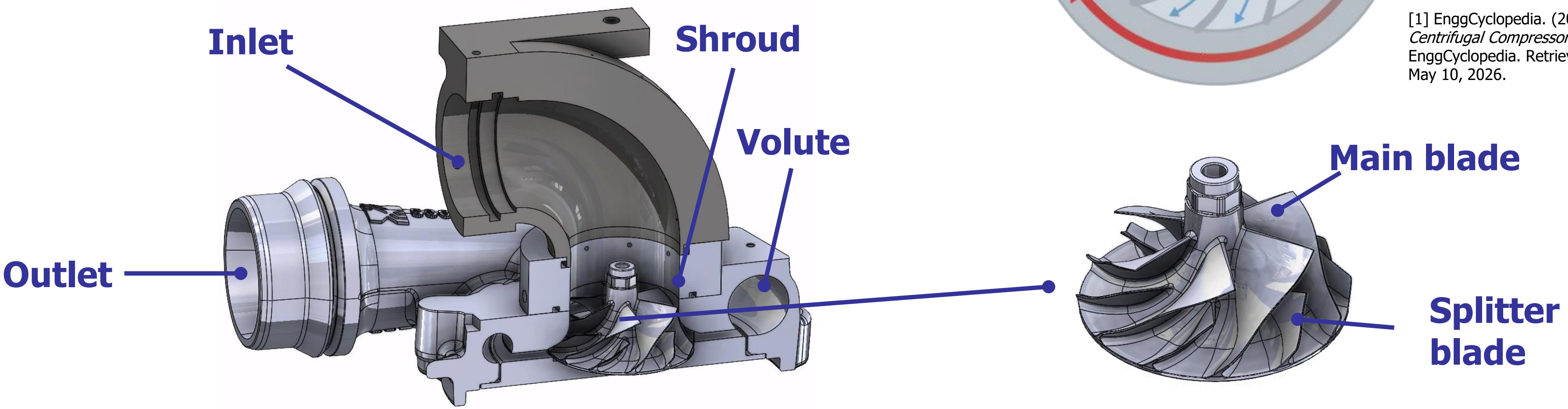
- What is a centrifugal compressor?
  - Compressor → **Increase pressure**
  - **Type** of compressor:
    - **Centrifugal** → Radial direction
  - Parts of a centrifugal compressor:

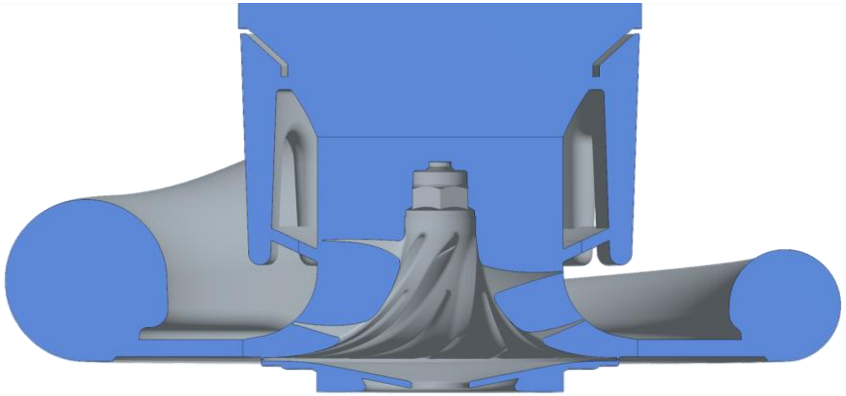


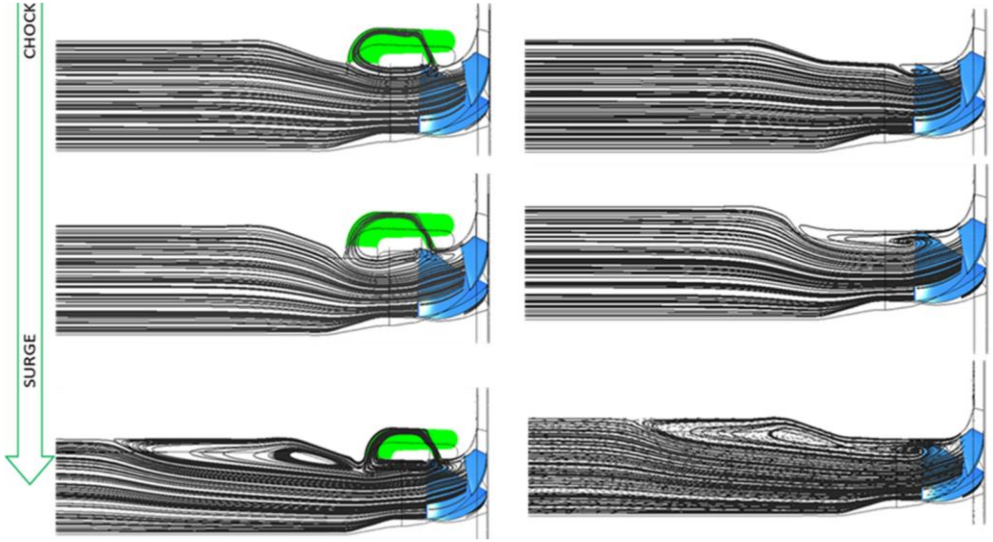
[1] EnggCyclopedia. (2023). *Centrifugal Compressors*. EnggCyclopedia. Retrieved May 10, 2026.



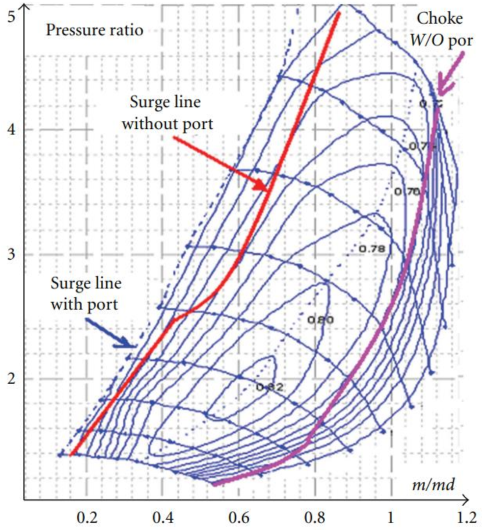
❖ What is a centrifugal compressor?

- Impeller Backside Cavity (**IBC**)
- **Ported-Shroud**
  - **Extends** the compressor **operating range**





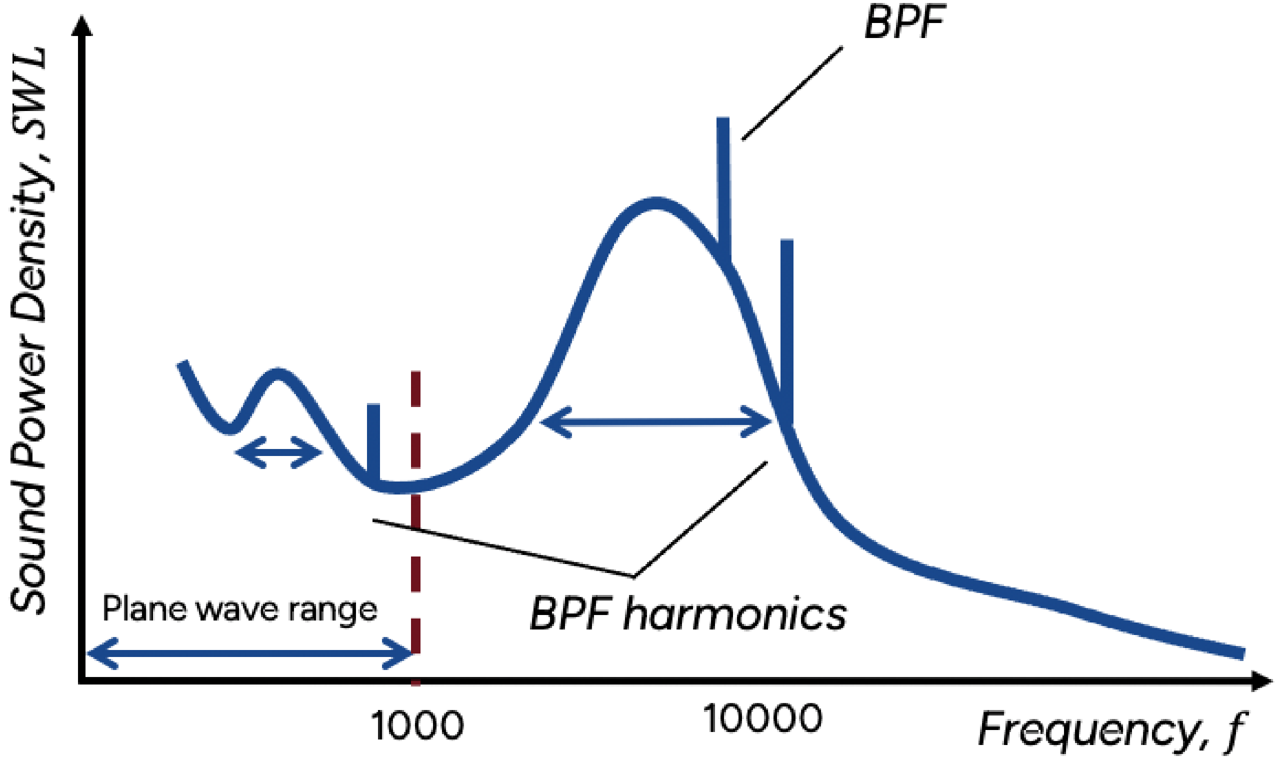
[2] Cravero, C.; Leutcha, P.J.; Marsano, D. Simulation and Modeling of Ported Shroud Effects on Radial Compressor Stage Stability Limits. Energies 2022, 15, 2571. https://doi.org/10.3390/en15072571



[3] Xu, C. & Amano, Ryoichi. (2012). Empirical Design Considerations for Industrial Centrifugal Compressors. International Journal of Rotating Machinery. 2012. 10.1155/2012/184061.

❖ Compressor Noise

- **Aeroacoustics?**
- **Tonal** features
  - **Blade passing frequency (BPF) and harmonics**, buzz-saw noise etc.
- **Broadband** components
  - Whoosh noise, tip-clearance noise (TCN) etc.
- **Surge noise**



[4] García-Tíscar, J. (2017) "Experiments on turbocharger compressor acoustics". *Doctoral Thesis*, Universitat Politècnica de València

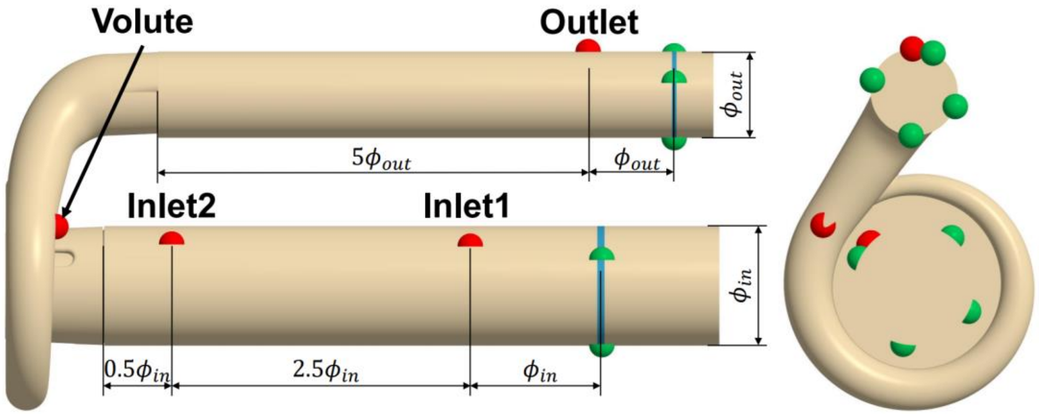
- Motivation
  - New engines are quieter
  - High computational cost (transient, LES, fine mesh…)
  - Ported-Shroud:
    - **Tonal noise** from the compressor at the **BPF**
      - BPF noise increase in ported-shroud compressor
  - Impeller Backside Cavity:
    - **Lack of previous studies** on the **aeroacoustic** influence of the impeller backside cavity (**IBC**) in **CCs**

- Objectives
  - Develop a **numerical tool** to predict the **BPF amplitude**
    - **Sensitivity** of the tool to **ported-shroud geometry** change
  - Determine the **IBC impact on CC**
    - Could the **IBC** be **removed?**

Contents

❖ Test Instrumentation

- Compressor tested by CMT at UPV
- Sensors:
  - Global Variables:
    - **Flow-meter** → MFR
    - **Thermocouples** → temperature
    - **Piezometric rings** → pressure
  - Acoustics:
    - **Piezoelectric sensors** → acoustic pressure signal
      - Inlet 1 & 2
      - Outlet
      - Volute



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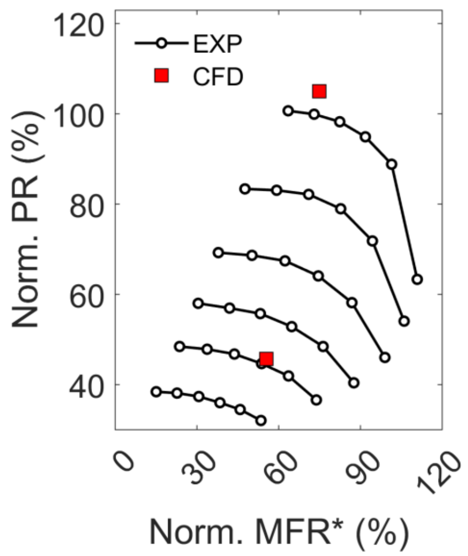
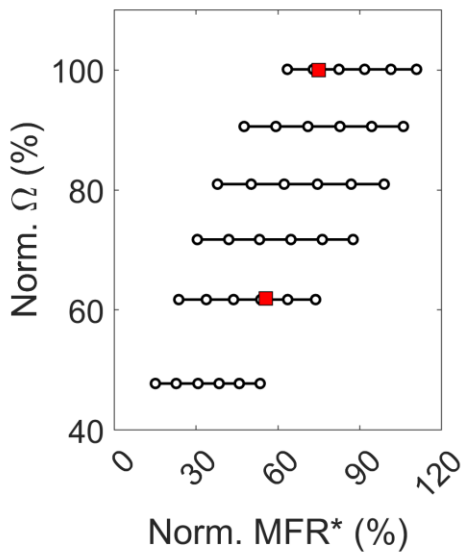
❖ Cases & Working Points

Working points

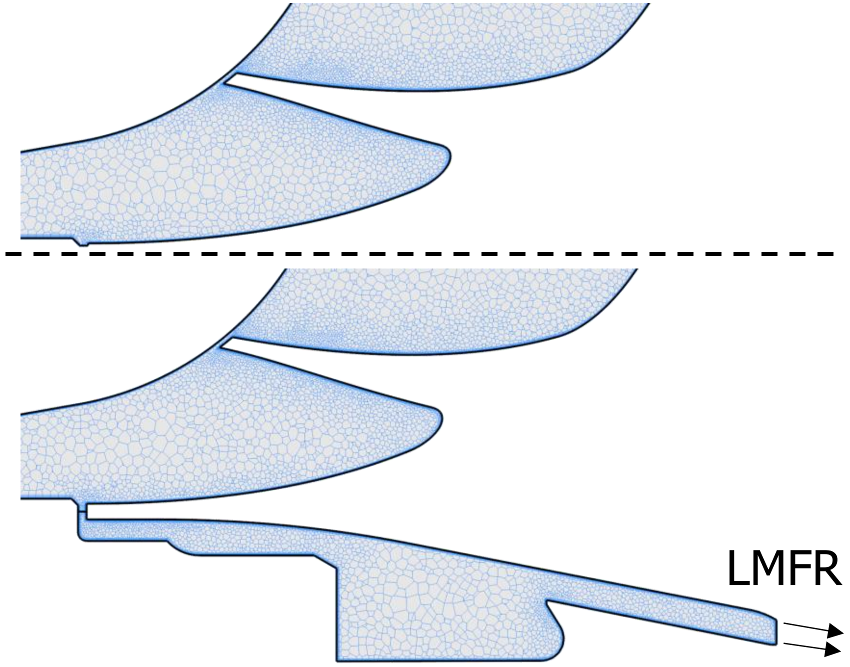
- Low-Load Regime
- High-Load Regime



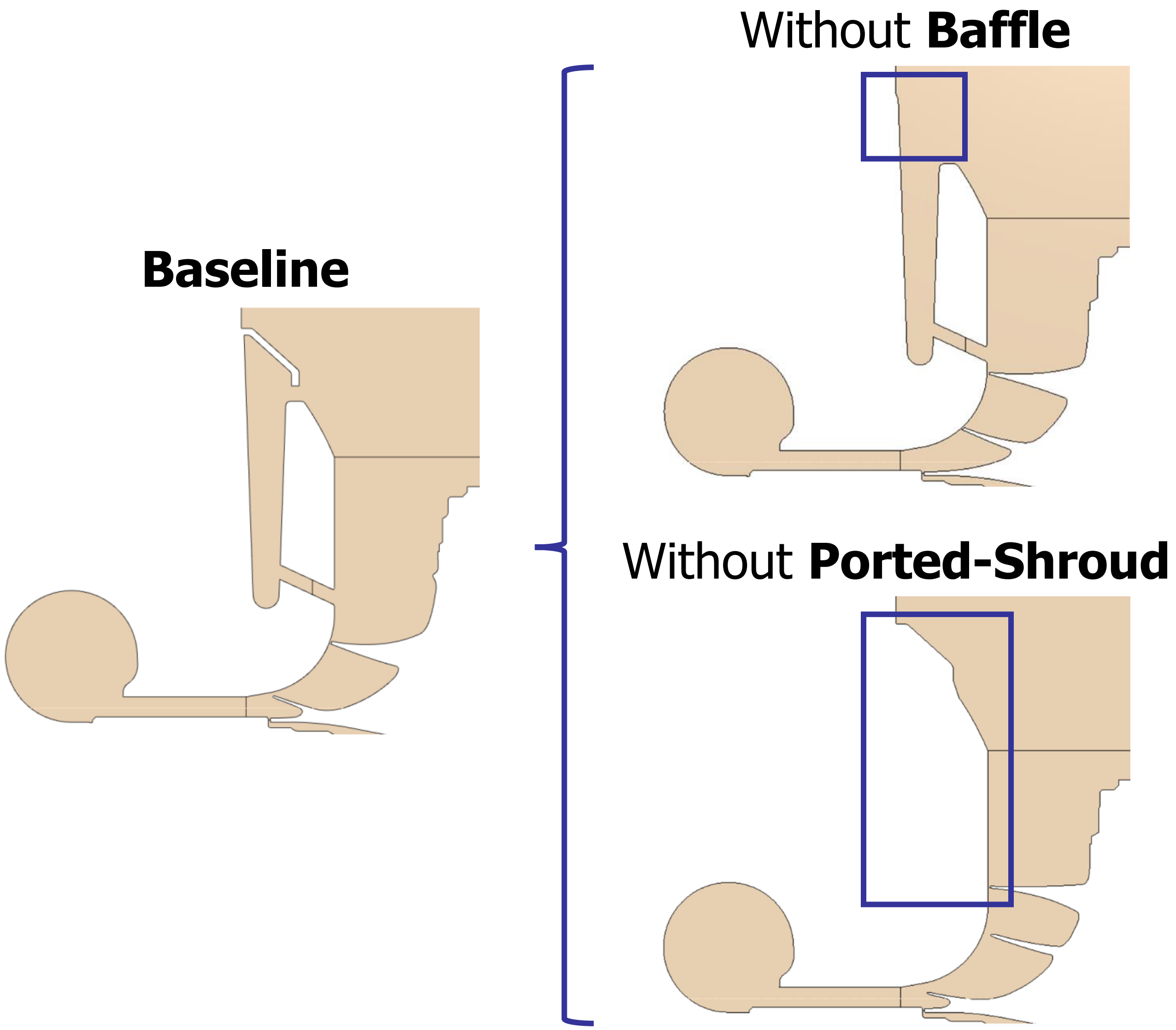


Impeller Backside Cavity Cases

- Wo IBC
- With IBC: LMFR 0%, 0.25% & 0.5%

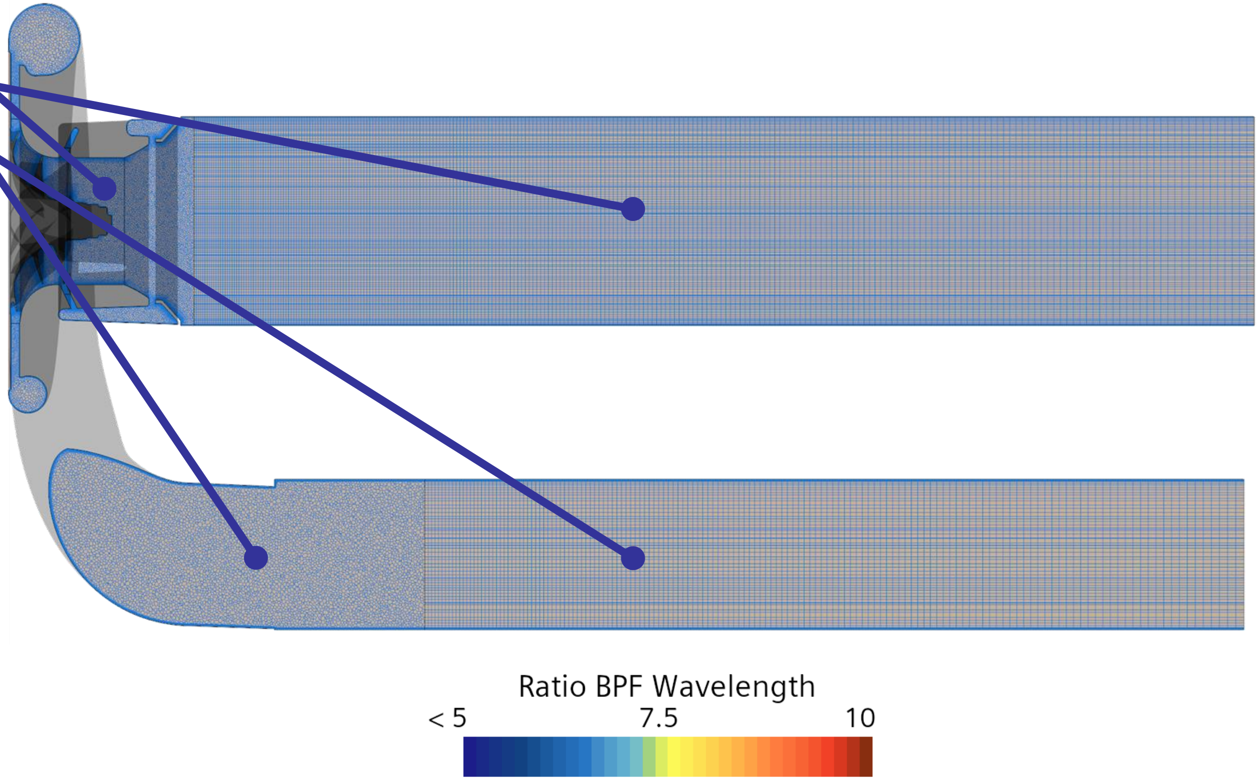


- Ported Shroud Geometries
  - **Three** compressor **geometries**
  - **Baseline** → **Validate** models with **experimental** data.
  - Two geometry changes to **modify** compressor **acoustics:**
    - Without Baffle:
      - **Increase** of **BPF** noise
    - Without Ported-Shroud:
      - **Decrease** of **BPF** noise



❖ Compressor Mesh

- **Meshing** Approach:
  - **Polyhedral** cells in the core
  - **Extruded** Mesh (**Sponge**)
- **Grid Validation**:
  - **Cells/wavelength > 10**
  - Ratio of resolved TKE
    - **98.8%** of the cells **TKE > 0.7**
  - Median y**+ < 1**
  - Median **l+ < 70**
- **Boundaries** → $\dot{m}$ inlet, p outlet
- **Noise extracted** from pressure signal
  - **Large Eddy Simulation**
- **STAR-CCM+** coupled solver



❖ Numerical Campaign Strategy

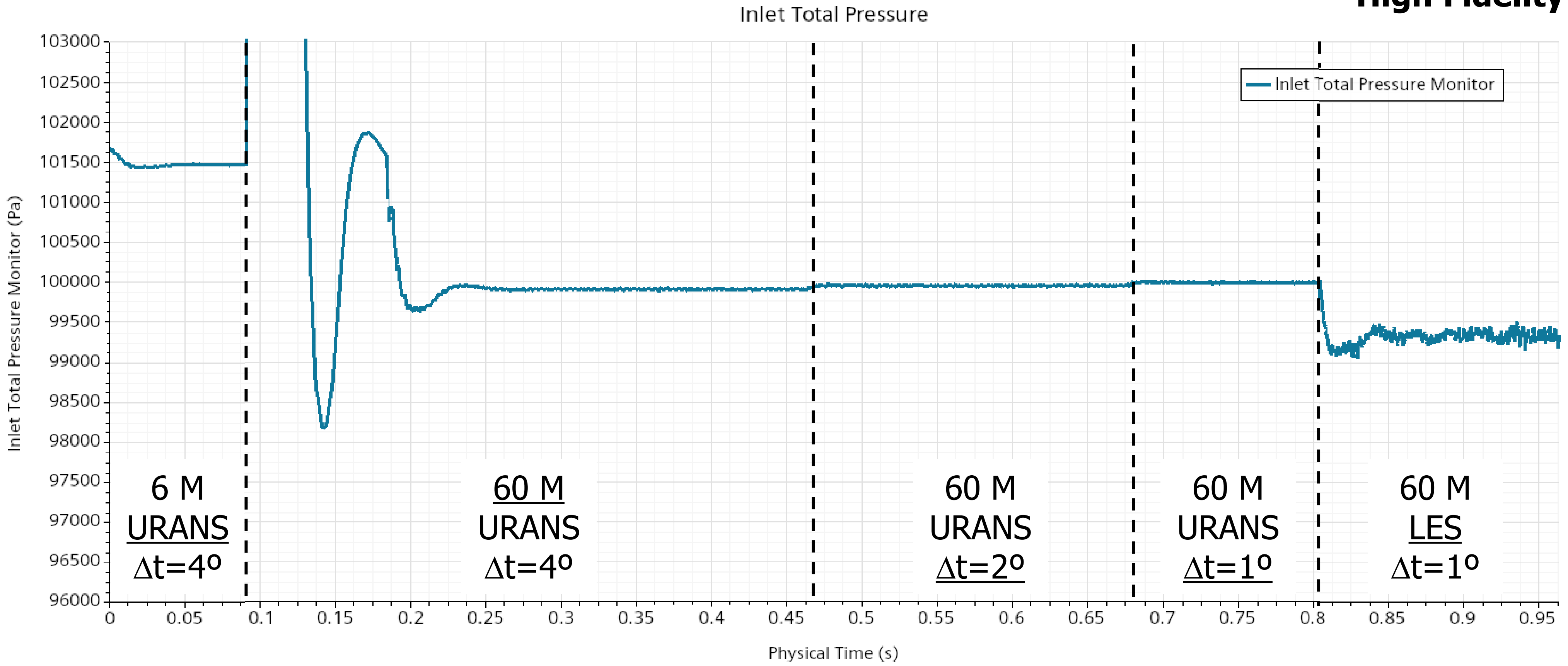
- Convergence Procedure - First geometry (baseline)

Low Fidelity → **High Fidelity**

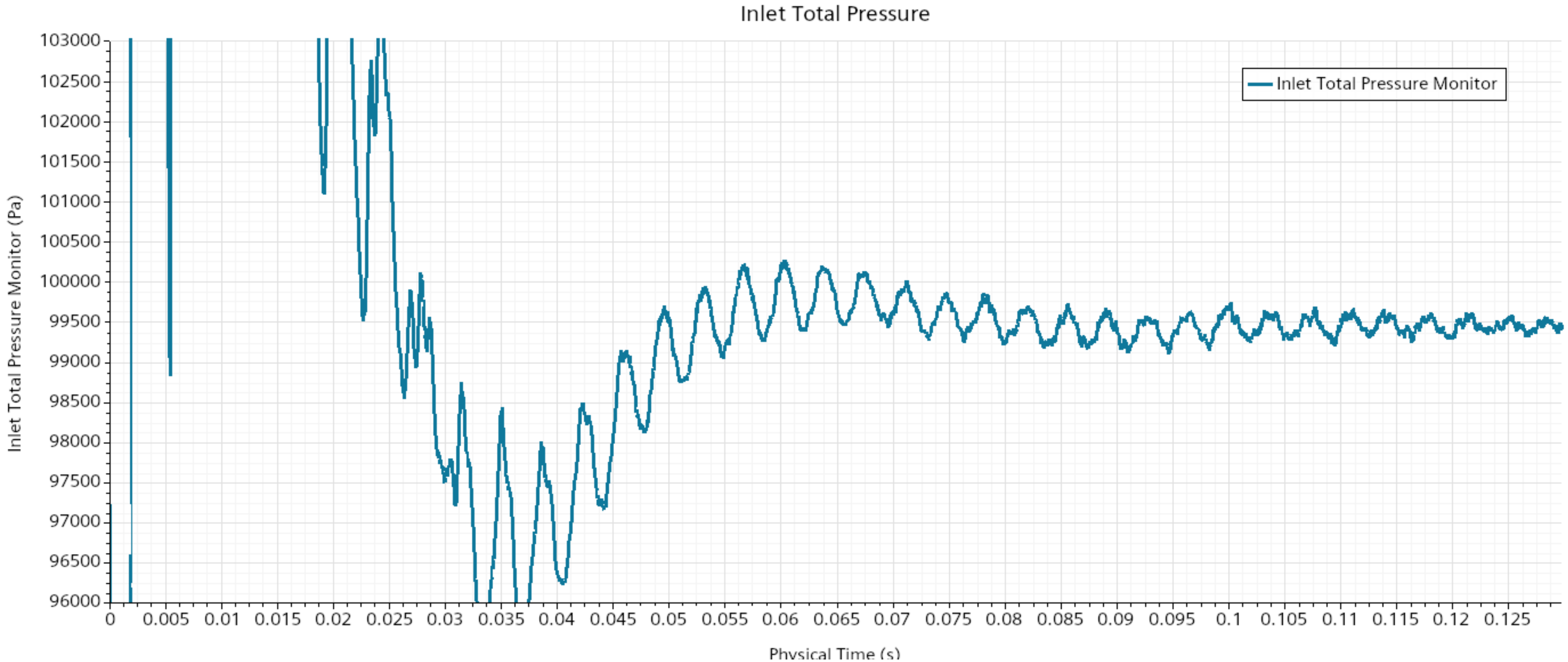
RANS, steady
6M cells

↑

Initial
conditions



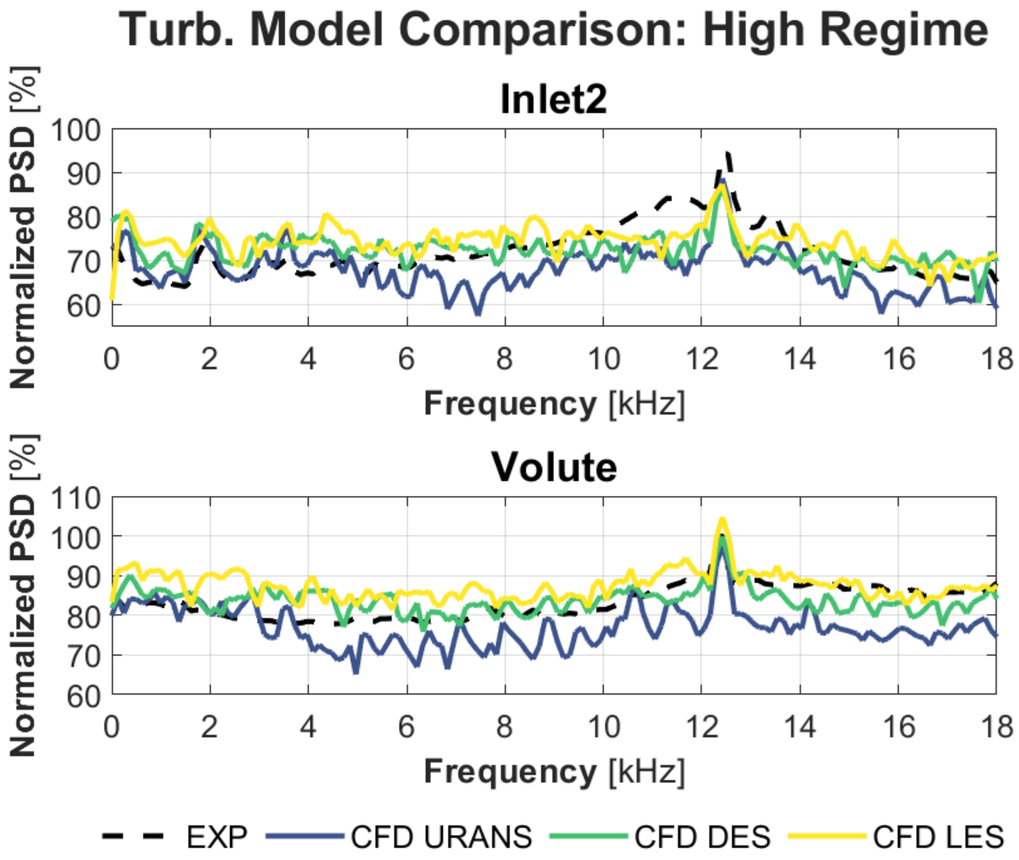
- Numerical Campaign Strategy
  - Convergence Procedure - Other geometries
    - **Initial conditions**: Converged 60M LES Δt=1º (**baseline** geometry)
    - Significant **reduction** in real **time for convergence**: 2-3 weeks vs 2-3 months



Turbulence Model Validation

- Global Variables
  - **Low differences** (within **±2%**)
- Acoustic Spectra
  - **DES and LES** differences **against URANS**
    - Generate a **flatter signal** (with fewer peaks)
    - **Higher intensity** level, especially LES
    - **Replicate experimental PSD values better** at medium and high frequencies
  - **LES** provides a **wider tonal peak around the BPF** than **DES and URANS**
    - More **similar** to the **EXP** results

Geom.	Meth.	Regime	$\dot{m}_{corr}$ [kg/s]	$\dot{N}$ [rpm]	PR [-]	η_s [%]
	URANS		1.37%	0.01%	1.24%	0.75%
Baseline	DES	High	-1.09%	0.01%	-1.06%	-2.00%
	LES		-	-	-	-



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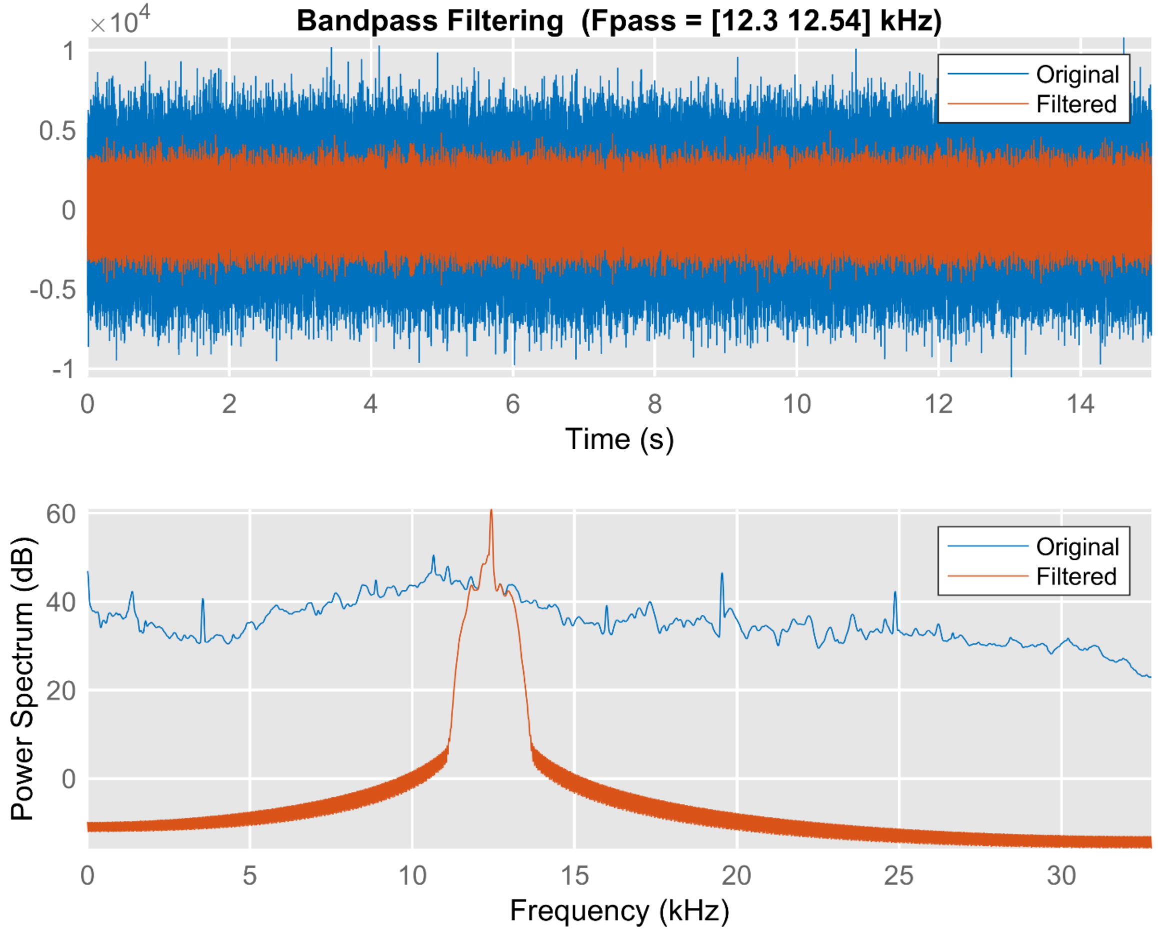
❖ Signal Postprocessing Approach

- **Acoustic Spectrum:**
  - **PSD** (Power Spectral Density)
  - **CFD & EXP comparison** → $\Delta f_{CFD} = \Delta f_{EXP}$
  - **Blocks → Δf = 1% of the BPF** & overlapping of 50%
- **BPF** Amplitude:
  - **SPL** (Sound Pressure Level)
  - BPF **calculated** utilizing a Finite Impulse Response (FIR) **Filter**
    - **EXP**: **full signal** is employed
    - **CFD**: A **single window** is considered at the end of the signal, with **Δf = 0.5% BPF**



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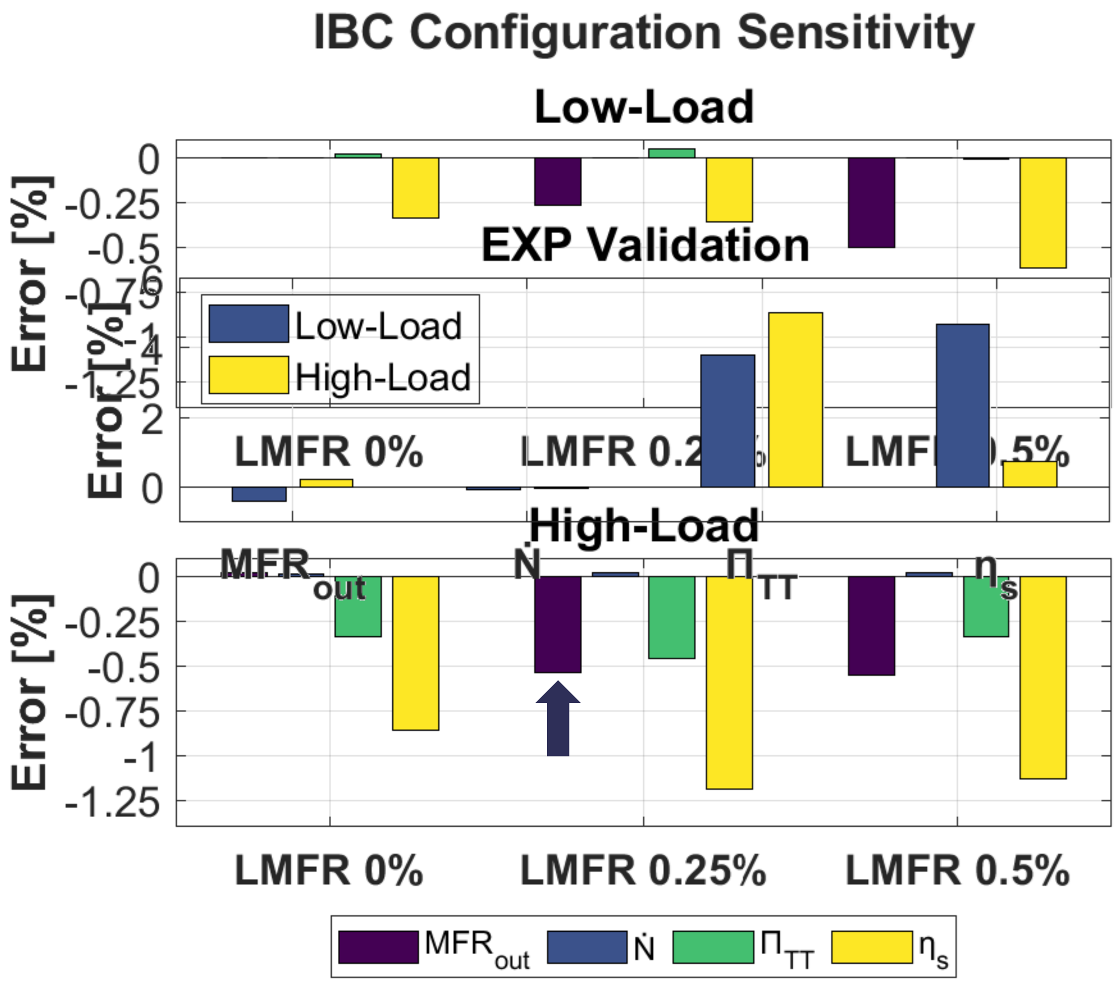
Results & Discussion – Impeller Backside Cavity

❖ Global Variables

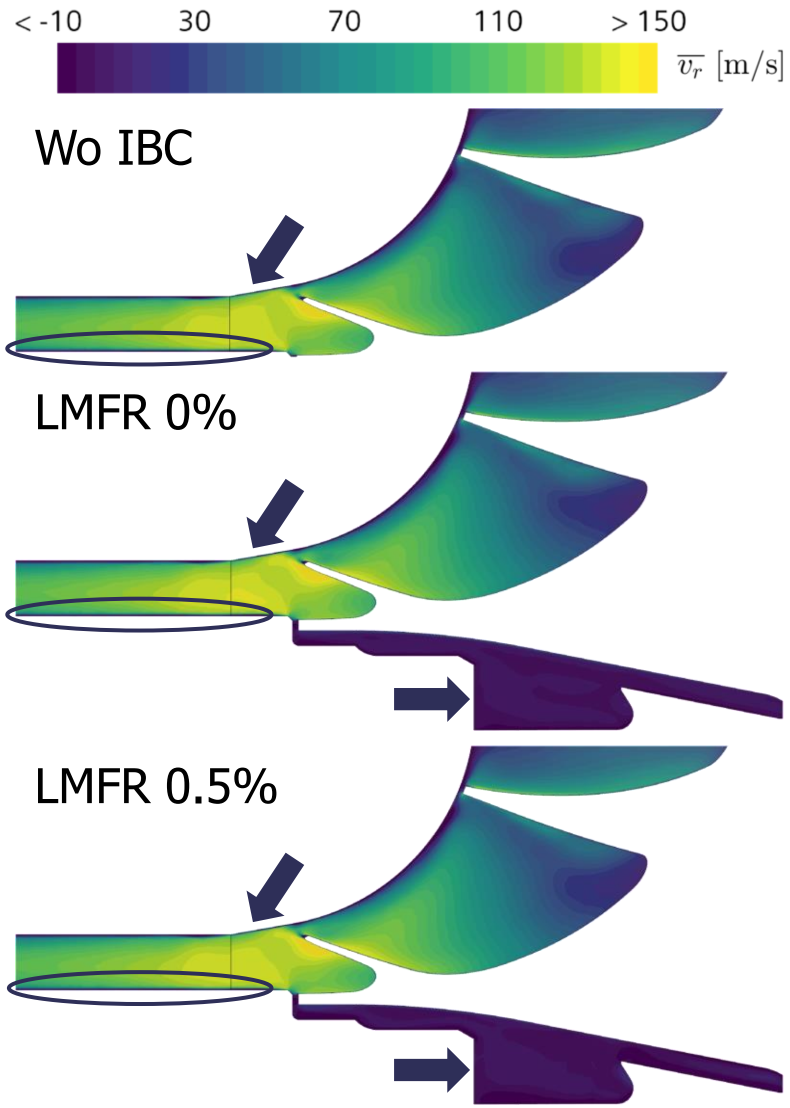
- **Wo IBC** experimental **validation**
  - **PR** and $\boldsymbol{\eta_s}$ **errors** noticeable but **controlled**
- **IBC** configuration **sensitivity**
  - **No big differences** observed…
    - …except for **lower** $\boldsymbol{\eta_s}$ due to the **IBC**
  - For the **LMFR 0.25% high regime** case, MFR_{out} is **not 0.25%**
    - Simulation **oscillations**



❖ Flow Field

○ Low-load regime

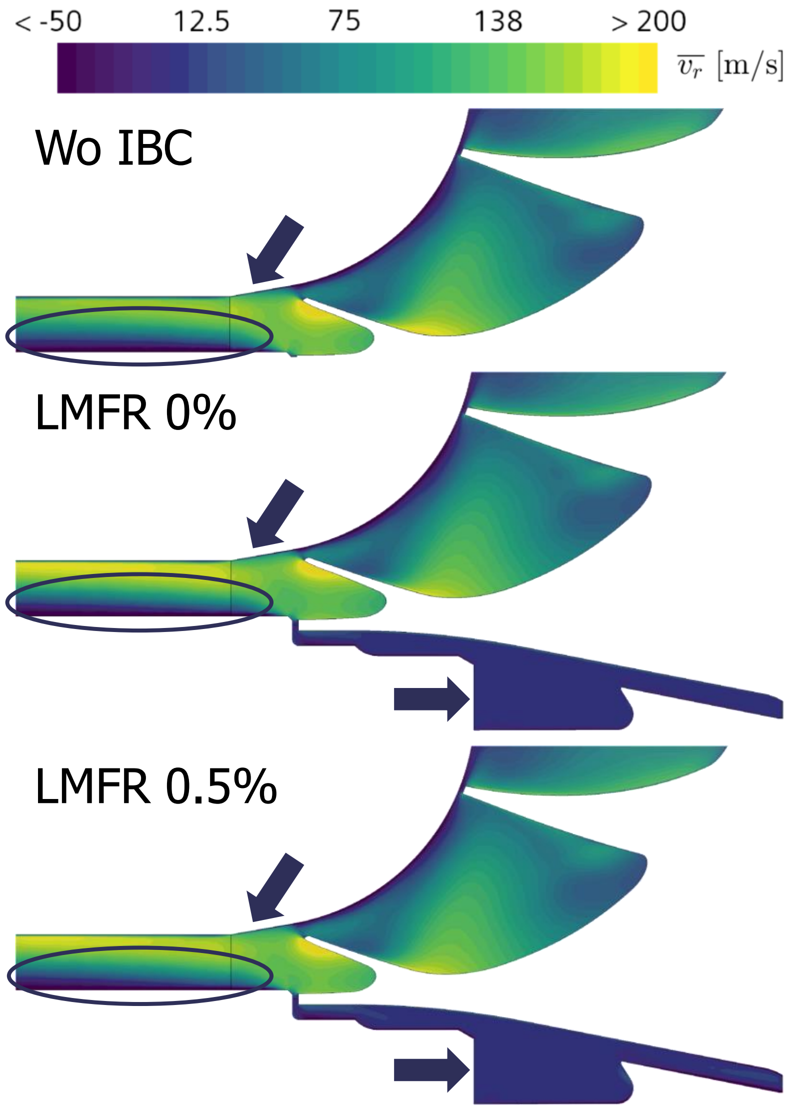
- Practically **identical** $\overline{v_r}$ fields
- **Boundary layer** attached and thin
- **Including** the **IBC** slightly increase ($\overline{v_r}$) fields near the impeller/diffuser interface
- **No** significant $\nabla \overline{v_r}$ within the **IBC**



Results & Discussion – Impeller Backside Cavity

❖ Flow Field

- **High-load regime**
  - Practically **identical** $\overline{v_r}$ fields
  - **Boundary layer** detached
    - $\overline{v_r} < 0$ due to flow recirculation
    - **Independent** of the **LMFR** configuration
  - **Including** the **IBC** slightly increase $\overline{v_r}$ fields near the IBC/impeller interface
    - **Slightly** change **diffuser flow field**
  - **No** significant $\nabla\overline{v_r}$ within the IBC

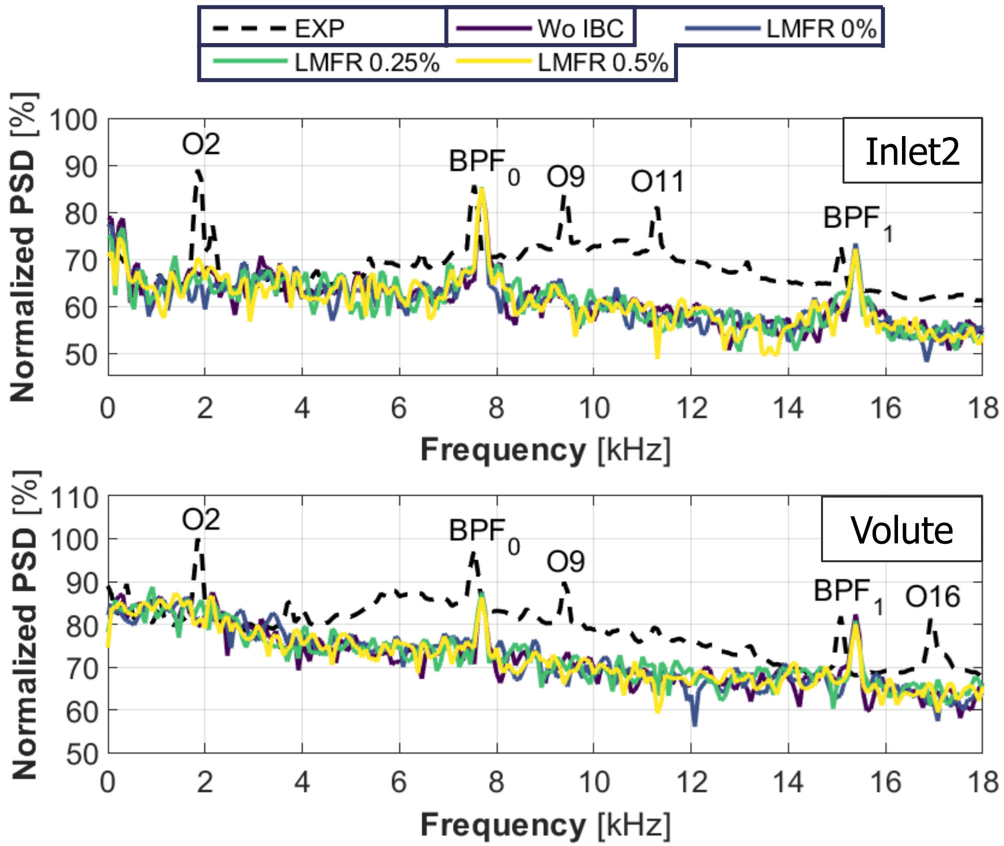


Results & Discussion – Impeller Backside Cavity

❖ Acoustics

○ Low-load regime

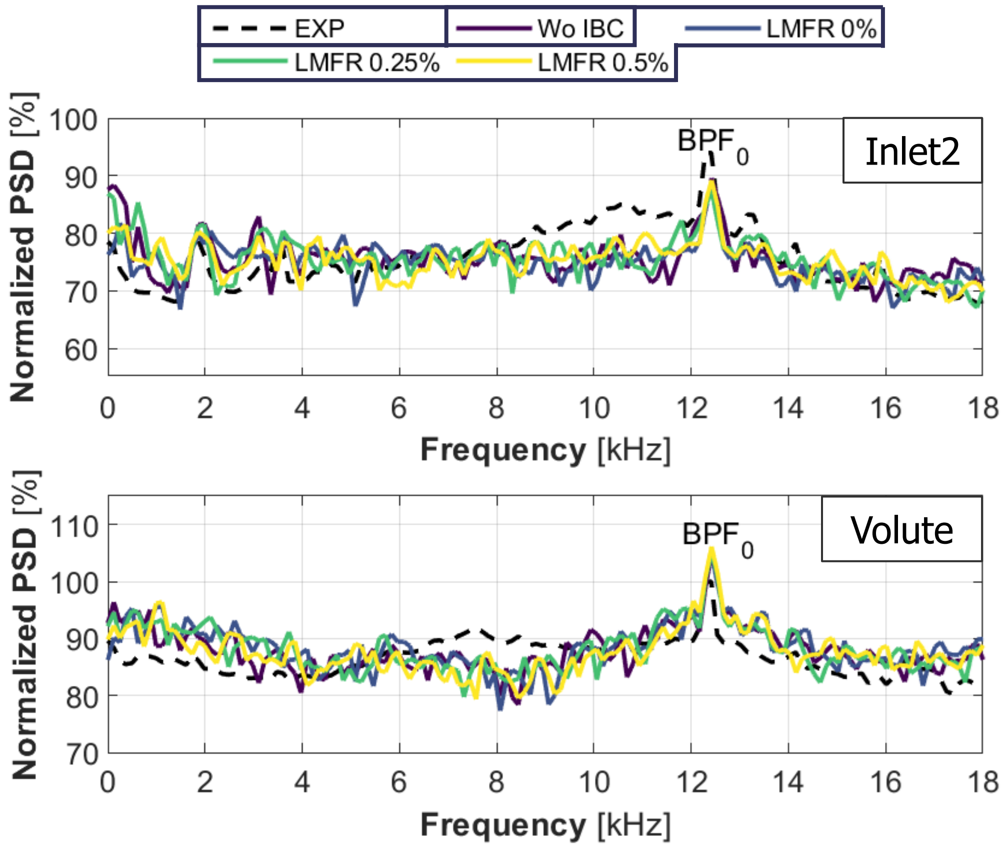
- Experimental **Validation**:
  - Generally **good agreement with EXP** data
  - **Broadband**:
    - » **Good** prediction at **low frequencies**
    - » **Underprediction** for **f>4 kHz**
      - **TCN?**
  - **Tonal** noise:
    - » **Good** prediction of $\mathbf{BPF_0}$ **&** $\mathbf{BPF_1}$
    - » **Rotating orders not reproduced** numerically
- Sensibility Analysis:
  - Quite **similar acoustic** spectra and BPF values
  - **Differences** within the **numerical error**



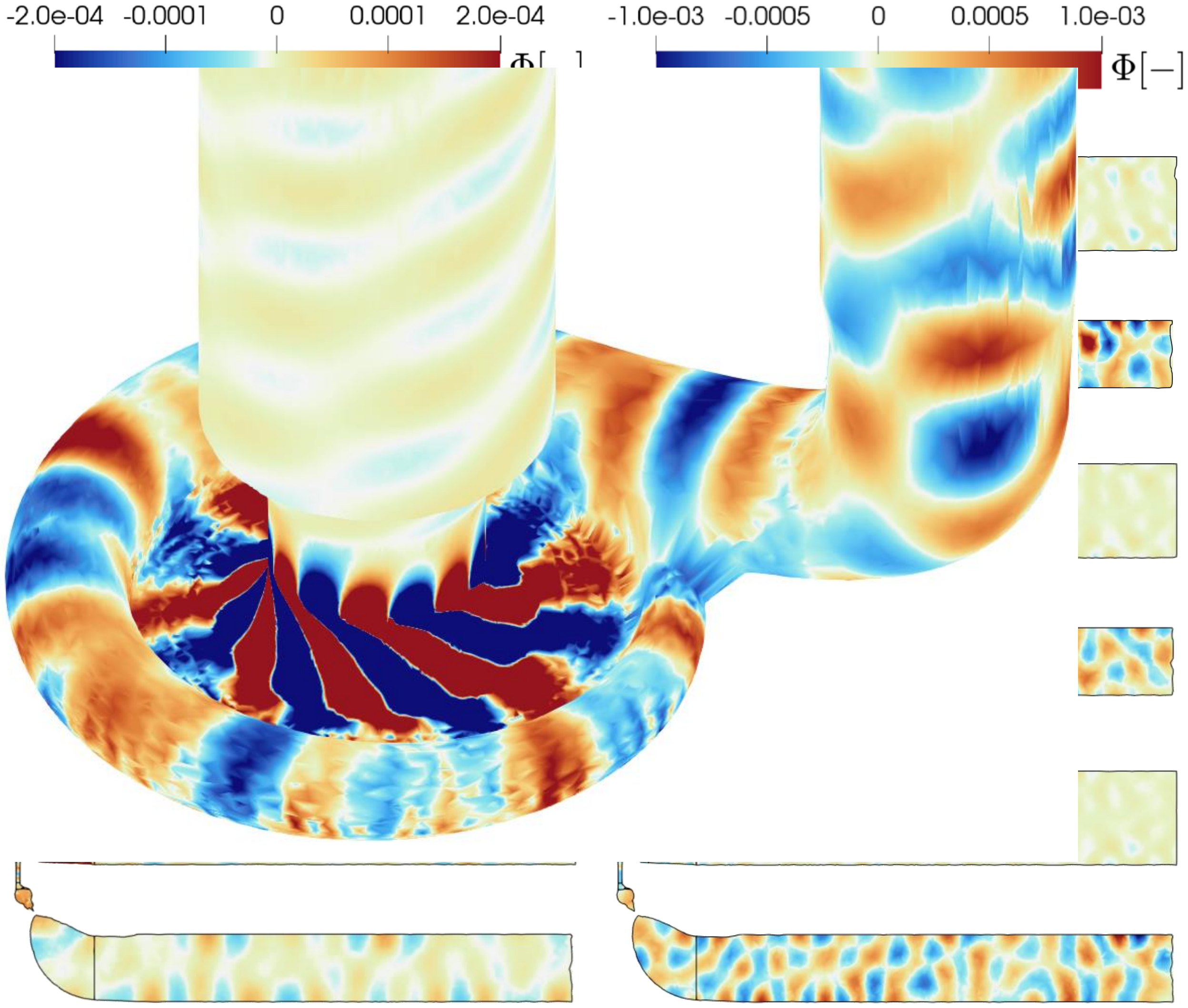
Results & Discussion – Impeller Backside Cavity

❖ Acoustics

- **High-load regime**
  - Experimental **Validation**:
    - **Broadband**:
      - » **Close agreement** between methodologies
      - » **Some regions** slightly under- and **overestimated**
        - **TCN?**
    - **Tonal** noise:
      - » **Good** prediction of $\mathbf{BPF_0}$
  - **Sensibility** Analysis:
    - Quite **similar acoustic** spectra and BPF values
    - **Differences** within the **numerical error**



- Dynamic Mode Decomposition
  - **BPF** mode
  - **Low**-Load Regime
    - **Modal patterns** quite **similar** for the four **IBC setups**
    - **Without IBC** shows **higher peak** absolute values
  - **High**-Load Regime
    - **Compared to low-load regime**:
      - **More excited** flow
      - Larger **difference** in **Φ** peak values **between ducts**
    - Comparing **IBC configurations**
      - **Similar** energetic **pattern**
      - **Higher** absolute **Φ** → **Wo IBC**



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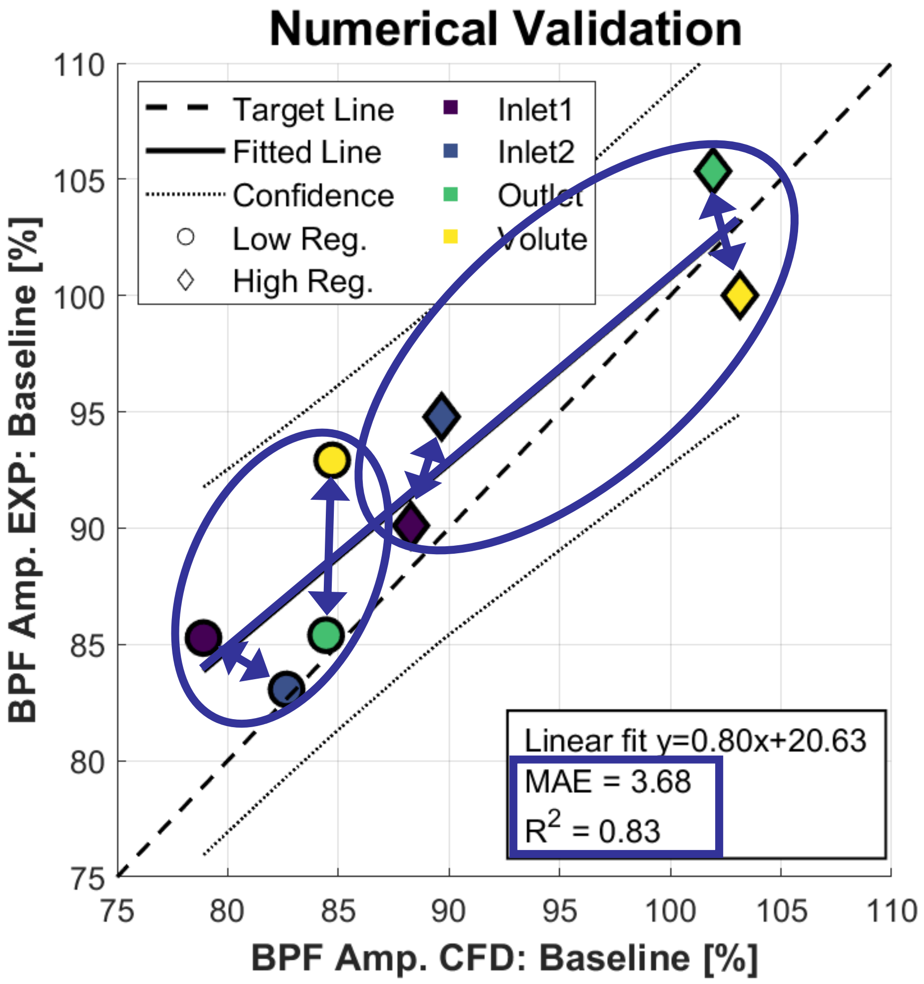
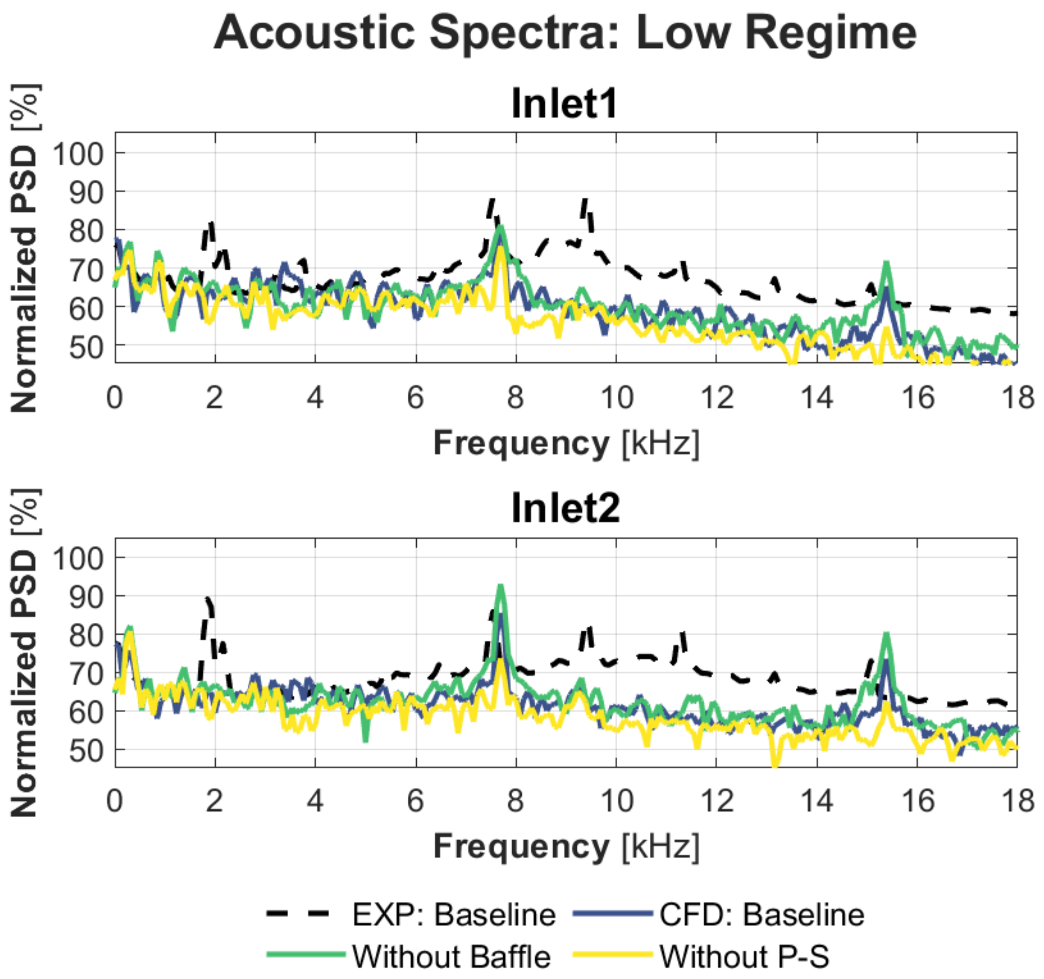
❖ BPF Amplitude Validation

- **Limited dispersion** between **CFD** and **EXP**
- **CFD tends to underpredict BPF** amplitude
  - Specially under **low-load regime** conditions
- **CFD model** correctly **capture** acoustic **differences between regimes**
- Strong influence of **probe location** on both methodologies



Results & Discussion – Ported-Shroud

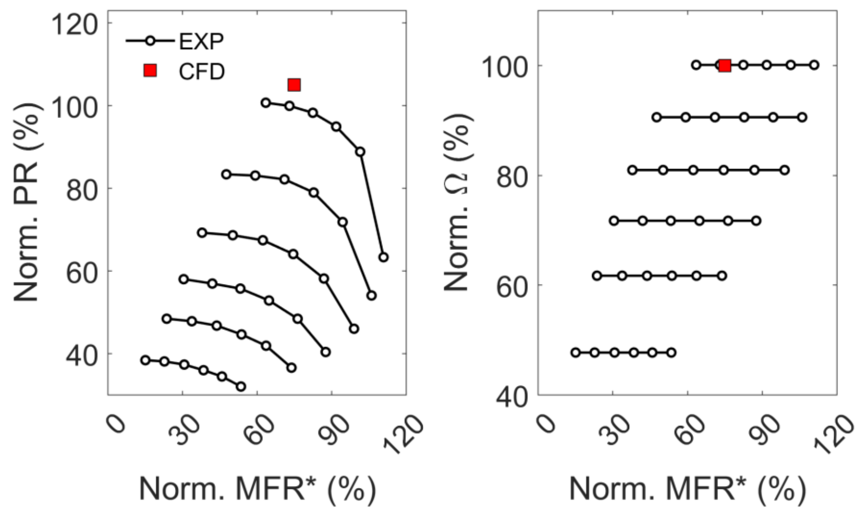
- Acoustic Spectrum
  - **Low-load regime**
    - **Outlet and Volute** sensors:
      - **Similar spectra** between geometries
    - **Inlet** duct sensors:
      - **Without baffle**:
        - **Higher energy** content than **baseline**
      - **Without ported-shroud**:
        - **Lower energy** content than **baseline**

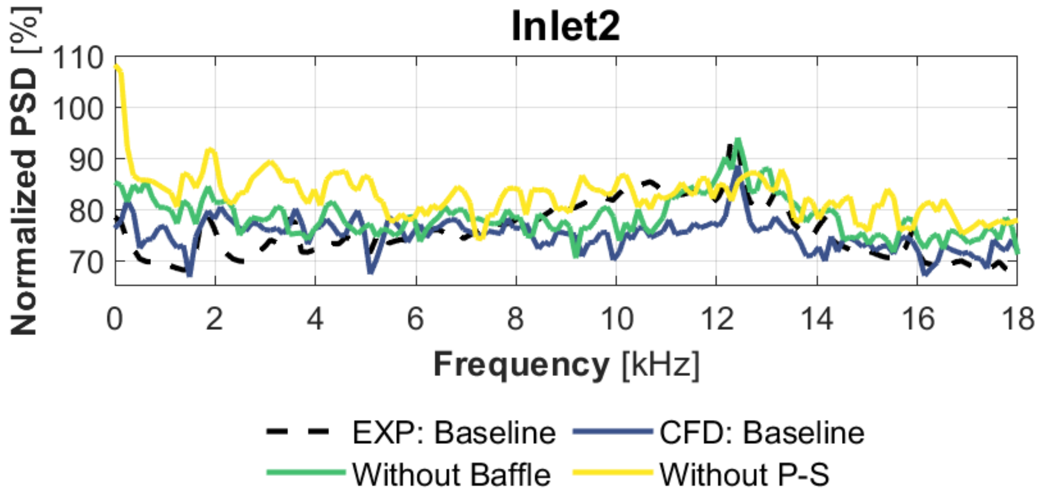


Results & Discussion – Ported-Shroud

❖ Acoustic Spectrum

- **High-load regime**
  - **Outlet and Volute** sensors:
    - **Similar spectra** between geometries
  - **Inlet** duct sensors:
    - **Without baffle**:
      - **Higher energy** content than **baseline**
    - **Without ported-shroud**:
      - **Higher energy** content (broadband) and BPF not so tonal
        - **Solution oscillation**

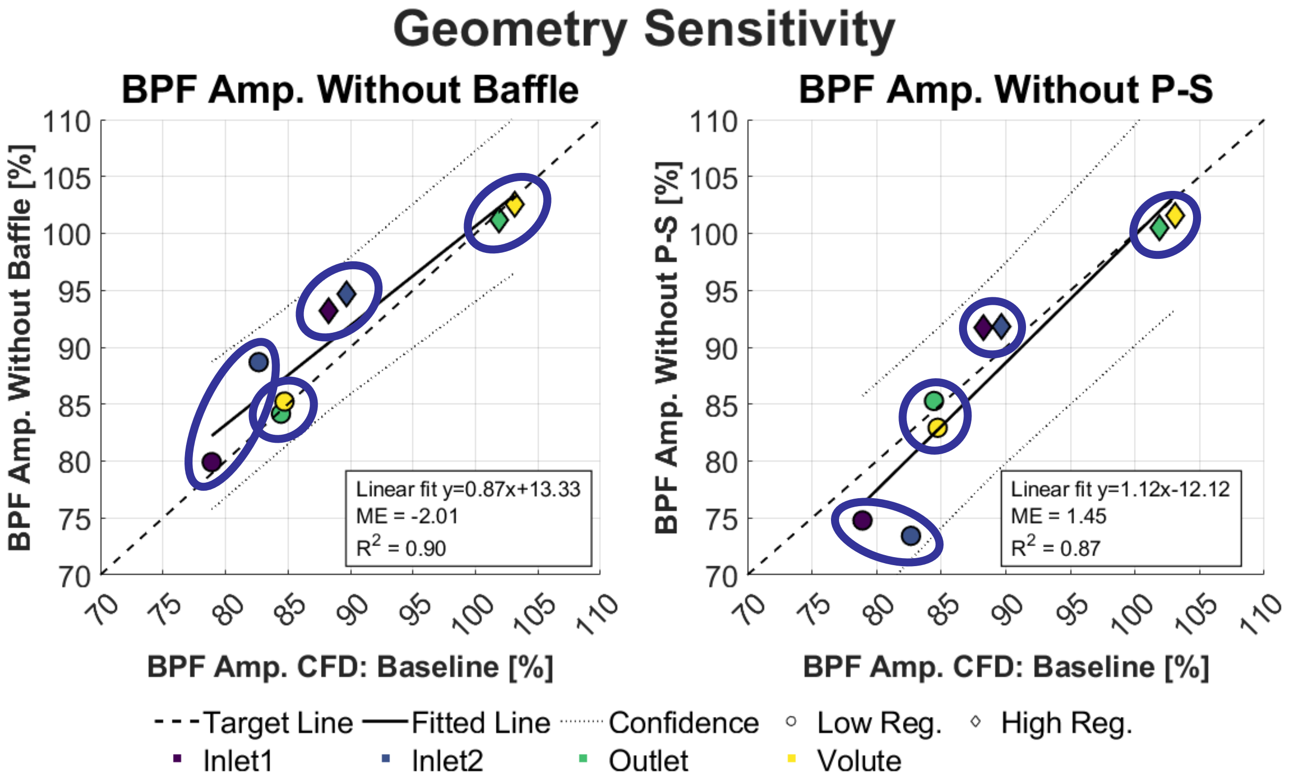




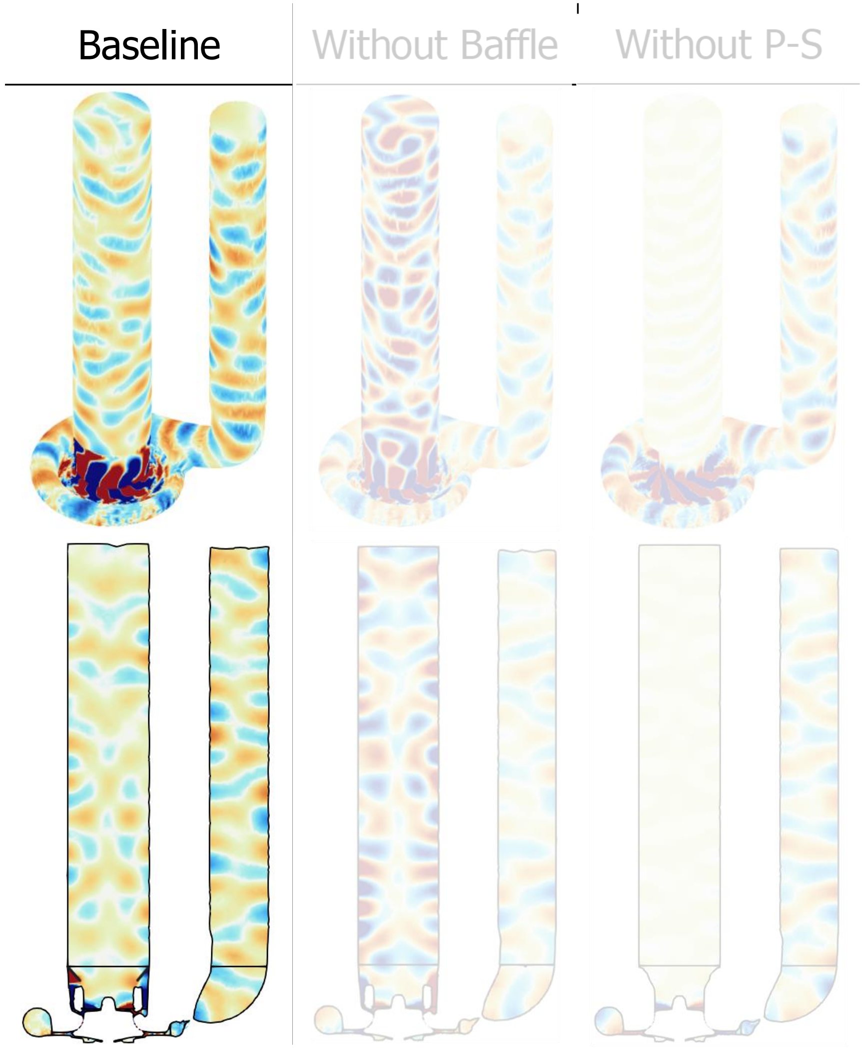
Results & Discussion – Ported-Shroud

❖ BPF Amplitude

- **Outlet and Volute** sensors:
  - **Similar BPF amplitude** between geometries
- **Inlet** duct sensors:
  - **Without Baffle**:
    - **BPF tonal noise** is **higher** than the baseline case
  - **Without Ported-Shroud**:
    - **BPF tonal noise** is **lower** than the baseline under **low regime** conditions
    - **High regime** results are strongly **influenced** by **surge** conditions



❖ Proper Orthogonal Decomposition
- **BPF** mode & **Low**-Load Regime
- Most **relevant mode**:
  - **Baseline** & **Without Baffle** → **1st**
  - **Without Ported-Shroud** → **2nd**
- Inlet duct **energy content**:
  - Without Baffle **>** Baseline
  - Without Ported-Shroud **<** Baseline
- Inlet duct mode **pattern**:
  - It is highly **influenced** by the presence of the **ported-shroud**



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Concluding Remarks

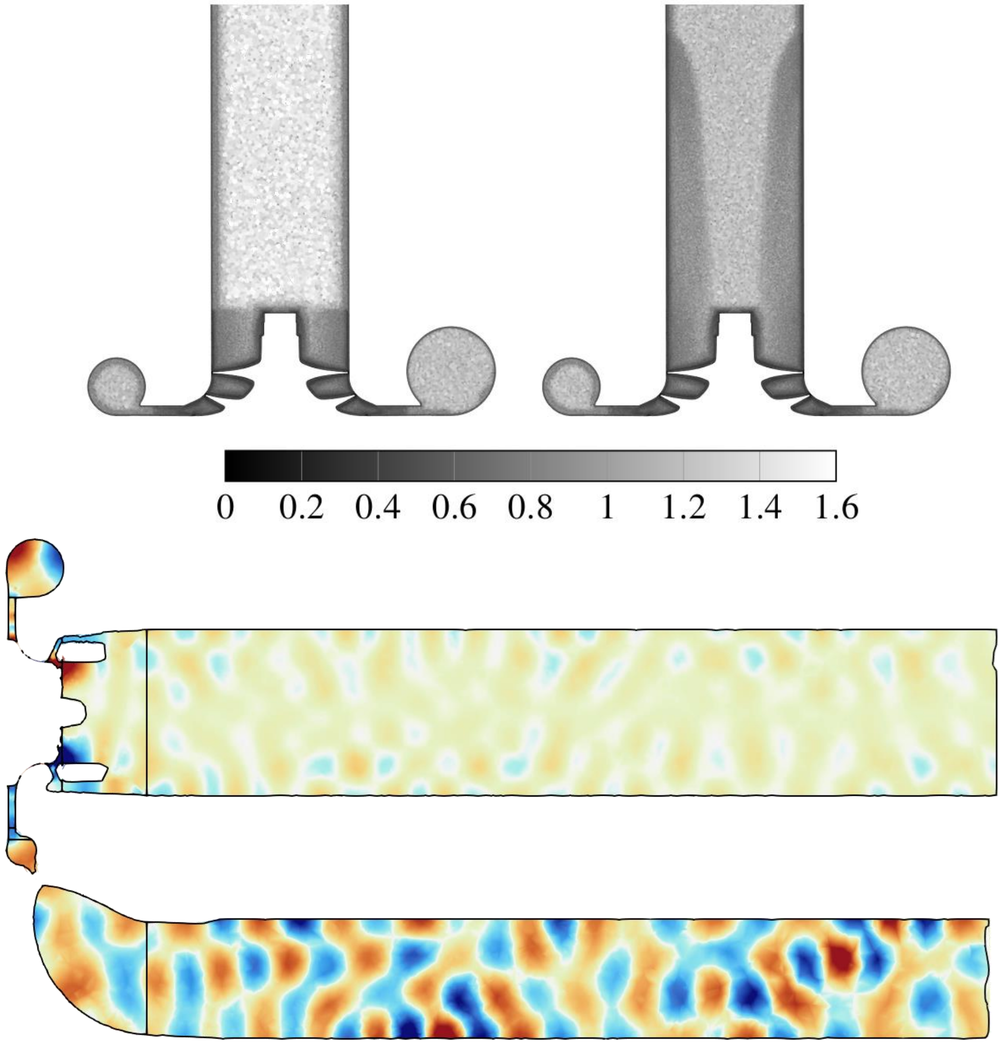
❖ Conclusions

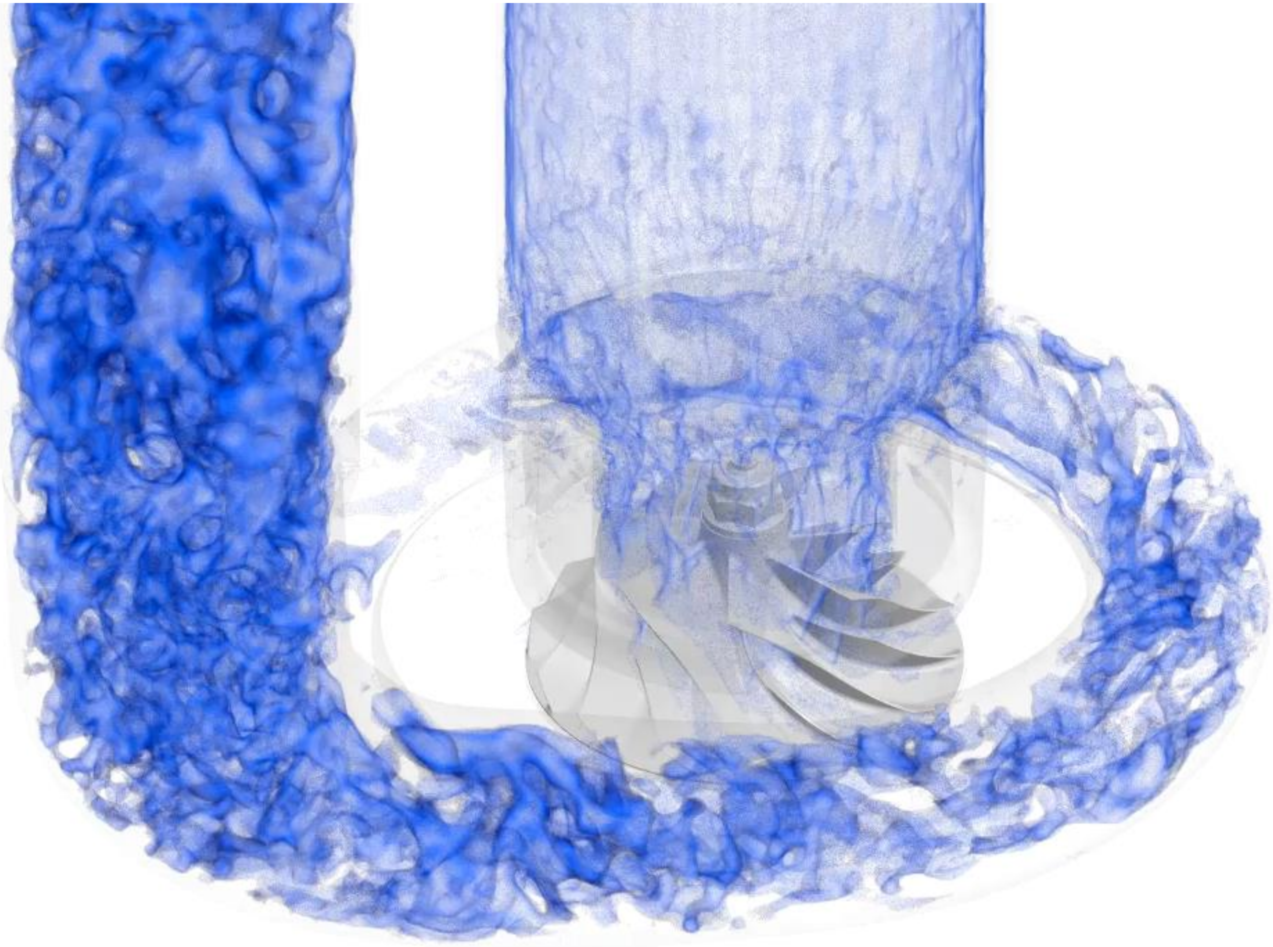
- **Probe location** sensitivity
- **Cutting-edge** computational capabilities
- Impeller Backside Cavity (**IBC**):
  - **Negligible differences** on global variables, flow field & acoustics
  - **Without IBC**, a slight **increase in energy content** is observed
  - For **Acoustic** Analysis → **removing the IBC** is recommended
    - **Number of cells reduced** by ~**20%**
- **Ported-Shroud**:
  - The **numerical model** adequately **captures acoustic** variations between the three geometries
    - **Without baffle** → **louder** BPF and broadband noise
    - **Without ported-shroud** → **quieter** BPF and broadband noise

Concluding Remarks

❖ Future Work

- **Recirculation** zone **sensitivity** to **mesh** approach
  - Zone refinement, overkill & AMR
- **Tip clearance** and rotor **aeroelasticity**
- **Probe location**
  - Extract values directly from **mode decomposition**
- **Reduce computational cost**
  - DES, 20M cells…
- **Optimize ported-shroud** geometry
  - Reduce BPF





THANKS FOR YOUR ATTENTION

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