Smart Mitigation of flow-induced Acoustic Radiation and Transmission for reduced Aircraft, Surface traNSport, Workplaces and wind enERgy noise

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Fan noise suppression with Over-Tip-Rotor liners: impedance modelling of acoustically treated circumferential grooves

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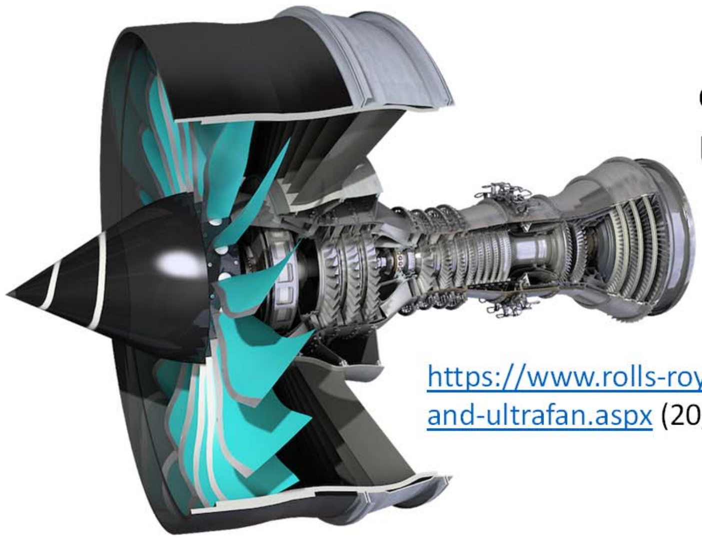
H2020 MARIE SKŁODOWSKA-CURIE ACTIONS

Outline

- Context
- Background
- Objectives
- Modelling of acoustically treated circumferential grooves:
  - Formulation of the analytical models
  - Benchmark high-order FEM simulations
  - Cross-verification of analytical and numerical results
- Conclusions
- Future Work
- References

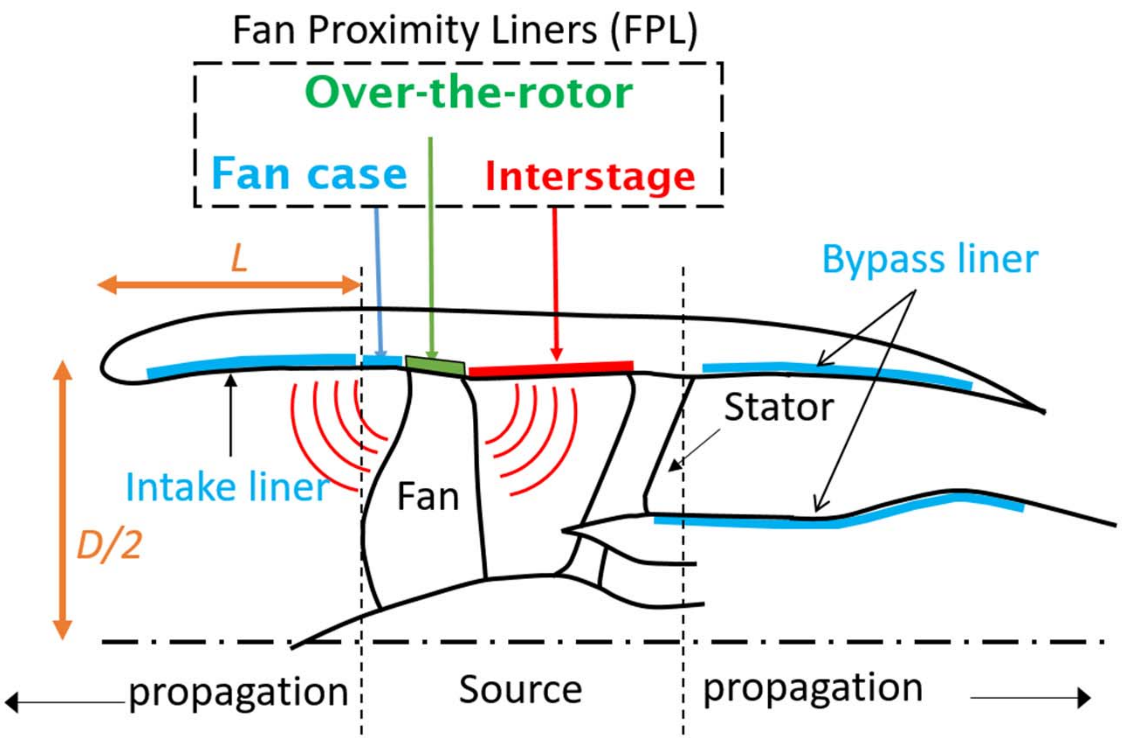
Context

Dominant Noise	
Approach	Departure
• Fan Noise • Airframe Noise	• Fan Noise • Jet Mixing Noise



e.g. Rolls-Royce Ultrafan, BPR 15+

https://www.rolls-royce.com/innovation/advance-and-ultrafan.aspx (20/09/17)



- Mitigation of Fan Noise remains critical in noise reduction for the next generation of engines (2020).
- BPR for large engines:

$\sim 10:1 \ \rightarrow 15:1 +$ ➡ Reduced liner performance due to lower L/D

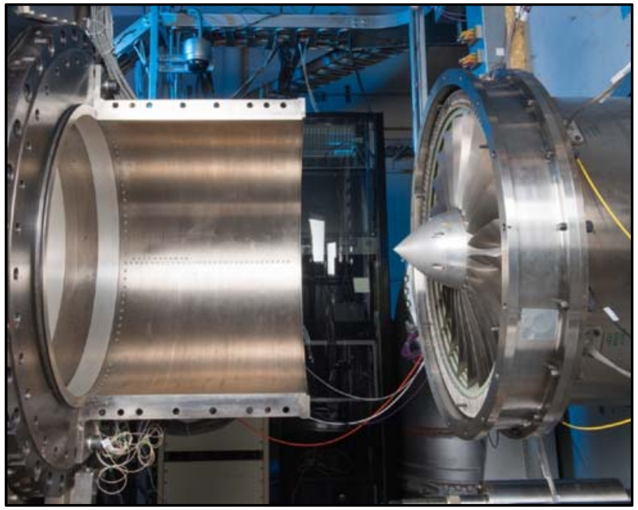
- Optimise liner effect by exploiting available space

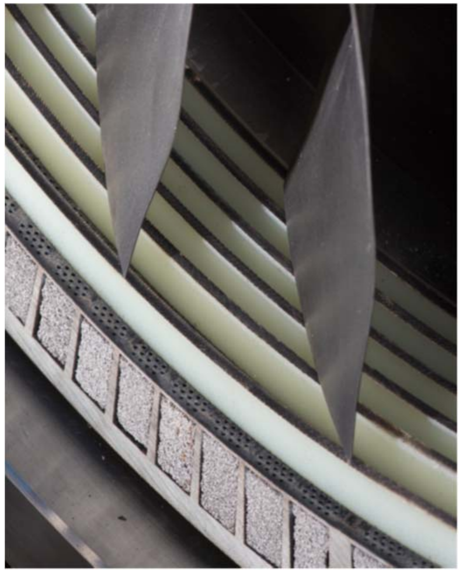
Background

- *Over-The-Rotor (OTR) Acoustic Treatments*
  - **Physical Mechanism**
    - Source modification
    - Absorption of acoustic waves
    - Reduced rotor-stator noise
  - **Experimental Data**

Publication	Noise Attenuation	Loss in Adiabatic Efficiency
Sutliff et. al. [1]	4 dB PWL (inlet & aft)	-
Elliot et. al. [2]	1 dB OAPWL	-
Sutliff et. al. [3][4]	5 dB inlet PWL / 2.5 dB OAPWL	1-2 %
Hughes and Gazzaniga [5]	-	6.5 - 9.3 %
Bozak et. al. [6]	-	0.75 %
Gazella et. al. [7]	1 dB / 3 dB (inlet/aft) PWL	-
Bozak and Dougherty [8]	2.5-3.5 dB (inlet) PWL	-

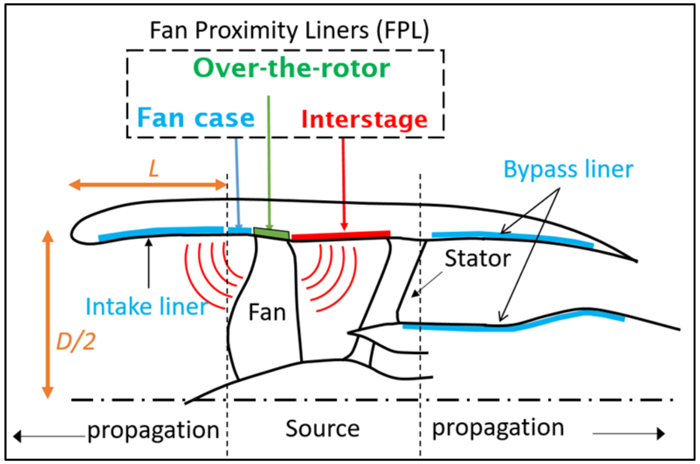
  - **Design & Modelling**
    - Prediction method for OTR liner design

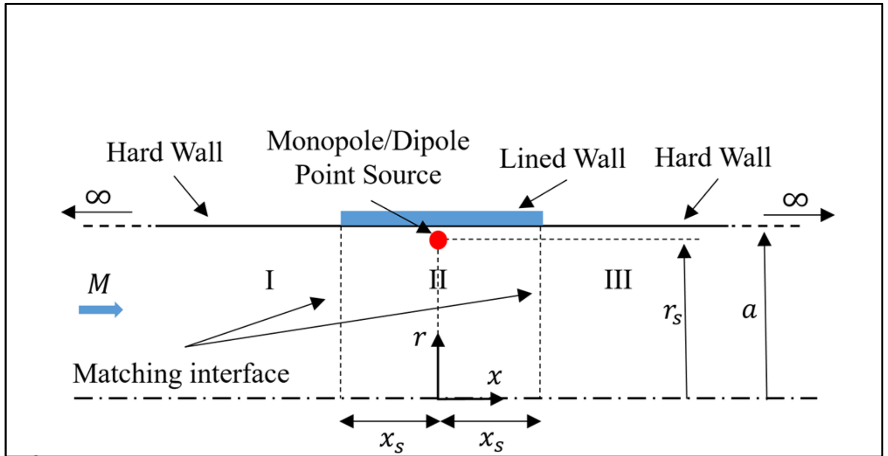

W-8 Single Stage Axial Compressor facility [8]


OTR acoustic casing treatment [8]

Objectives

- Improve the understanding of the acoustic attenuation of OTR liners through the development of theoretical models, numerical simulations and experimental validation.
- Use the acquired understanding to provide a prediction method to guide the choice of low-TRL fan proximity liner designs for optimal noise reduction.

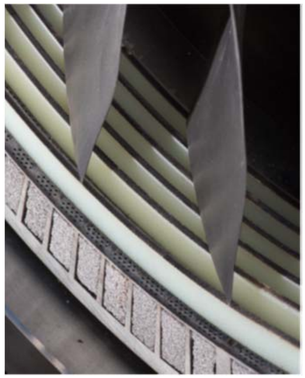




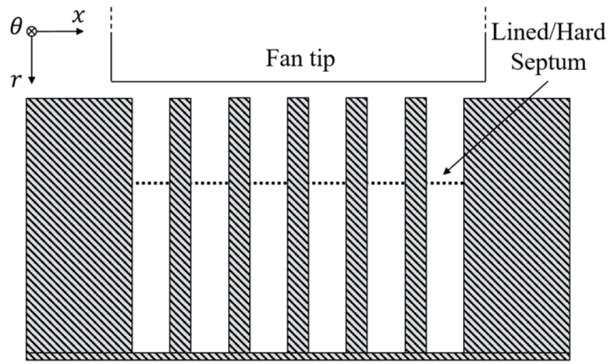
Source modelling: based on the Green's function for a lined circular duct containing uniform mean flow.

Mode-matching scheme: based on continuity of mass and momentum and source model.

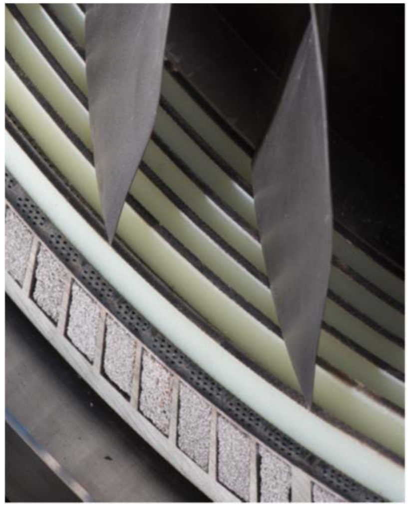
Impedance modelling: to obtain an equivalent impedance of acoustically treated circumferential grooves



OTR acoustic casing treatment [8]

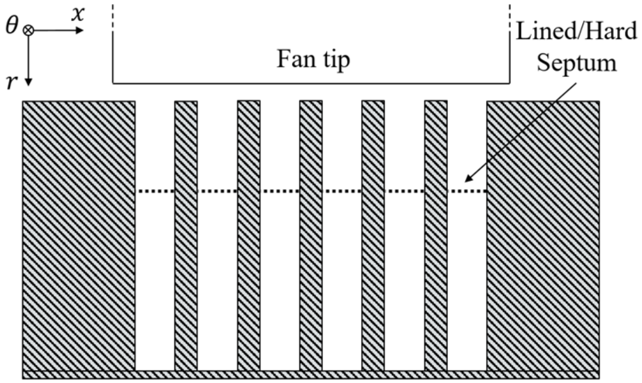


Formulation of the analytical models – previous work



OTR acoustic casing treatment [8]

Acoustically treated circumferential grooves

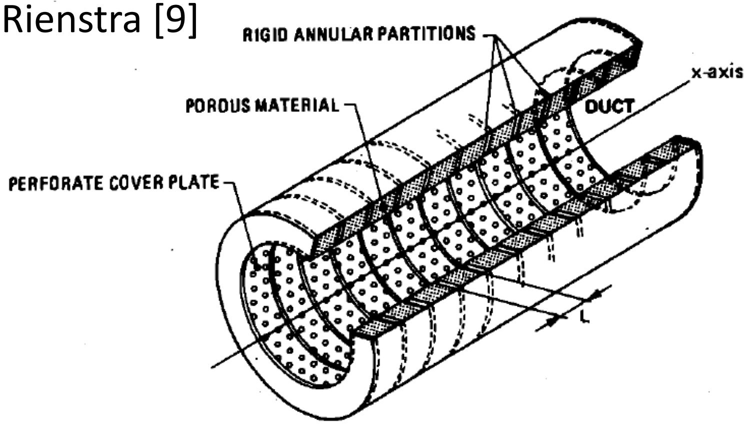


Hard grooves: it could be obtained as a particular case of:

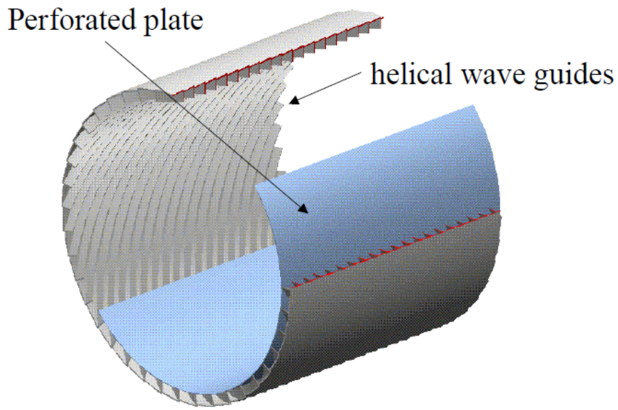
1. Bulk-reacting liner with annular partitions [9], with bulk properties matching those of air.
2. "Spiralling" liner [10], without perforated plate and spiral angle set to zero.

Lined grooves: equivalent to the hard groove with a SDOF boundary condition at the bottom.

Bulk-reacting liner with annular partitions, Rienstra [9]



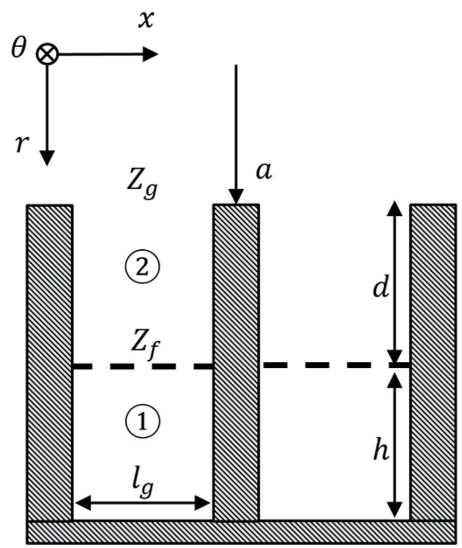
"Spiralling" liner, Sijtsma & Van der Wal [10]

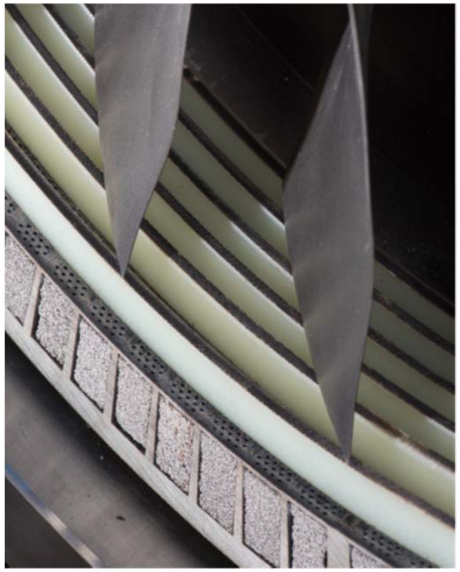


Formulation of the analytical models – Annular

Circumferential grooves (②) with acoustic treatment in the bottom of the grooves (①).

- Azimuthal propagation in ② matches that in the main duct.
- Axial or azimuthal flow in ② currently neglected.
- Section ② non-locally reacting in the azimuthal direction.
- Section ② locally reacting the axial direction.
- Acoustic treatment ① behave as SDOF cavity liner.




OTR acoustic casing treatment [8]

The pressure field can be expressed as:

$$p(x,r,\theta) = \sum_{m=-\infty}^{\infty} e^{-jm\theta} \sum_{n=0}^{\infty} p_n(x) p_{mn}(r) \quad \begin{cases} p_n(x) = A_n \cos(\kappa_n x) + B_n \sin(\kappa_n x), \kappa_n = n\pi/l_g \\ p_{mn}(r) = J_m(\alpha_n r) + K_m Y_m(\alpha_n r) \end{cases}$$

For the geometry used in W-8, f>30 kHz for the first axial mode. Only $n = 0$ considered → Dispersion relation reduced to $\alpha_n = \pm\sqrt{\omega^2 - \kappa_n^2} = \omega$

$$Z_g = -j \frac{J_m(\omega) + K_m Y_m(\omega)}{J'_m(\omega) + K_m Y'_m(\omega)} \qquad K_m = -\frac{J'_m(\omega[1+d]) + j\dfrac{J_m(\omega[1+d])}{Z_f}}{Y'_m(\omega[1+d]) + j\dfrac{Y_m(\omega[1+d])}{Z_f}}$$

(A) Annular Model

Impedance modelling - Analytical

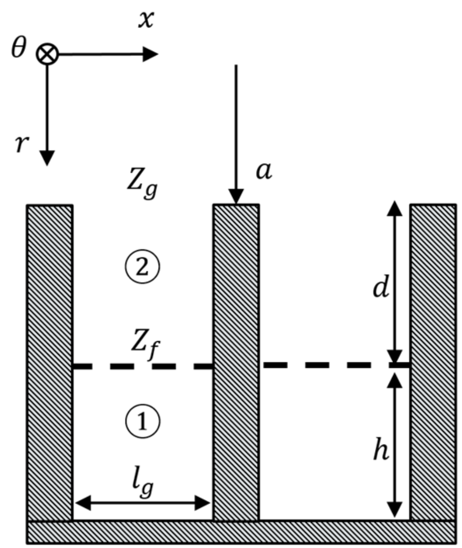
Formulation of the analytical models – Cartesian

- Approximation of the annular casing by a linear section by assuming that $d/a \ll 1$.
- Neglecting any axial propagation:

$$p(r,\theta) = p_m(r)e^{-jm\theta} \approx p(y,z) = p_m(y)e^{-jk_z z}, \quad k_z = m$$

where

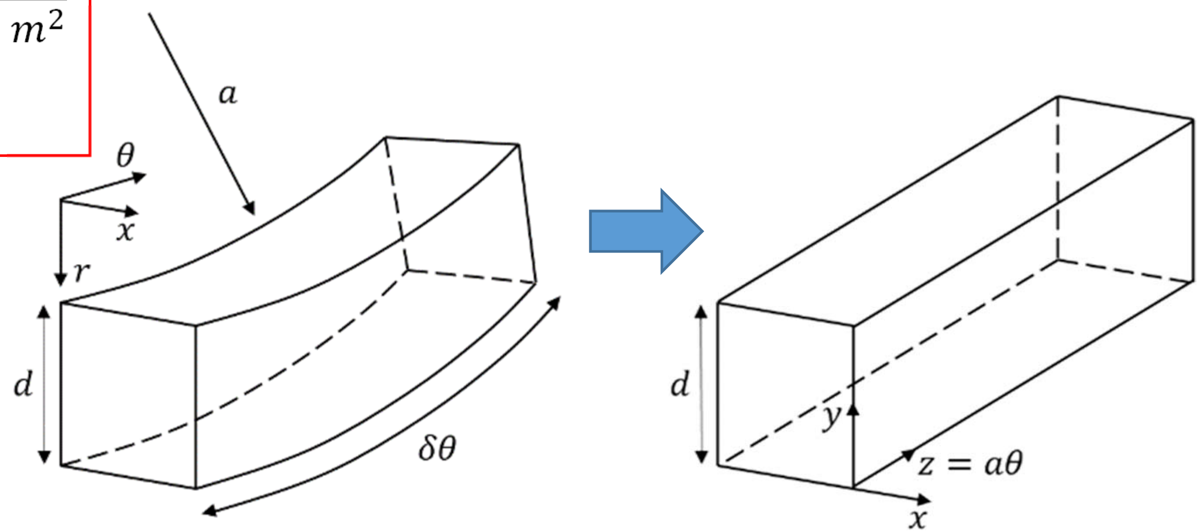
$$p_m(y) = A_n \cos(k_y y) + B_n \sin(k_y y)\,,\ k_y = \sqrt{\omega^2 - m^2}$$



OTR acoustic casing treatment [8]

$$Z_g = -\frac{j\omega}{k_y}\left[\frac{\cot(k_y d) + \frac{j\omega}{Z_f k_y}}{1 - \frac{j\omega}{Z_f k_y}\cot(k_y d)}\right] \quad \begin{cases} k_x = 0 \\ k_y = \sqrt{\omega^2 - m^2} \\ k_z = m \end{cases}$$

(B) Cartesian Model

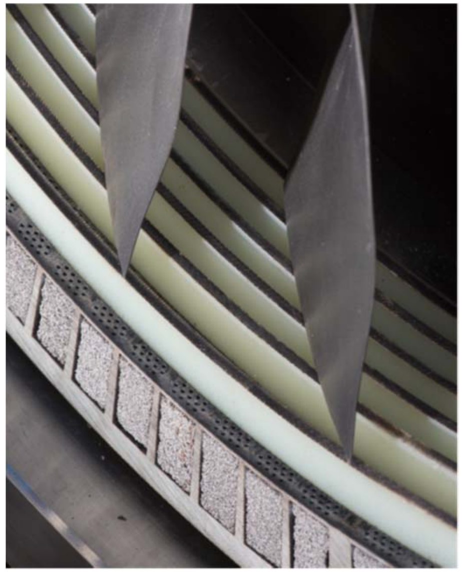


Impedance modelling - Analytical

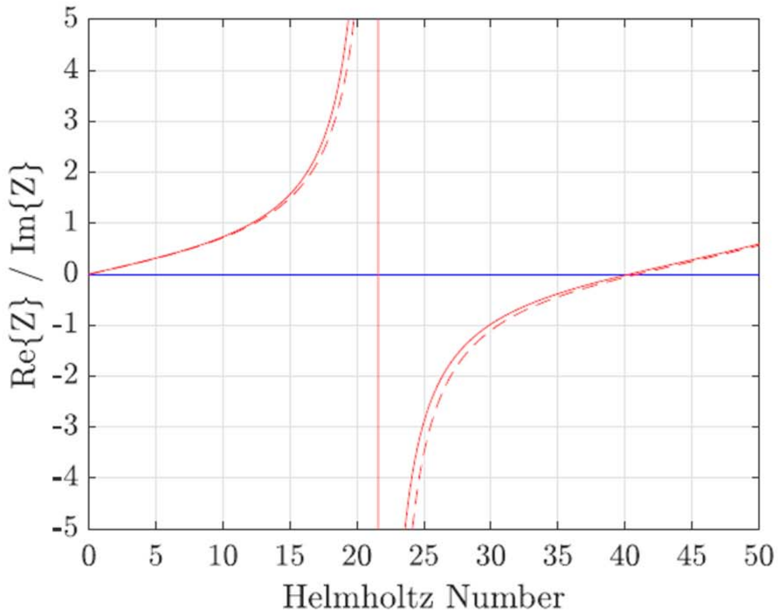
Formulation of the analytical models – Comparison

$$Z_f(\omega) = R_f + j\left[\frac{\omega}{a}\frac{t+d}{\sigma} - \cot\left(\frac{\omega h}{a}\right)\right]$$

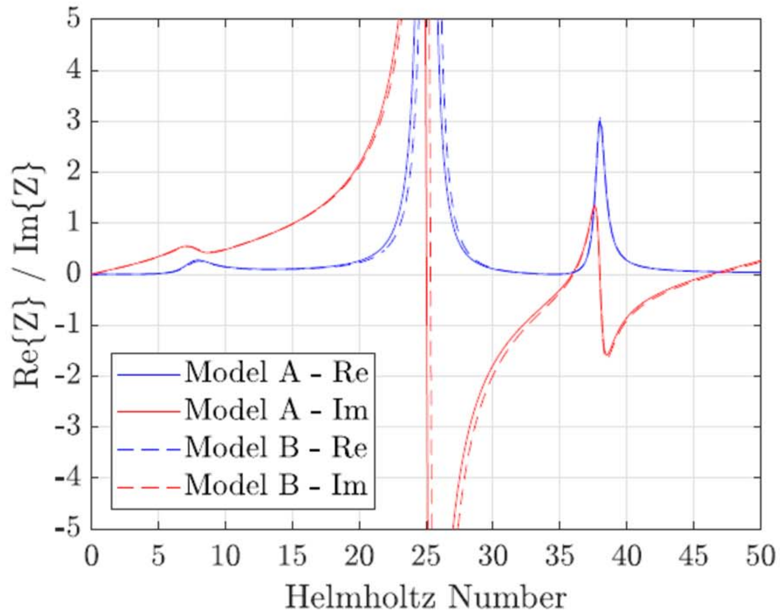
R_{fs}	t_{fs}	d_{fs}	σ	h	d
0.5	1.5 mm	0.89 mm	0.1	25.4 mm	12.7 mm



OTR acoustic casing treatment [8]



Hard groove



Lined groove

Model A: Annular

Model B: Cartesian

$m = 22$

$d/a \sim 0.046 \ll 1$

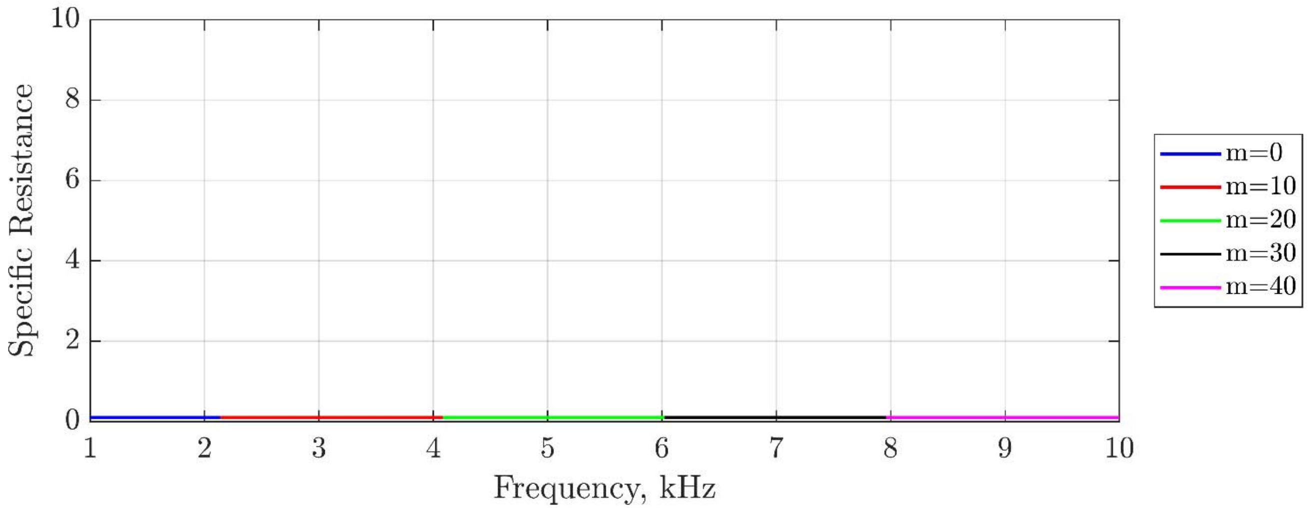
Impedance modelling - Analytical

Semi-locally reacting circumferential groove - Resistance

Hard groove

$$Z_g = R_a - \frac{j\omega}{k_y}\cot(k_y d)$$

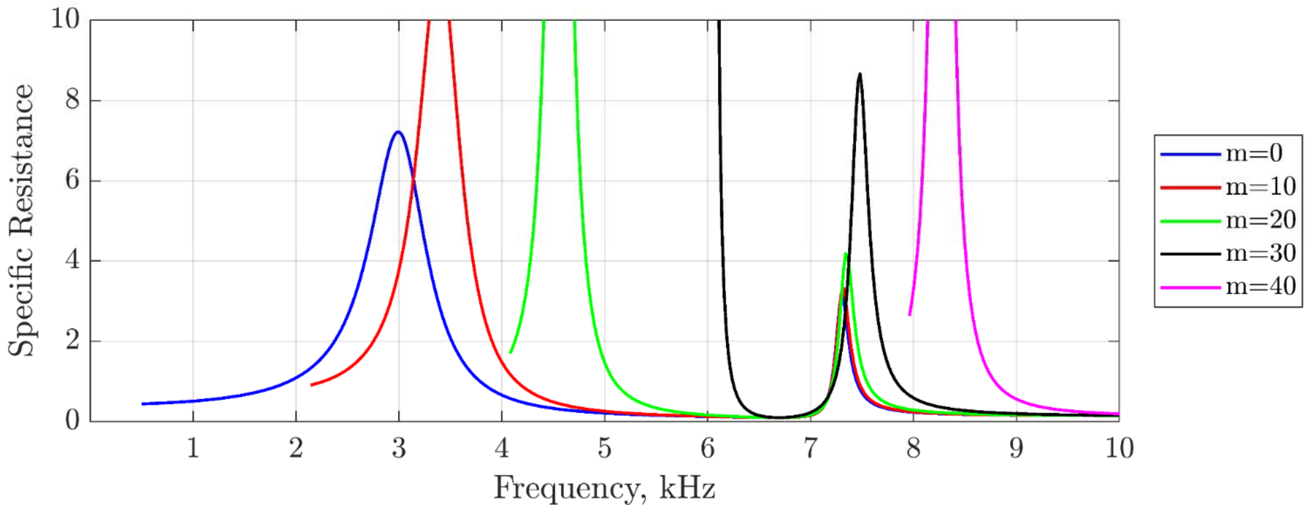
$$k_y = \sqrt{\omega^2 - m^2}$$



Lined groove

$$Z_g = -\frac{j\omega}{k_y}\left[\frac{\cot(k_y d) + \frac{j\omega}{Z_f k_y}}{1 - \frac{j\omega}{Z_f k_y}\cot(k_y d)}\right]$$

$$k_y = \sqrt{\omega^2 - m^2}$$



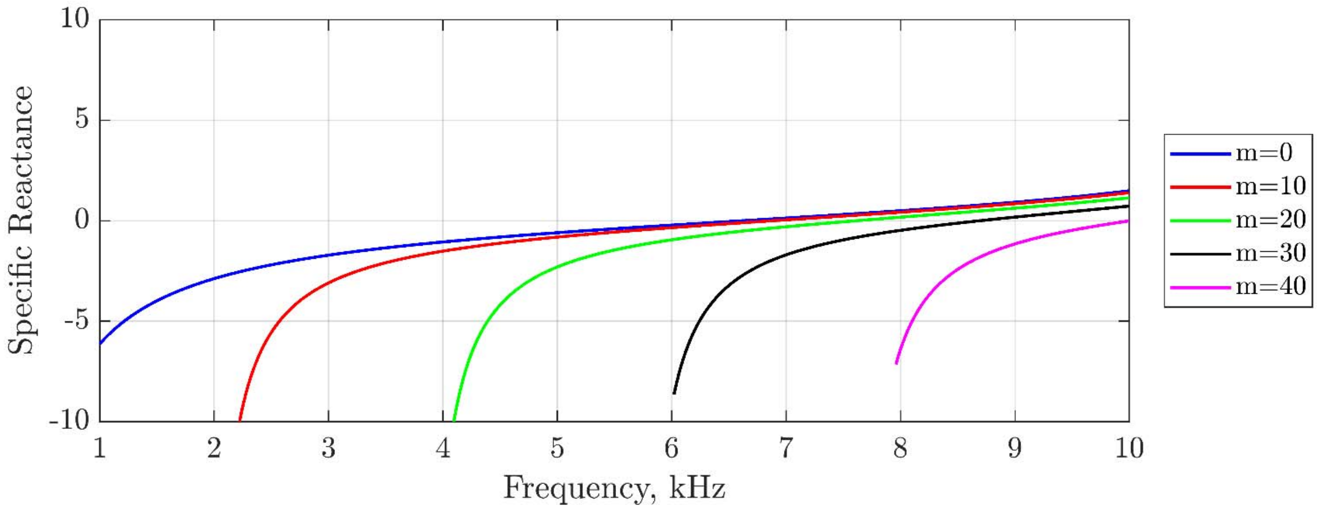
Impedance modelling - Analytical

Semi-locally reacting circumferential groove - Reactance

Hard groove

$$Z_g = {\color{red}R_a} - \frac{j\omega}{k_y}\cot(k_y d)$$

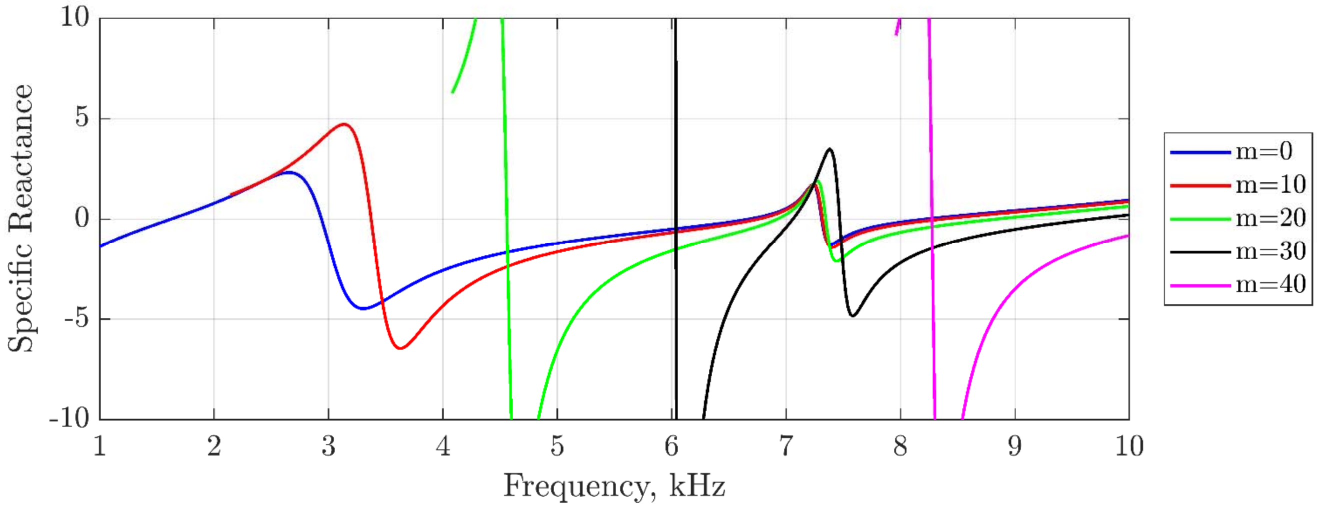
$$\omega = \sqrt{m^2 + \left(\frac{\pi}{2d}\right)^2} \rightarrow Z_g = 0$$



Lined groove

$$Z_g = -\frac{j\omega}{k_y}\left[\frac{\cot(k_y d) + \frac{j\omega}{Z_f k_y}}{1 - \frac{j\omega}{Z_f k_y}\cot(k_y d)}\right]$$

$$k_y = \sqrt{\omega^2 - m^2}$$

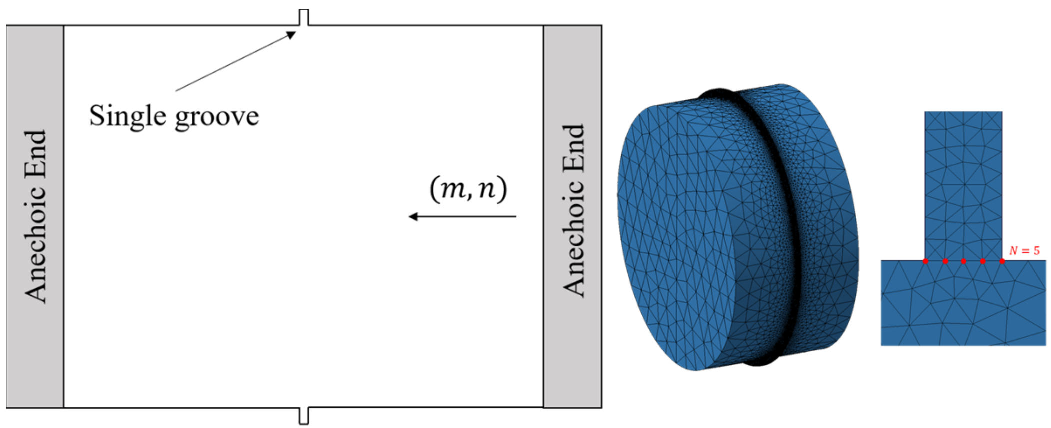


Impedance modelling - FEM

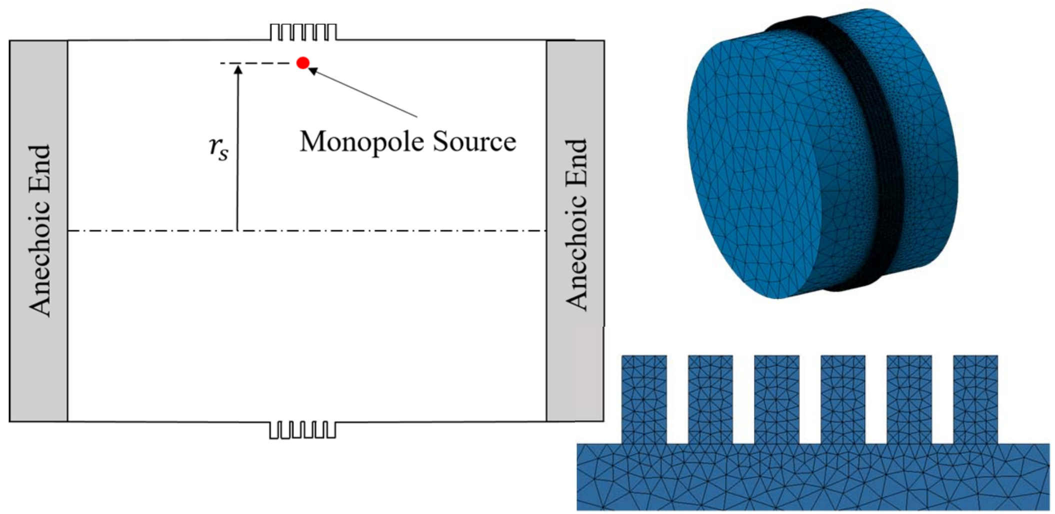
Benchmark high-order FEM simulations

- *FEM Software*: LMS Virtual.Lab (SIEMENS PLM)
  - High-order FEM solver with adaptive polynomial order based on *a priori* error indication (*p-refinement*) [11] .
  - Mesh refinement to represent the geometry and in regions with singularities (*h-refinement*).
- *Objetives:*
  1. Improve the understanding of the acoustic response of acoustically treated semi-locally reacting grooves.
  2. Provide a reference solution to cross-verify with the analytical impedance model.
- *Cases:* (groove geometry as tested in the W-8 rig)

A/B: Single/multiple grooves with incident duct modes

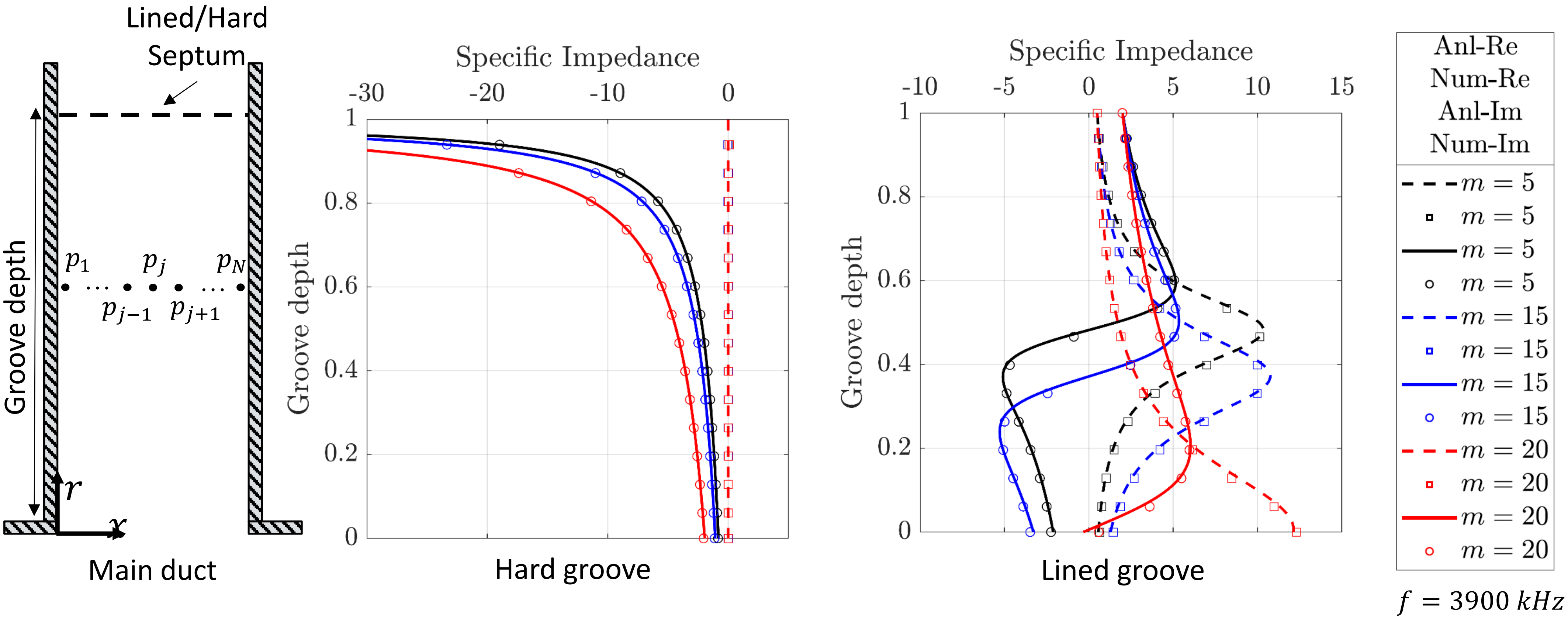


C: Multiple grooves excited by a monopole source



Impedance modelling - Verification

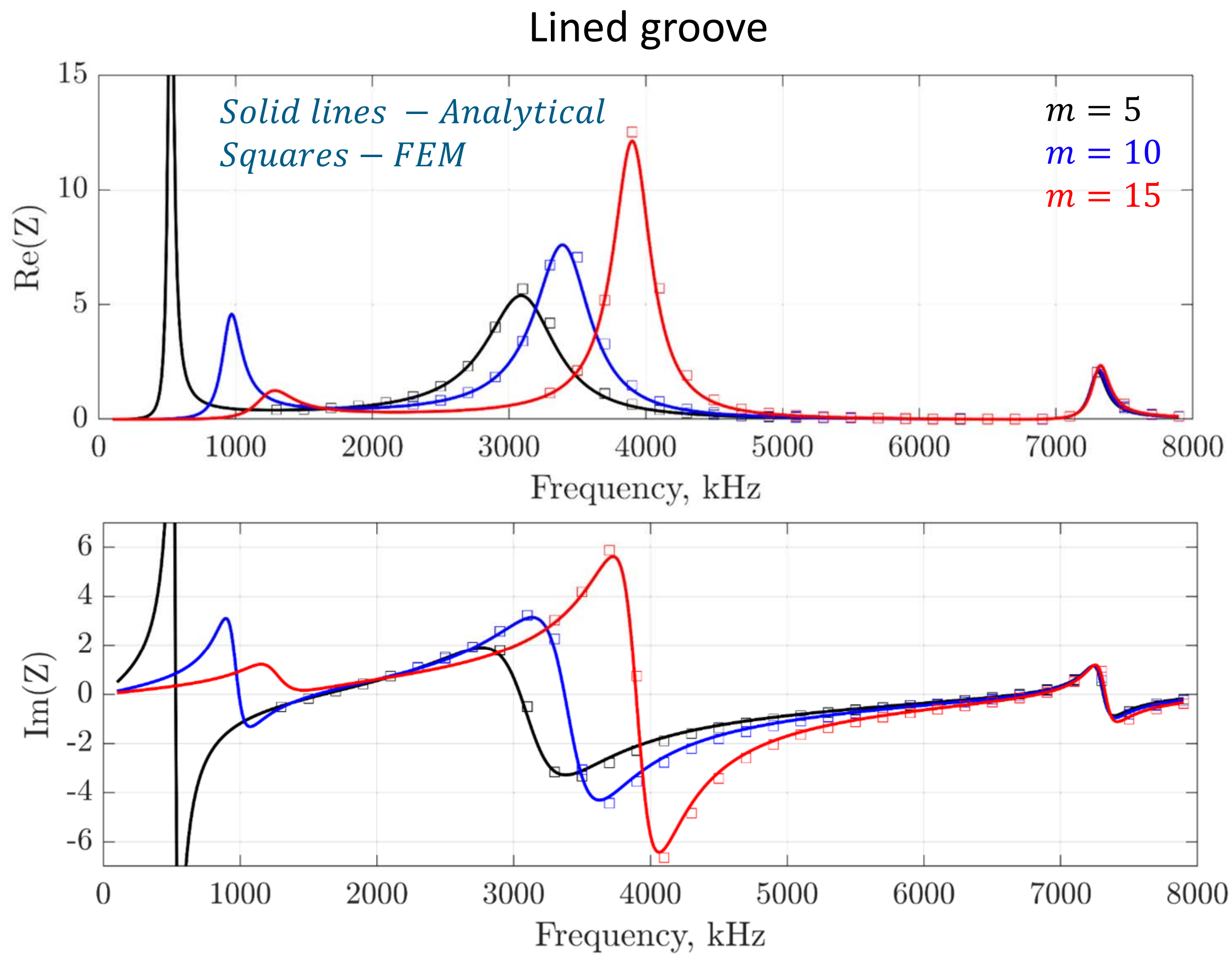
Benchmark high-order FEM simulations: Case A - Single groove with incident duct modes

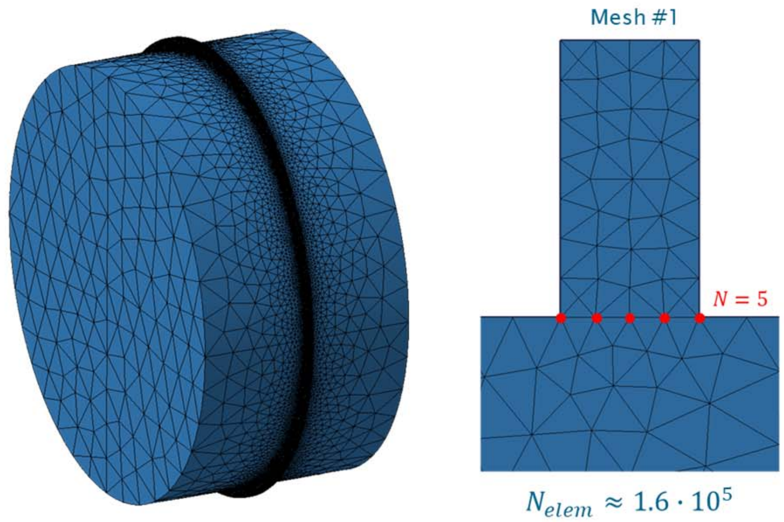


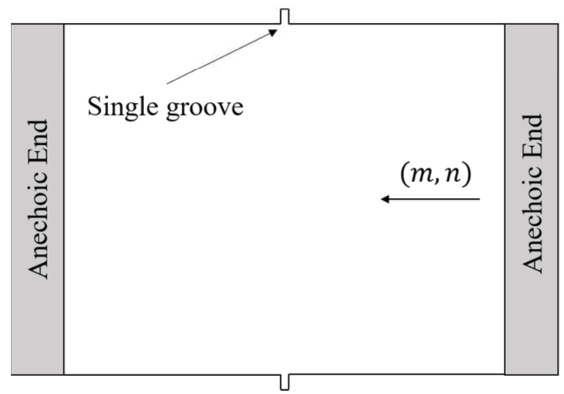
1. Average acoustic magnitudes in the axial direction (axially locally reacting). ➡ $\bar{p}(\omega, m, n, r)$ & $\bar{u}_r(\omega, m, n, r)$
2. Compute the effective axial impedance for each frequency and mode number. ➡ $\bar{Z}(\omega, m, n, r) = \dfrac{\bar{p}(\omega, m, n, r)}{\bar{u}_r(\omega, m, n, r)}$ ➡ Comparable to the analytical impedance models.

Impedance modelling - Verification

Benchmark high-order FEM simulations: Case A - Single groove with incident duct modes

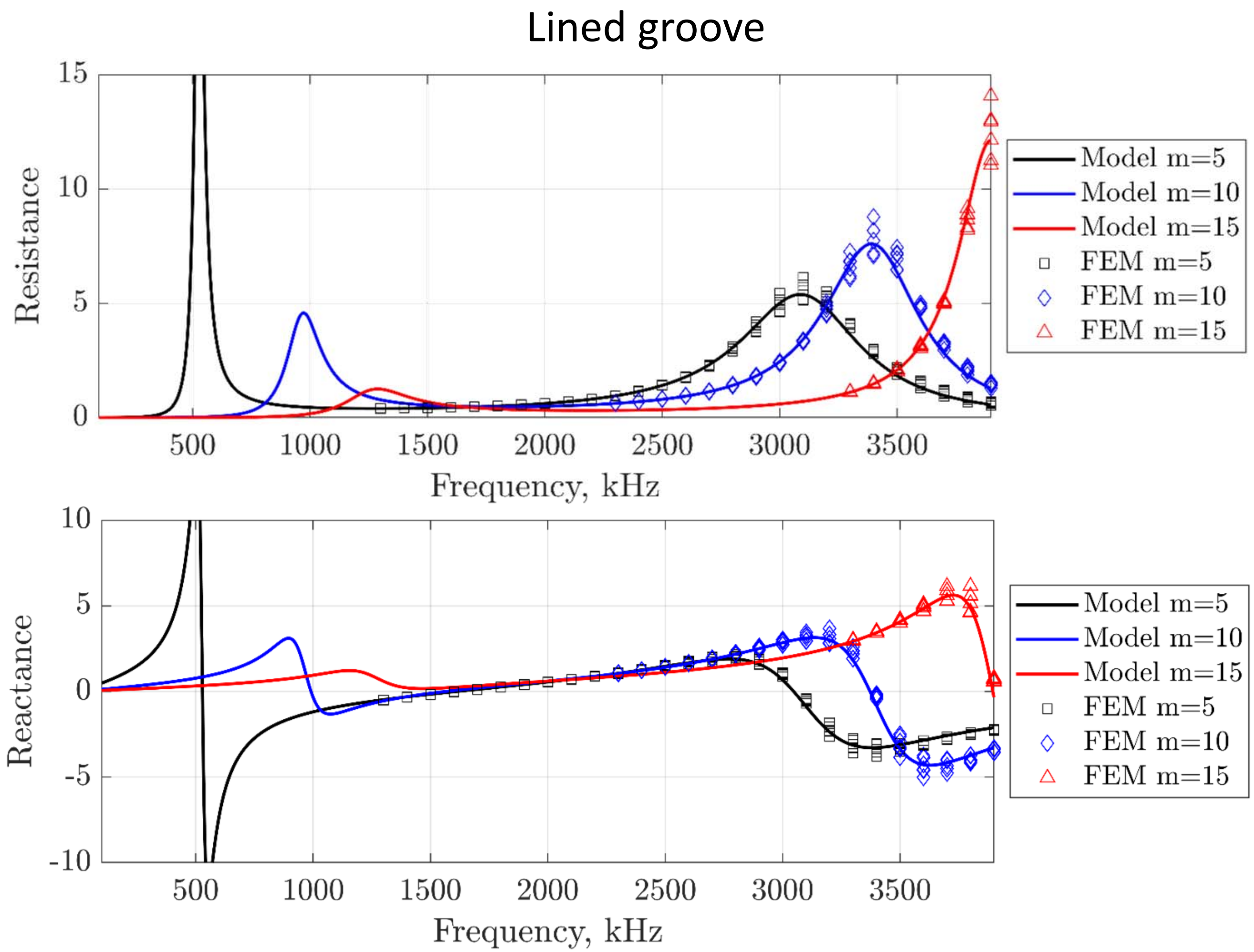


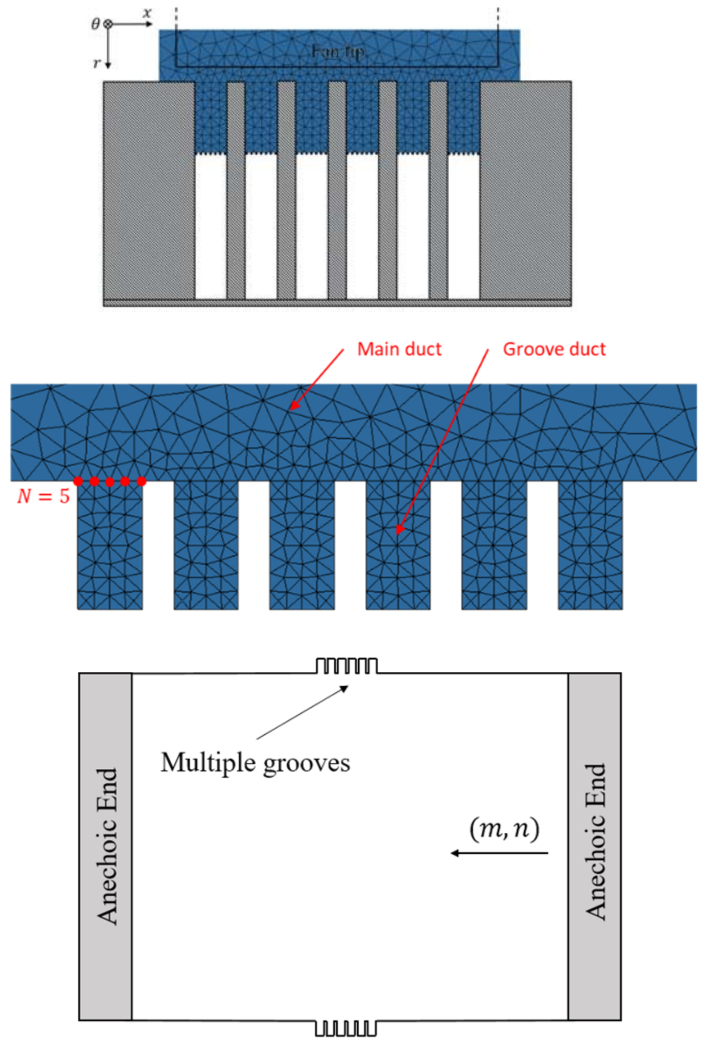




Impedance modelling - Verification

Benchmark high-order FEM simulations: Case B - Multiple grooves with incident duct modes





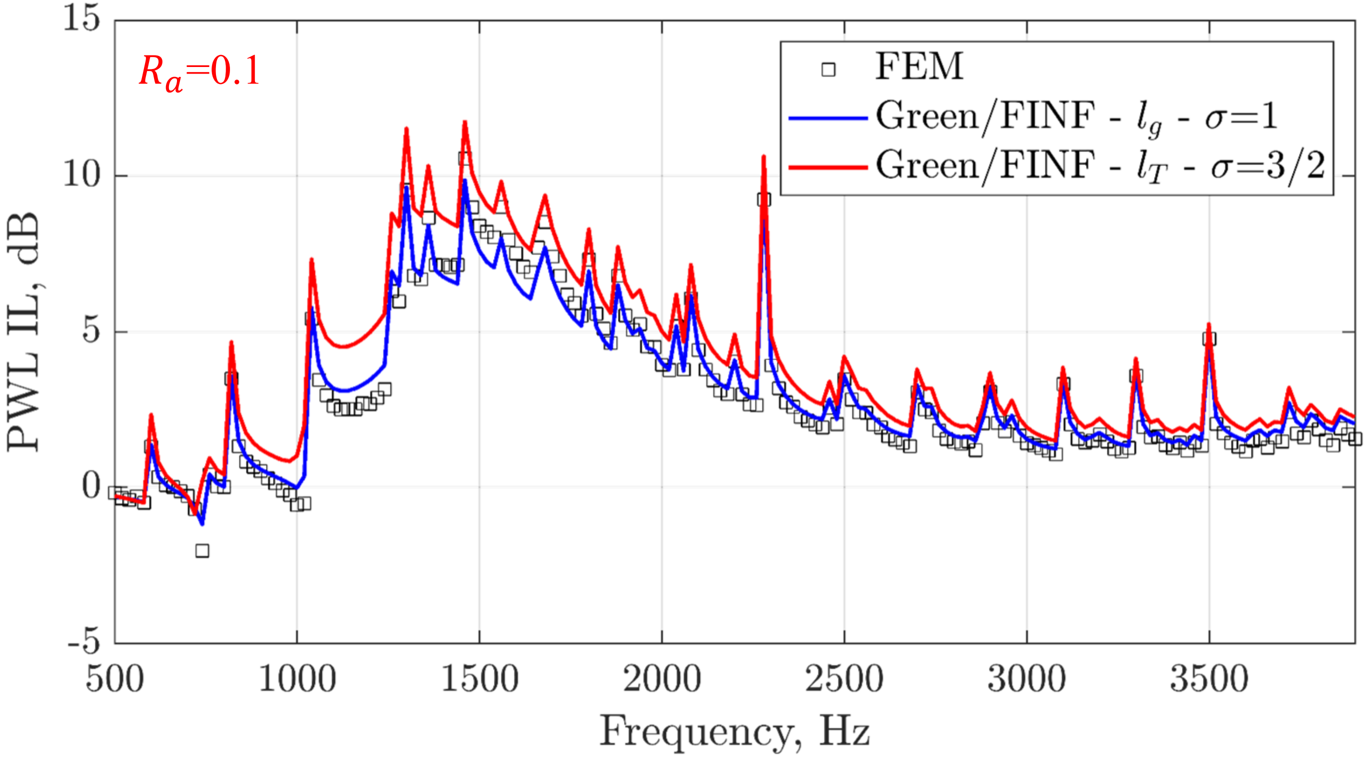
Impedance modelling - Verification

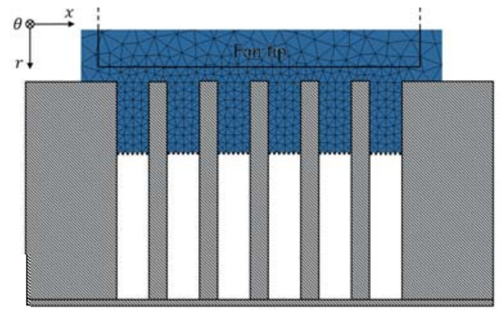
Benchmark high-order FEM simulations: Case C - Multiple grooves excited by a monopole source

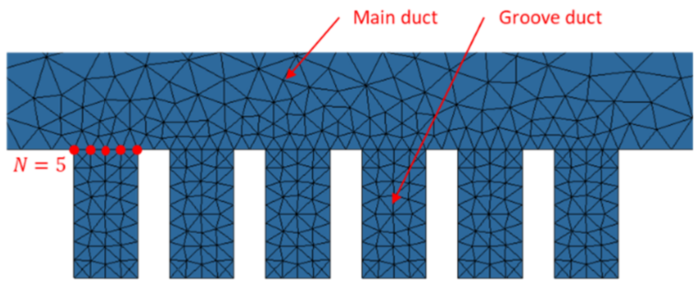
- Effective impedance for multiple grooves (continuity of mass in the r-direction):

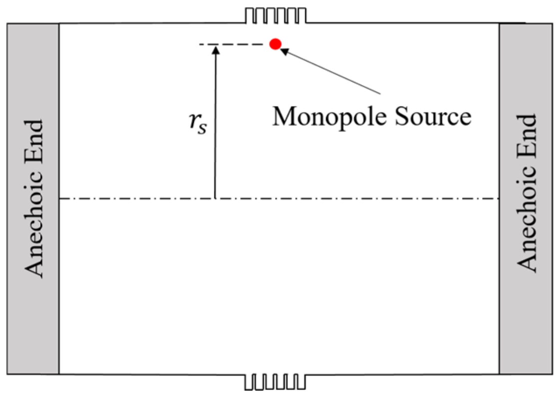
$$Z_{mul} = R_a + \sigma Z_{sin}\,, \qquad \sigma = \frac{l_g}{l_T}$$

l_T, l_g, total length of the treatment and the groove-duct interface









Conclusions

- ***Formulation of the analytical models***
  - Development of annular & Cartesian groove models, which show a good agreement for the geometry and frequencies of interest.
- ***Benchmark high-order FEM simulations***
  - Convergence study with groove & source region refinement.
- ***Cross-verification of analytical and numerical results***
  - *Case A:* The assumptions made in the analytical model for a single groove result in an excellent prediction of its equivalent impedance at the groove-duct interface.
  - *Case B:* If multiple grooves are present, the equivalent impedance in each groove interface can vary from one to another, but it is centred in the single groove prediction.
  - *Case C:* The ‘porosity’ assumption leads to peak deviations of <1 dB, providing reasonable agreement in the magnitude and trend away from the peak attenuation.

Future work

- In real groove OTR applications → fan induces swirling flow *within* the groove.

  - **Annular formulation**: assume swirling flow within the groove and match the azimuthal propagation to that in the main groove.
  - **Cartesian formulation:** assume uniform / sheared flow within the groove and match the azimuthal propagation to that in the main groove.

- Vortex-induced noise is beyond the scope of this project.

Acknowledgments

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- *Richard F. Bozak*, for the pictures and data of the OTR acoustic casing treatments and W-8 NASA test rig.

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Thank you for your attention