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

SmartANSWER

von KARMAN INSTITUTE FOR FLUID DYNAMICS

UNIVERSITY OF Southampton Institute of Sound and Vibration Research

Mid-Term Workshop: Modelling Techniques (M24)

M. Monfaredi, S. Palleja, C. Sanghavi, A. Zarri

Siemens PLM Software

SIEMENS

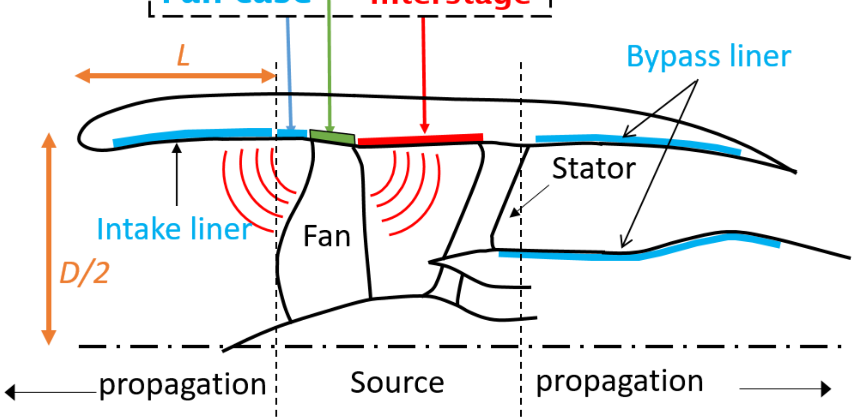
National Technical University of Athens

M24 SmartAnswer Mid-Term Workshop, Leuven, 20th February 2019

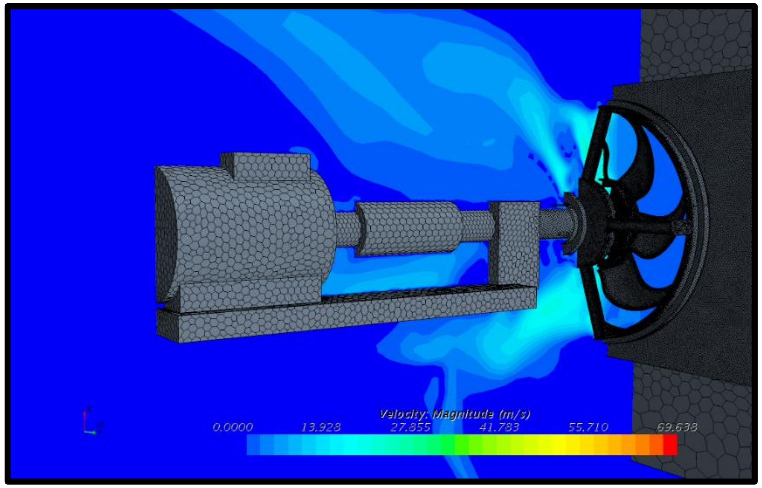
H2020 MARIE SKŁODOWSKA-CURIE ACTIONS

Applications

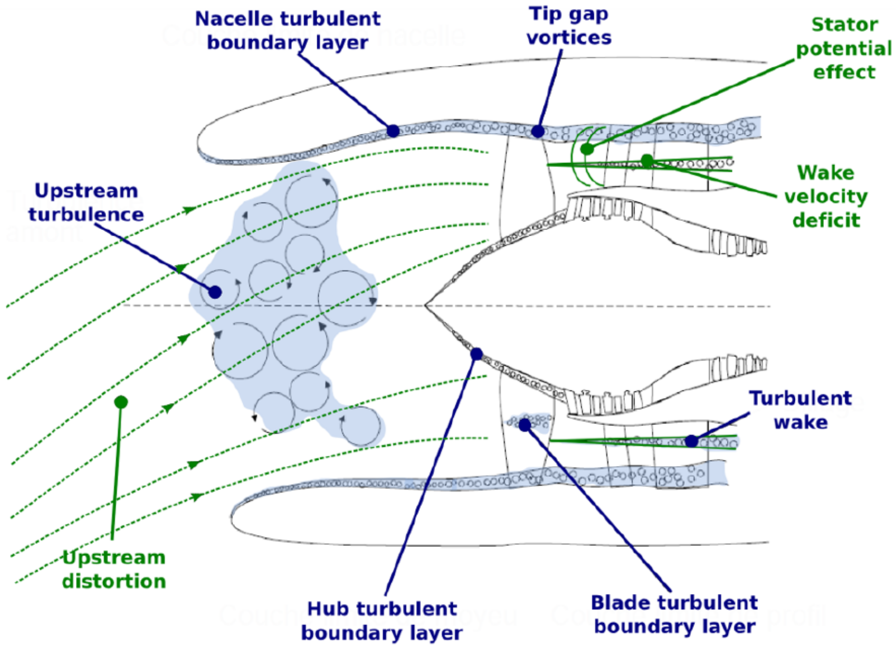
Aerospace



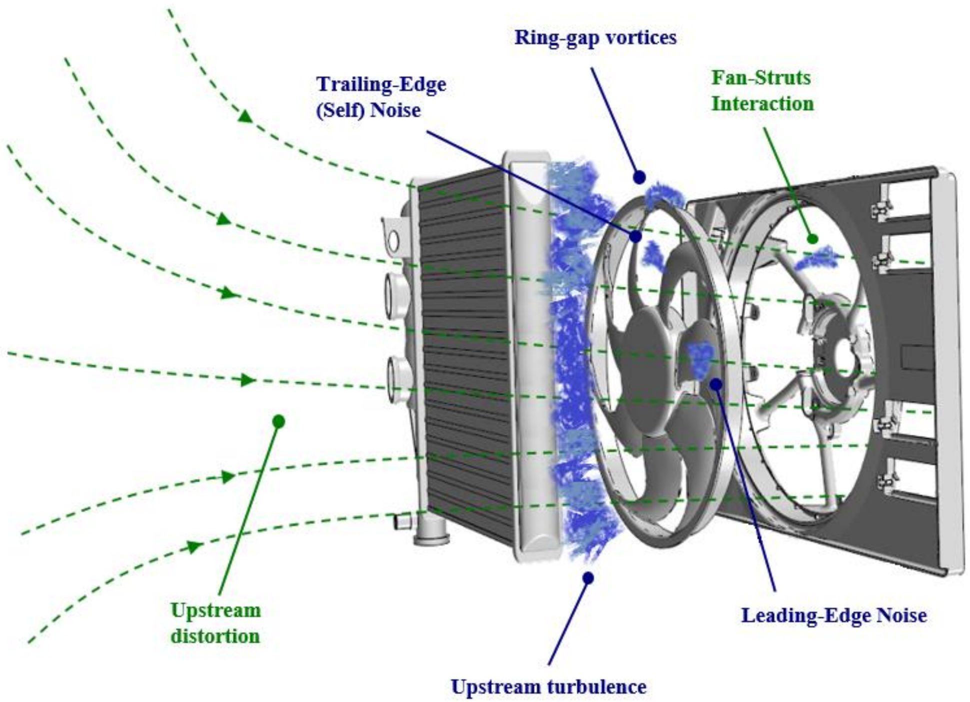
Automotive



Aerodynamic Fan Noise



Moreau, S.; *Turbomachinery Noise Predictions: Present and Future;* Acoustics. 1. 92–116.



Noise sources in common:

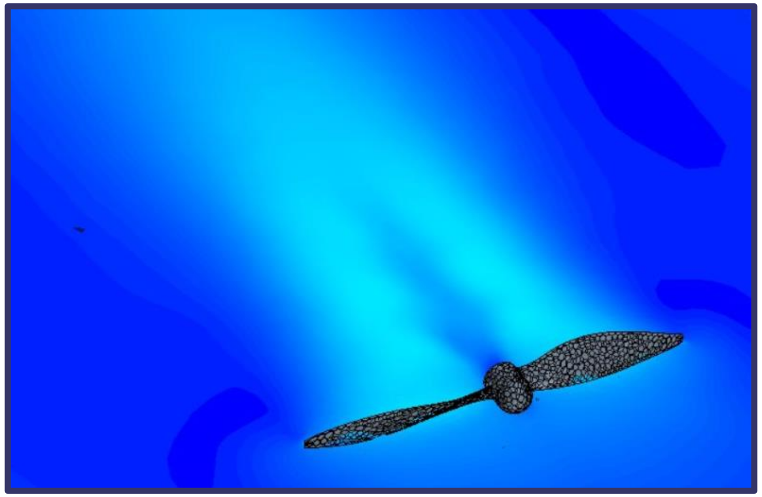
- Rotor-Stator Interaction
- Upstream Turbulence
- Rotor-self noise
- Non-uniform azimuthal velocity distribution
- Tip/Ring gap vortices

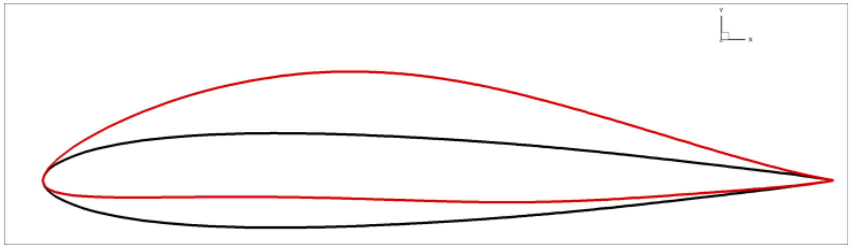
Turbofan specific noise sources:

- Thickness noise (monopolar)
- Buzz-saw noise

→ Generalizability of the chosen modelling methods

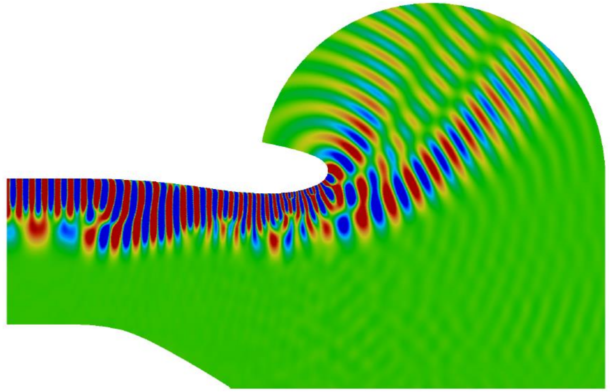
Acoustic Modelling and Mitigation





Near-field Fluid Dynamics

- Expensive CFD – LES, RPM, LBM
- Cheap CFD/Experiments + Source Characterization



Source Modelling and Propagation

- Analytical Models
- Numerical Techniques- DG-FEM,BEM
- Acoustical Analogies

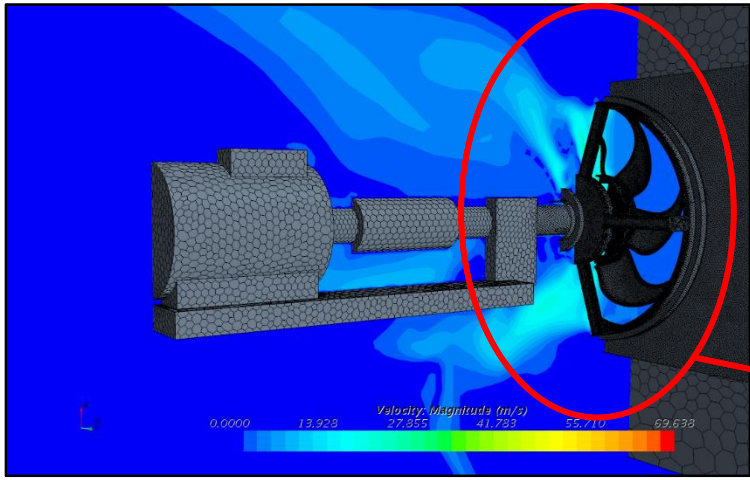
Mitigation Techniques

- Shape Optimization
- Acoustic Liners

PhD Projects

Aerospace

Automotive



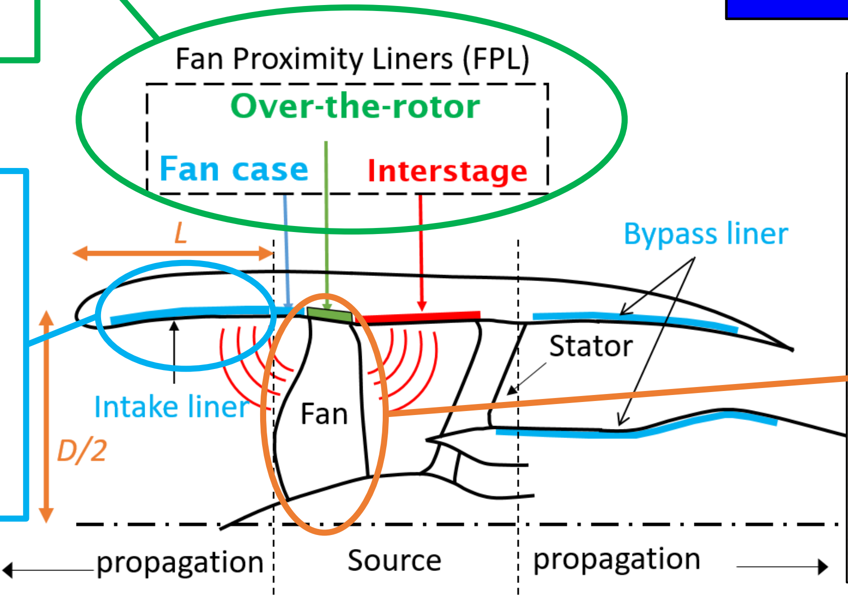
Fan Proximity Liner Modelling

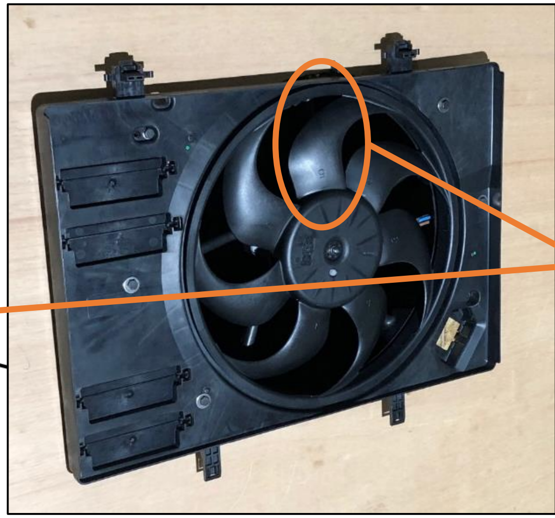
ESR: Sergi Palleja-Cabre

University of Southampton, Institute of Sound and Vibration Research

Low-Speed Cooling Fan Noise Modelling

ESR: Alessandro Zarri





FEM Modelling of non-locally reacting liners

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CFD-CAA analysis & optimization methods

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Low-Speed Cooling Fan Noise Modelling

A. Zarri, C. Schram, J. Christophe

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THE FRAMEWORK PROGRAMME FOR RESEARCH AND INNOVATION HORIZON 2020

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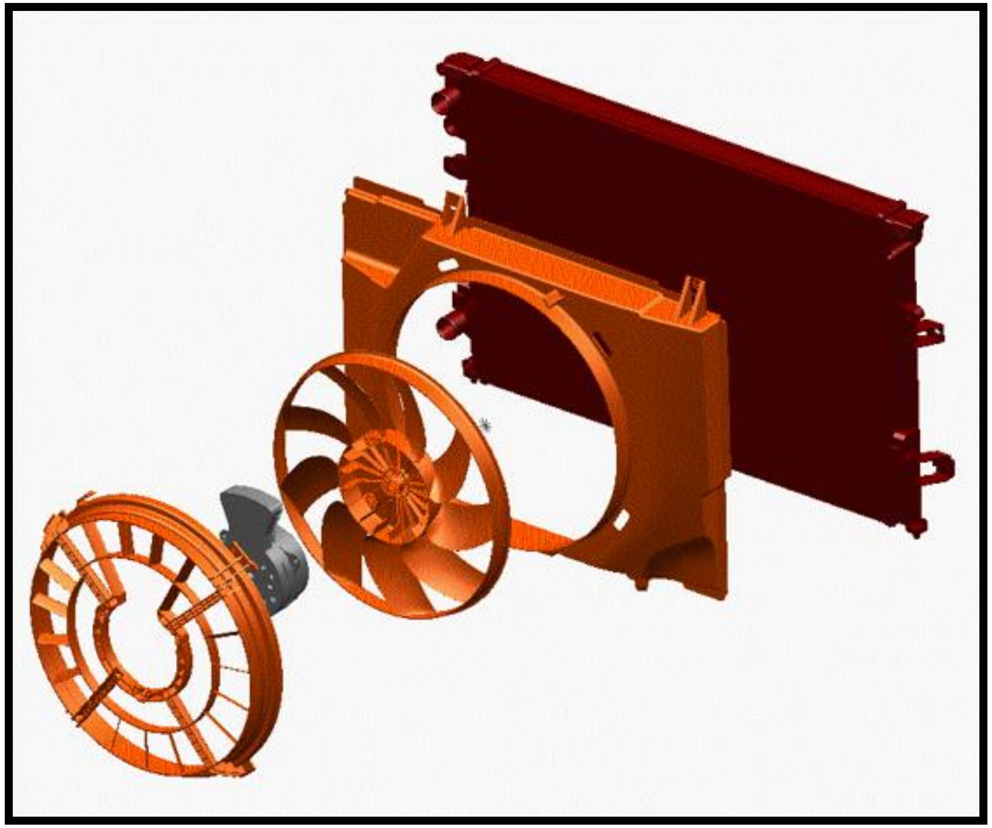
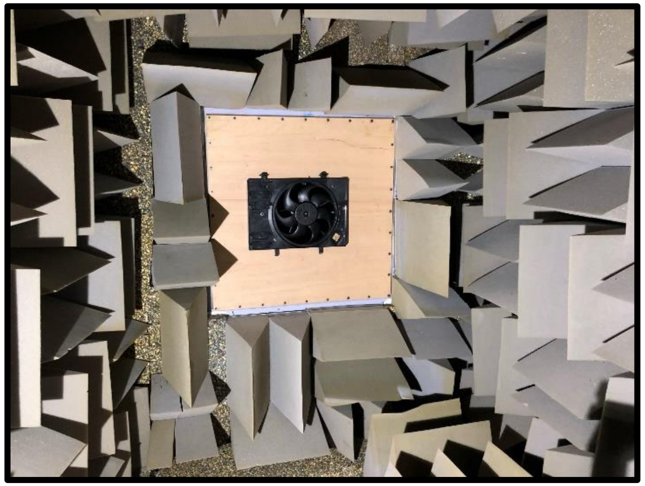
About ESR2 PhD Research

Dealing with: noise emitted by automotive **low-speed** cooling **fans**





Experimental work: to **isolate** and **localize** the acoustic sources

Numerical work: to **simulate** the **far-field noise** of the system

In order to: develop a **low-order** prediction noise **methodology**

Numerical Methodology

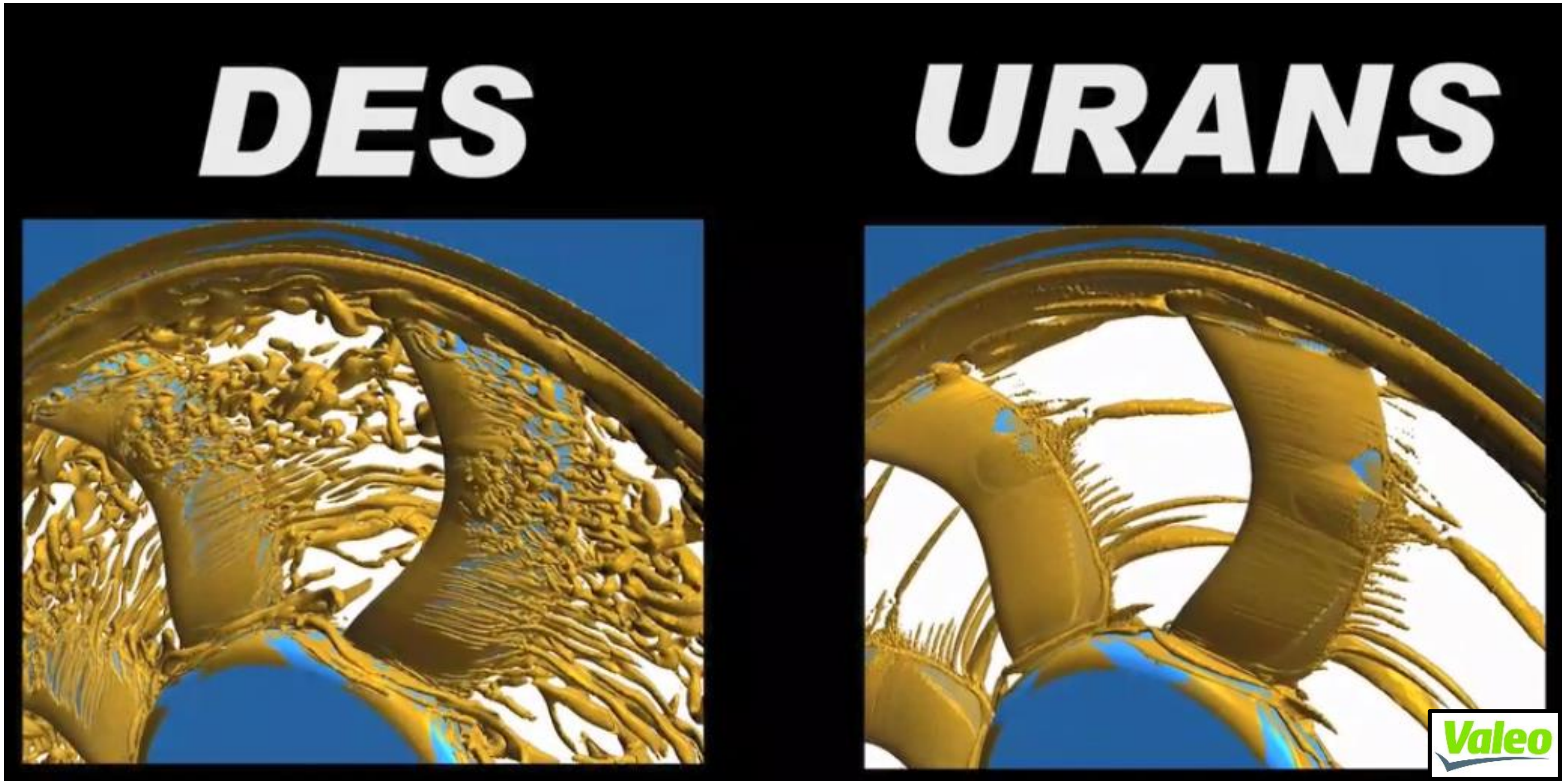
Far field acoustic **simulation**

Hybrid methods

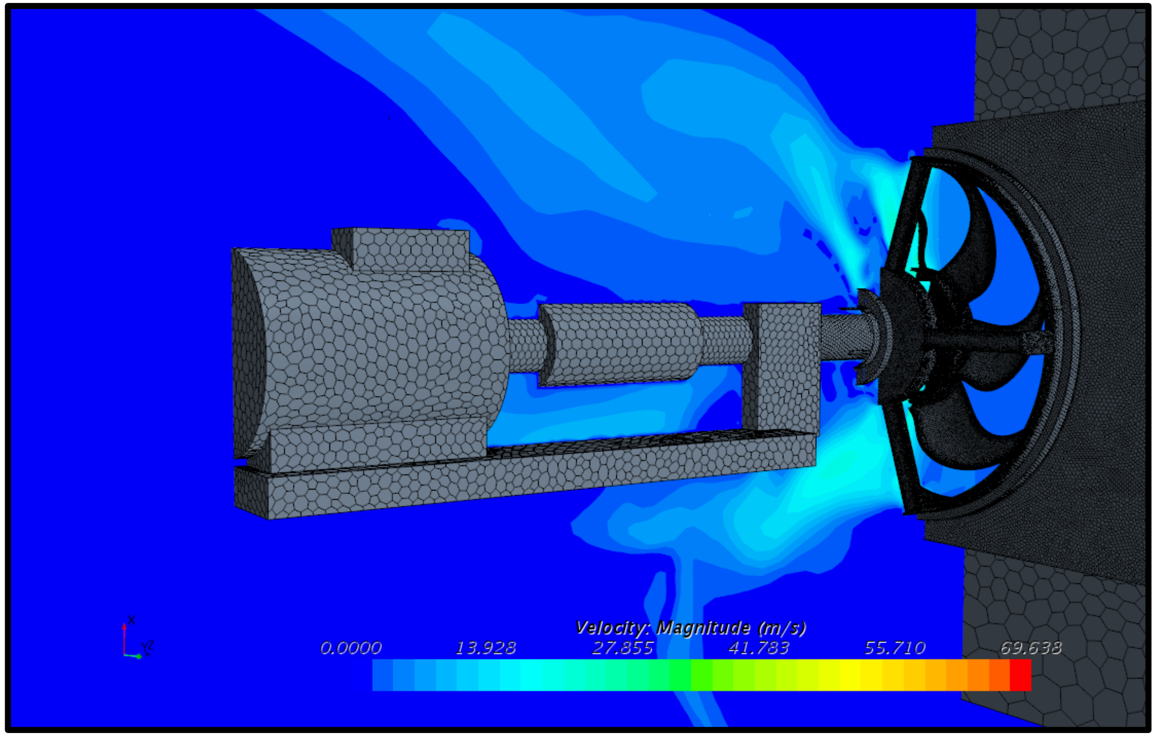
BATMAN

VKI in-house developed code based on **Amiet's theory**

CFD:
- **RANS**
- **URANS**
- DES
- LES
- …



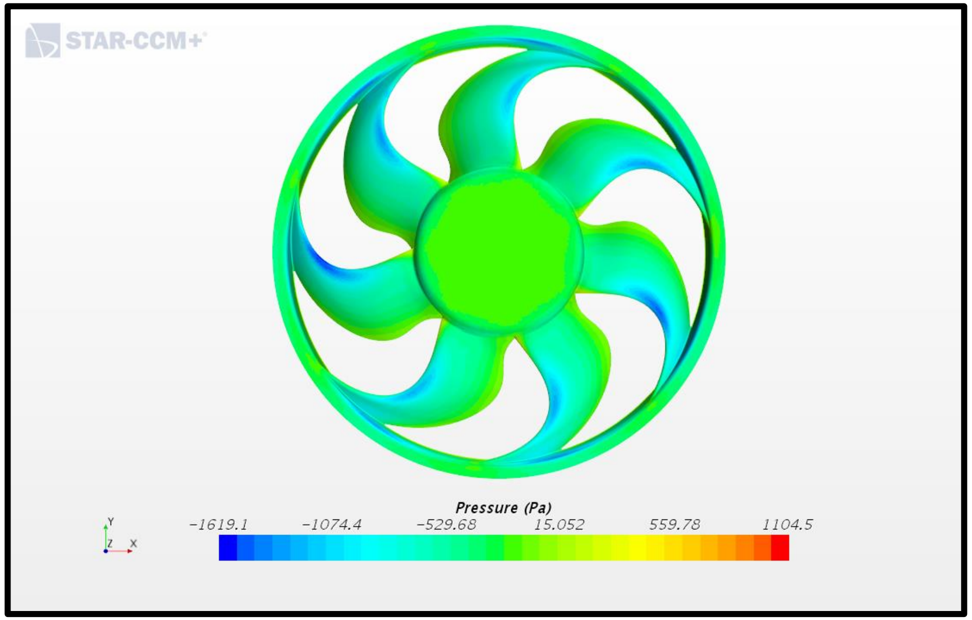
URANS CFD Results obtained at Valeo



Complete module simulation with the Heat Exchanger on the front.

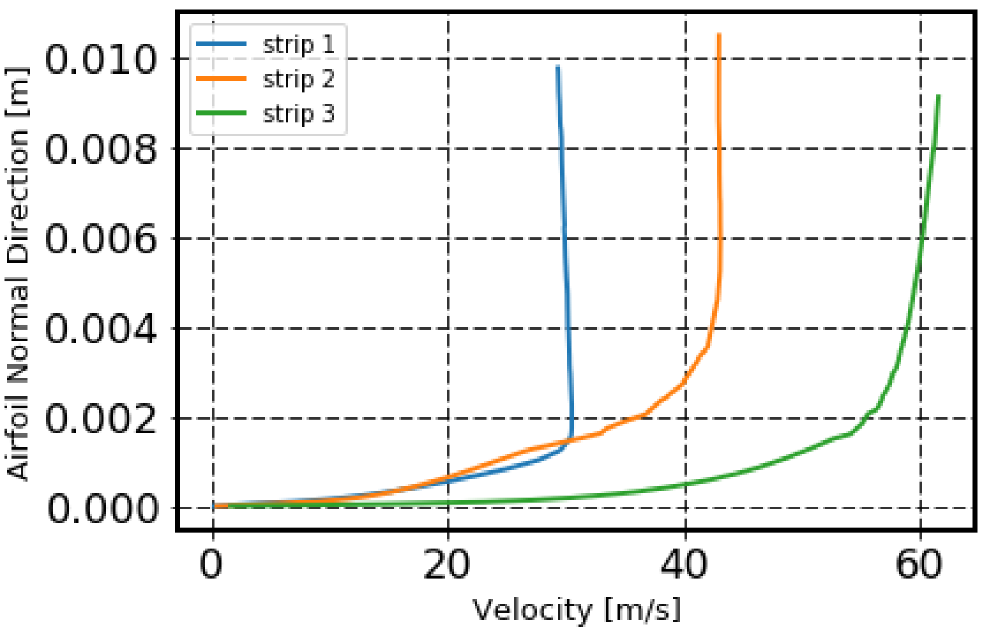
URANS gives the **averaged quantities,** as the pressure field below

Although they are considered a **low-order method**, the simulation is **rather complicated**

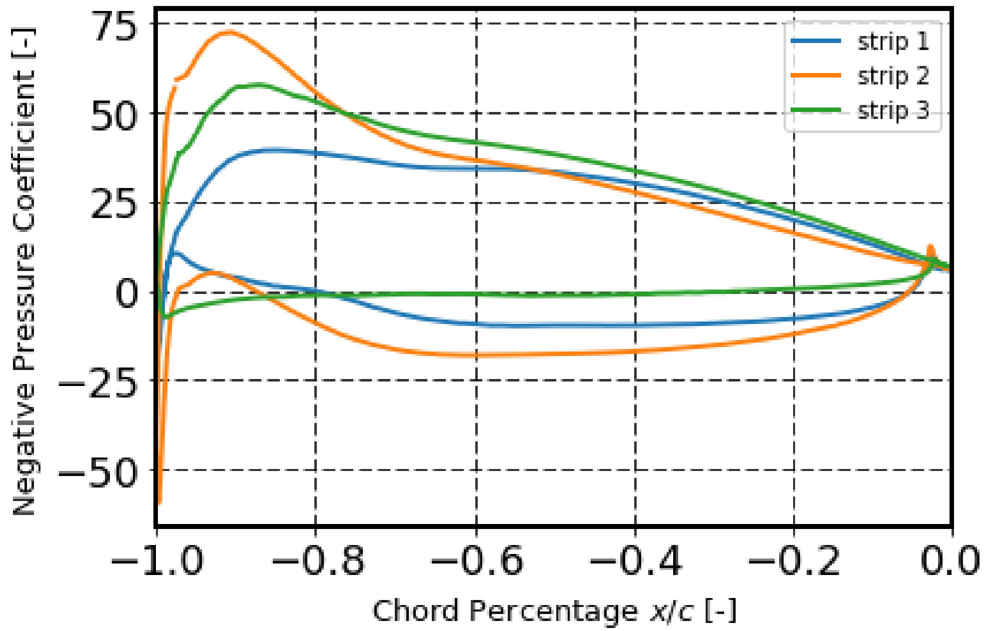


Velocity Profiles and Pressure Coefficients

Extracted Data from the CFD simulation at **3 different positions** along the blade

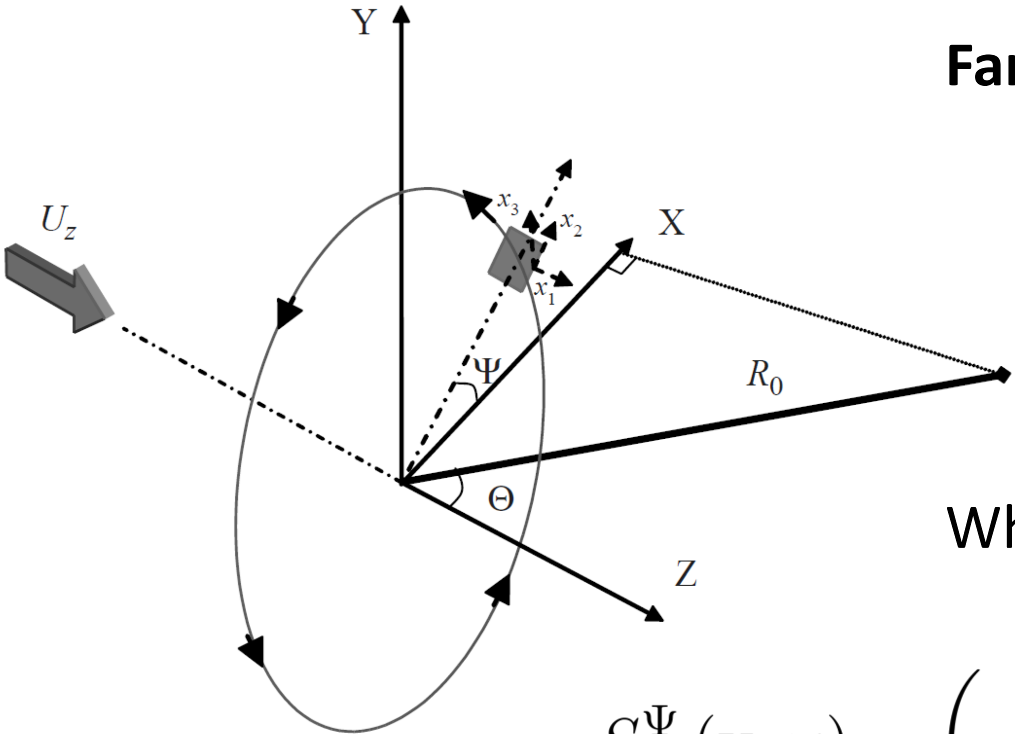


Velocity boundary-layer profiles at 3 spanwise regions



Pressure Coefficient Distributions at 3 spanwise regions

Amiet's trailing-edge noise model on rotating blades



Far-field sound pressure for a ventilator

$$S_{pp}(\mathbf{X},\omega) = \frac{B}{2\pi}\int_0^{2\pi} \frac{\omega_e(\Psi)}{\omega} S_{pp}^{\Psi}(\mathbf{x},\omega_e)d\Psi$$

Where the **PSD of a blade strip** reads:

$$S_{pp}^{\Psi}(\mathbf{x},\omega) = \left(\frac{\omega c x_3}{2\pi c_o S_0^2}\right)^2 \frac{L}{2}\left|\mathcal{L}\left(\frac{\omega}{U_c},\frac{\bar{k}x_2}{S_0}\right)\right|^2 \Phi_{pp}(\omega) l_y(\omega)$$

Φ_{pp} Wall-pressure spectrum

l_y Spanwise correlation length

Assuming a **translational local displacement** of each strip

Wall-pressure models

Empirical Models

- WPS is given as a function of frequency
- Information only from velocity profile

$$\frac{\varphi_{pp}}{\varphi^*} = \frac{A(\omega^*)^B}{[I\ (\omega^*)^C + D]^E + [F(R_T)^G \omega^*]^H}$$

For zero pressure gradient flows

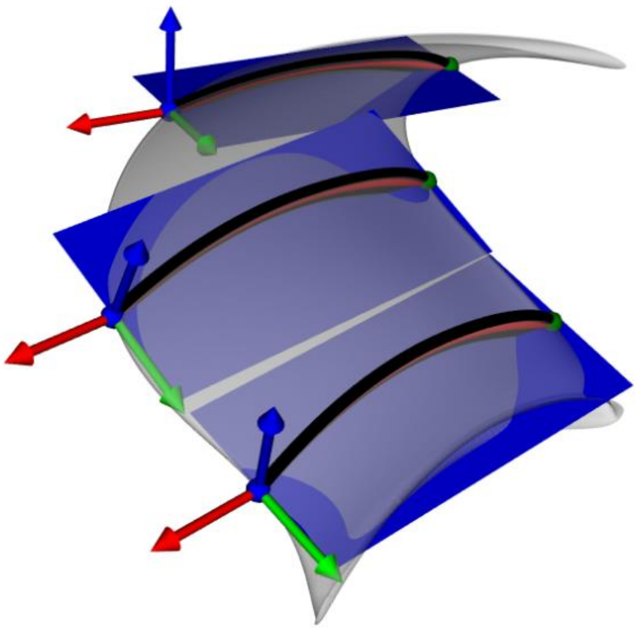
I. Goody model — *Base*

For adverse pressure gradient flows

II. Rozenberg
III. Lee
IV. Kamruzzaman

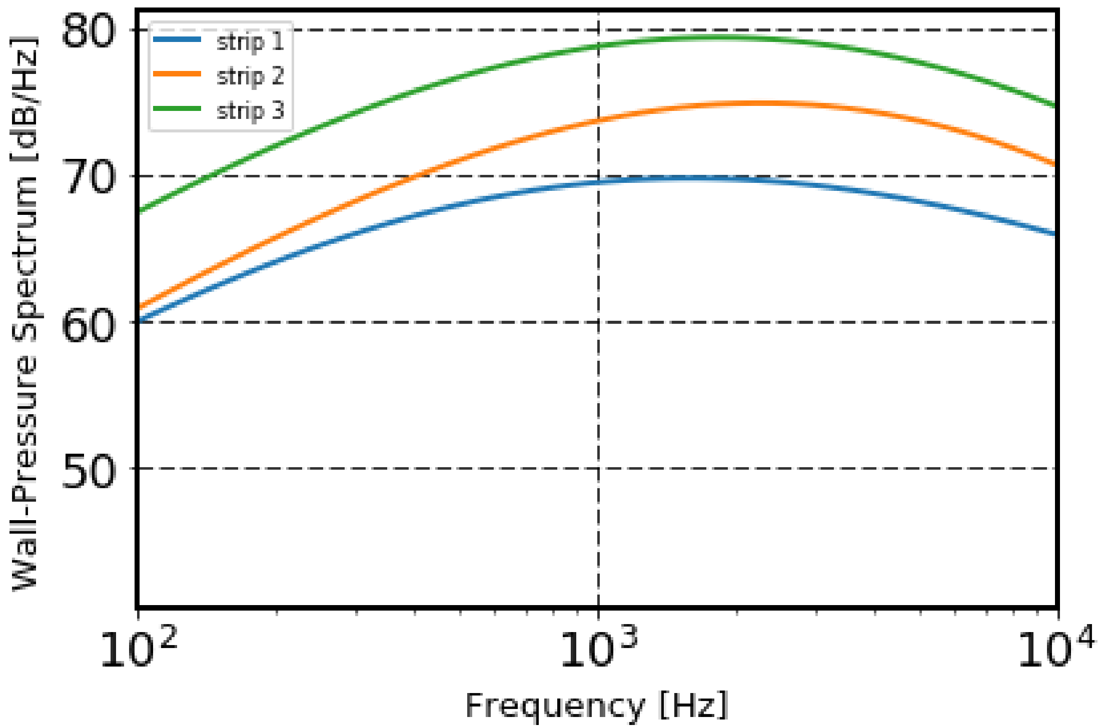
} *Airfoil data*

Amiet's Planes and Wall-Pressure Spectra

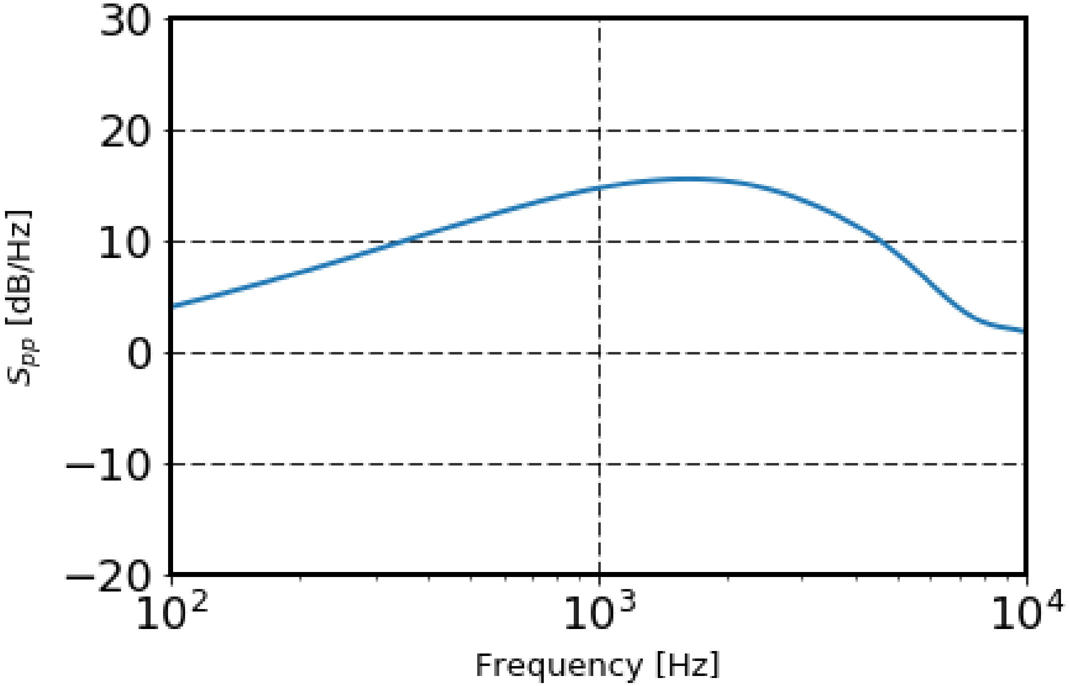


Fan blade planes division

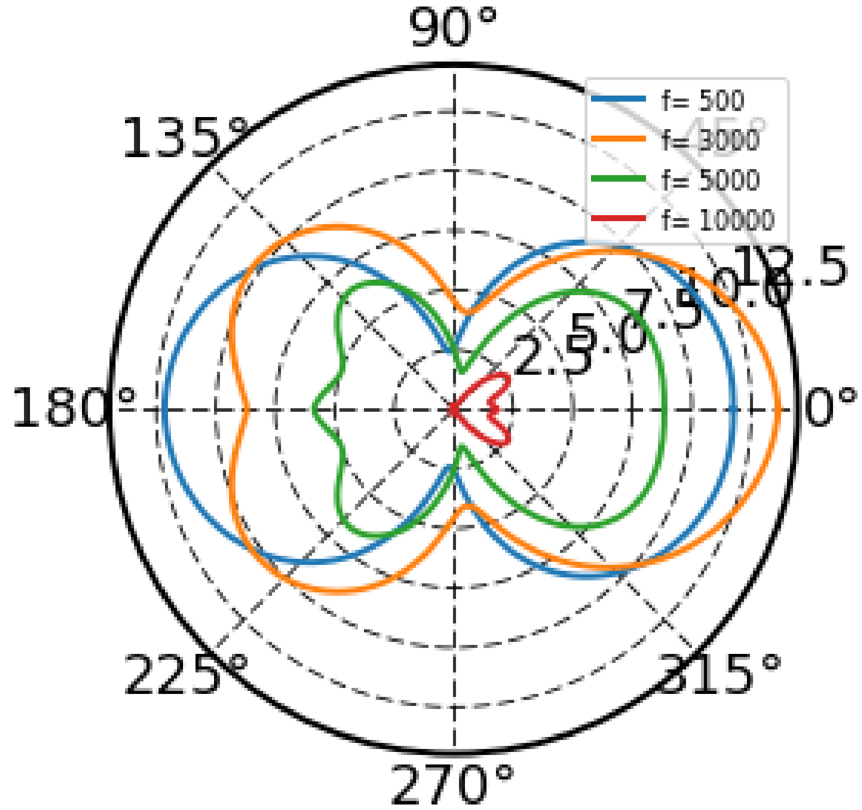
WPS applying Rozenberg's Model



Trailing-Edge Noise Results



PSD far-field noise results



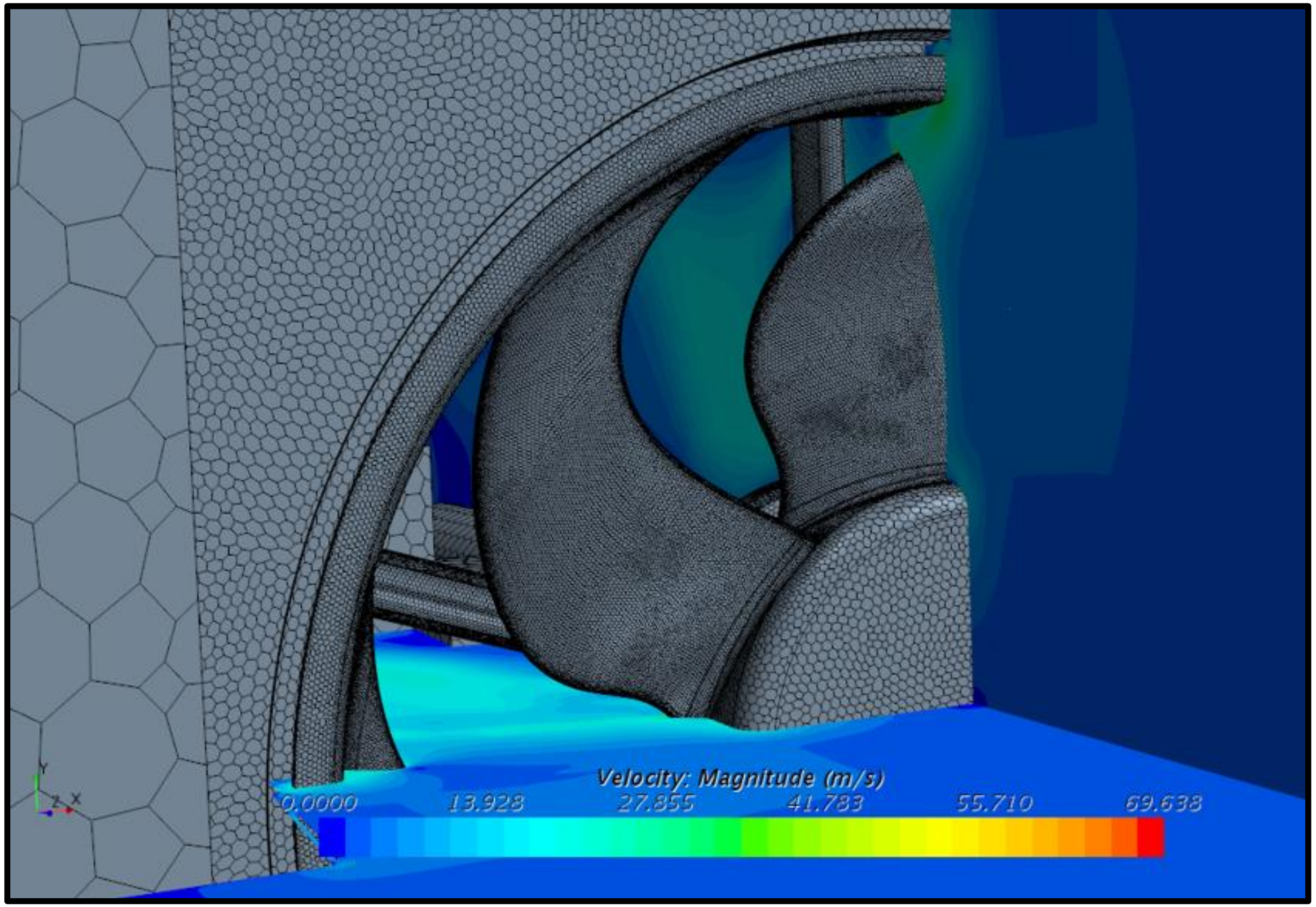
Fan directivity results

Future Numerical Work

- **Improvements** on BATMAN to take into account **sweep angles**, **leading-edge noise**, more accurate **wall-pressure models.**

- **Simpler CFD simulation** with **rotor-alone** non-axial-symmetric configuration.

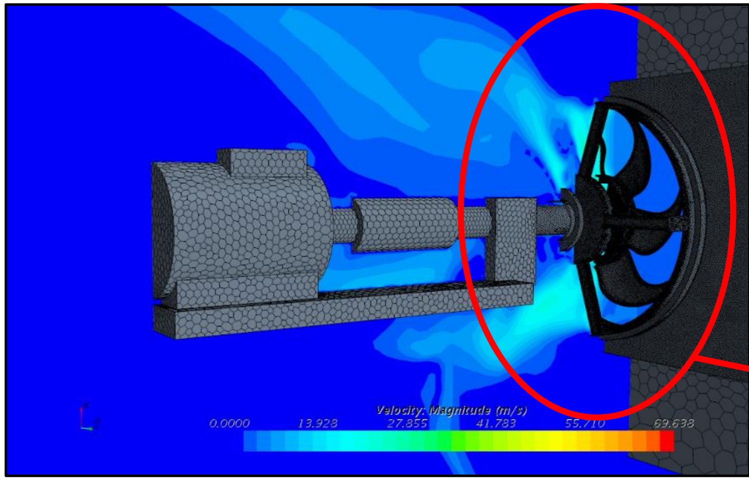
- Better definition of the **flow past the heat exchanger.**



PhD Projects

Aerospace

Automotive



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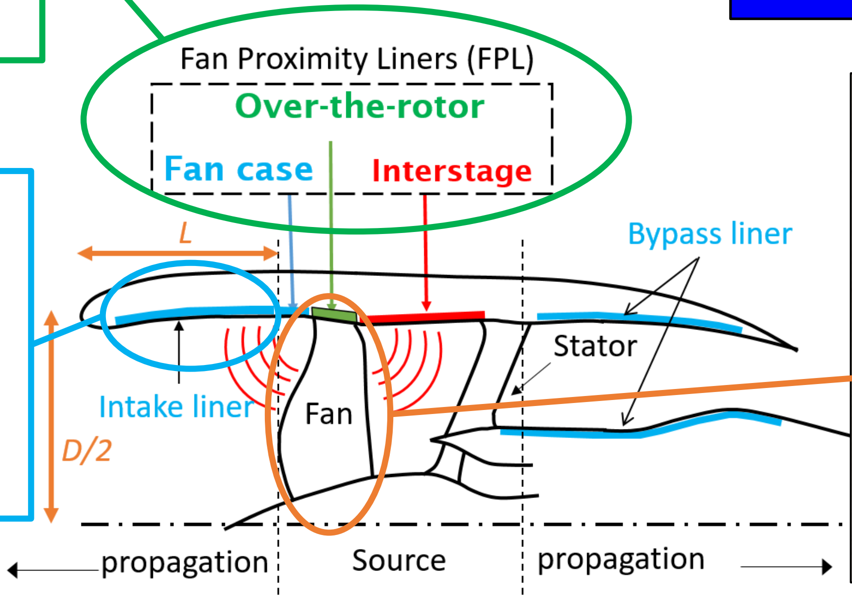

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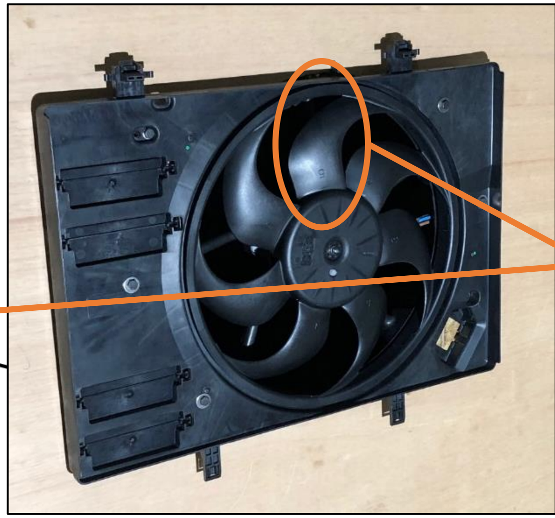

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UNIVERSITY OF Southampton
Institute of Sound and Vibration Research

Fan Proximity Acoustic Treatments for Improved Noise Suppression in Turbofan Engines

Sergi Pallejà Cabré – ESR9

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Supervisors: ***Brian Tester, Jeremy Astley***

Secondment supervisors: ***Michel Roger*** *(ECL),* ***Hadrien Bériot*** *(SIEMENS PLM),* ***Néstor González Díez*** *(TNO)*

M24 SmartAnswer Mid-Term Workshop, Leuven, 20th February 2019

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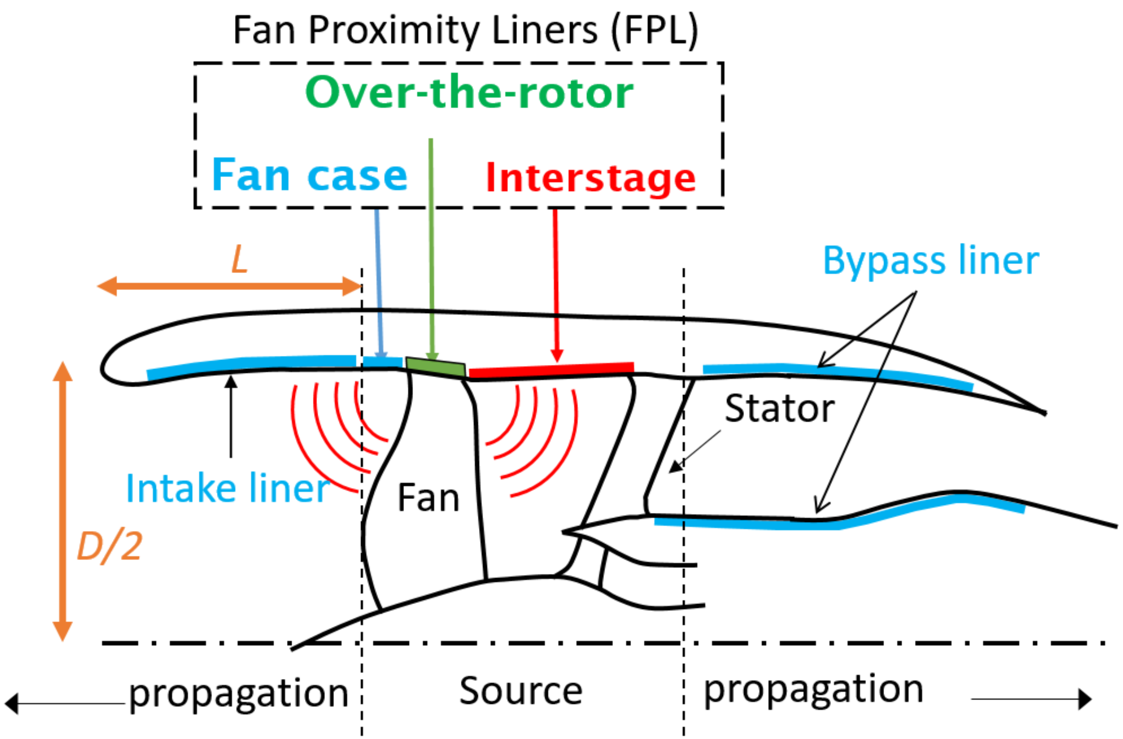
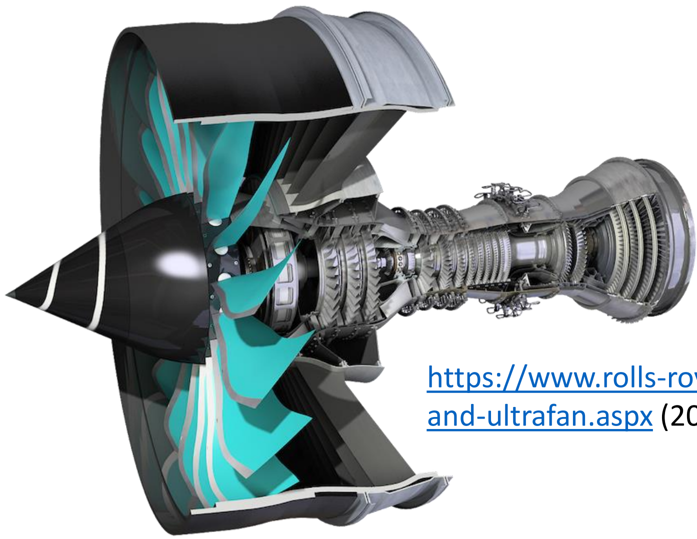
Context

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)

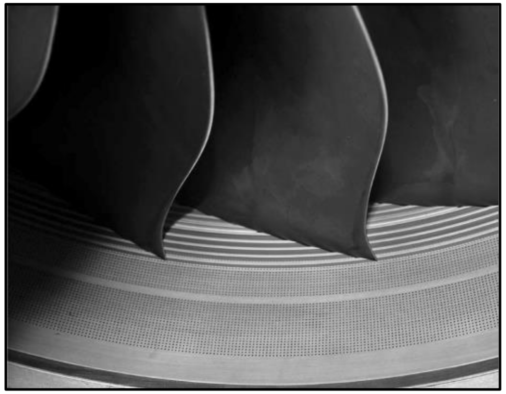
- Mitigation of Fan Noise remains critical in noise reduction for the next generation of engines (2020).
- BPR for large engines:

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

- Optimise liner effect by exploiting available space

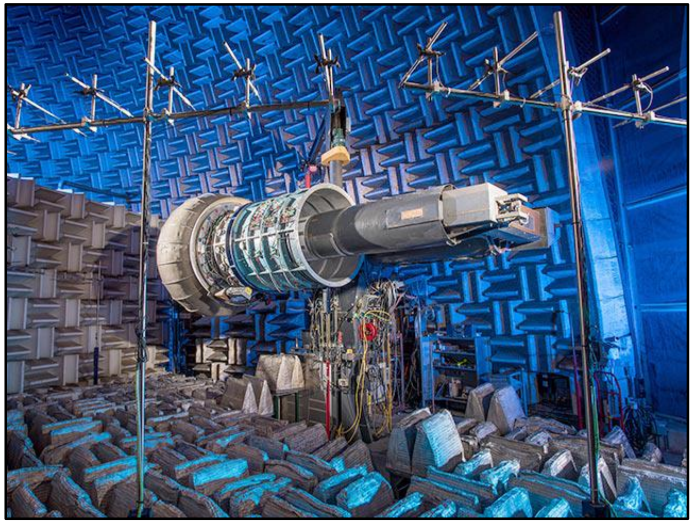
Background

- ***Over-The-Rotor (OTR) Acoustic Treatments***
  - **Physical Mechanism**
    - Source modification
    - Absorption of acoustic waves
    - Reduced rotor-stator noise
  - **Experimental Data**
    - ***Noise Attenuation***
      - AAPL at NASA GRC
      - Test data: ANCF, ADP, FJ44-3A
      - 1 – 5 dB OAPWL
    - ***Aerodynamic Performance***
      - Penalty variability with design
      - 0.75 – 9.8 % loss in adiabatic efficiency
  - **Design & Modelling**
    - Prediction method for OTR liner design



Close-up of foam metal liner installed in FJ44-3A (Sutliff, D. L. et al., 2013)

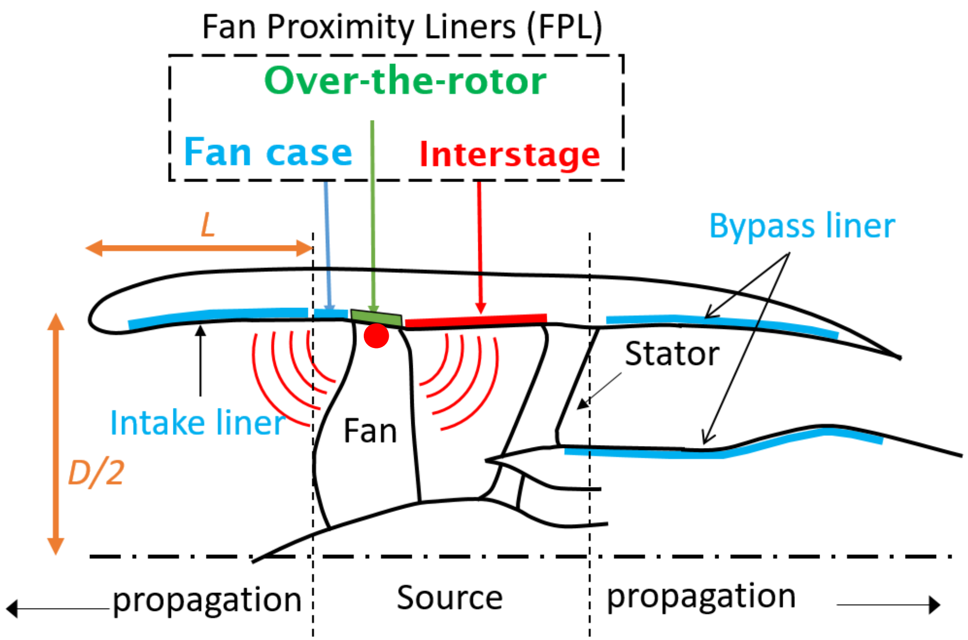
Williams International FJ44-3A engine(Sutliff, D. L. et al., 2013)



Advanced Noise Control Fan (Gazella, M.R. et al., 2013)

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.

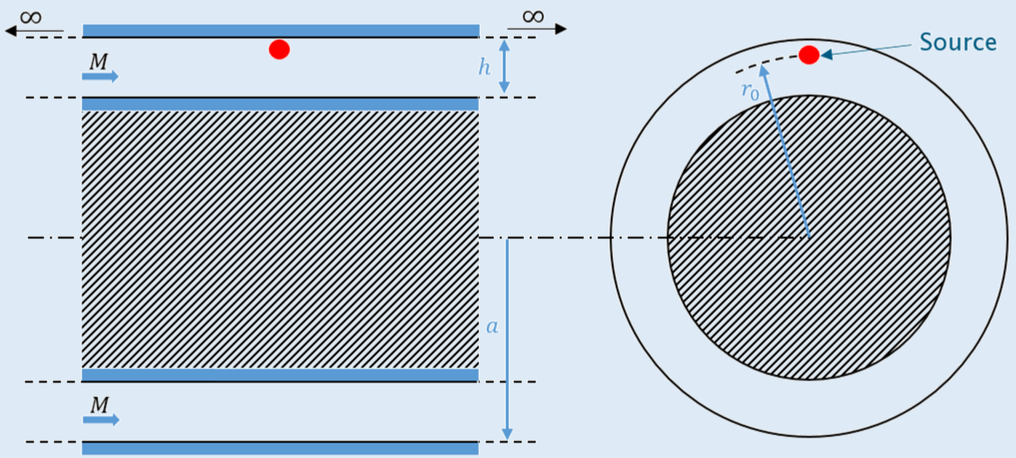


Methodology

ANALYTICAL APPROACH

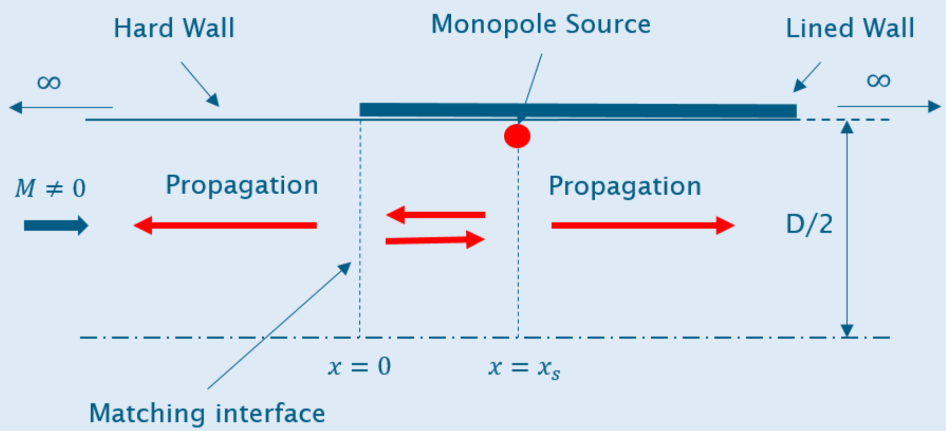
Infinite lined duct with mean flow (Green/INF)

- Based on Green's function for a lined circular duct containing uniform mean flow (Rienstra, S.W. and Tester, B.J., 2008).
- Hollow & Annular section.
- Hard & Lined walls.
- Source: static point monopole/dipole
- Cross-verified against Rienstra, S.W. and Tester, B.J., 2008 results & FEM simulations.



Semi-Infinite lined-hard duct (Green/SINF)

- Source: static monopole/dipole.
- Gain understanding on the effects of different parameters on the noise radiation by using the inlet power Insertion Loss (IL):
  - Source radial & axial position: r_0/a ; x_s/a
  - Excitation frequency: He
  - Preliminary inlet power Insertion Loss (IL) impedance map.
  - Effect of the Mach number

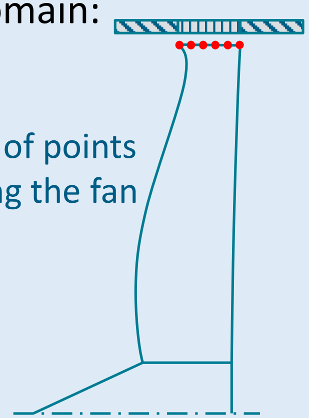


Methodology

ANALYTICAL APPROACH

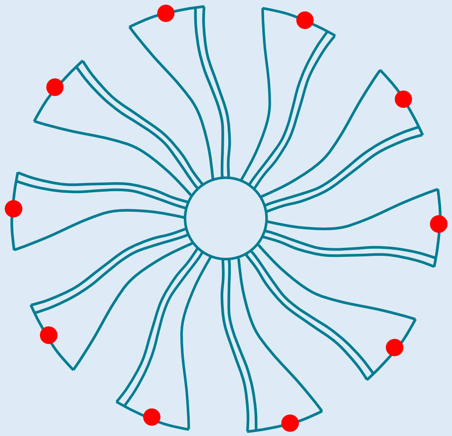
Green/INF & Green/SINF with multiple sources

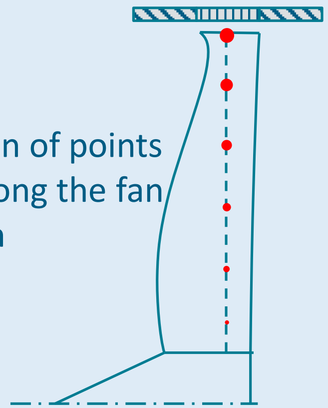
- Based on Green/INF + Multiple sources (Coherent/Incoherent)
- It considers different distributions of point sources in the domain:



- Distribution of points sources along the fan blade chord

- Distribution along the circumferential direction – **B blades**

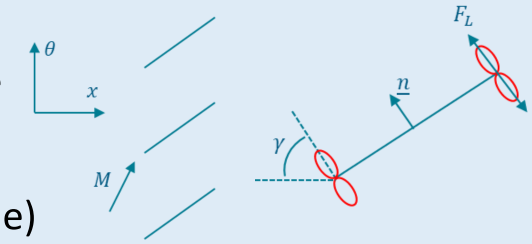




- Distribution of points sources along the fan blade span

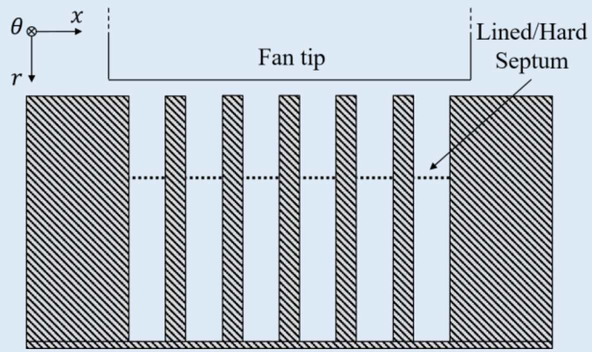
Source modelling

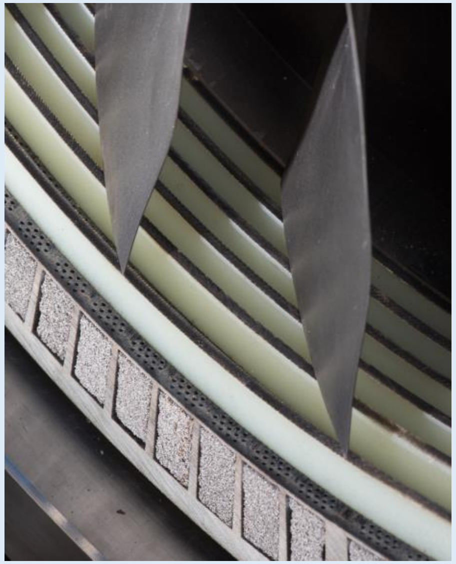
- Static point monopole
- Static point axial dipole
- Static point lift dipole
- (Rotating point lift dipole)



Impedance modelling

- Circumferential grooves with acoustic treatment
- Non-locally reacting in the azimuthal direction.





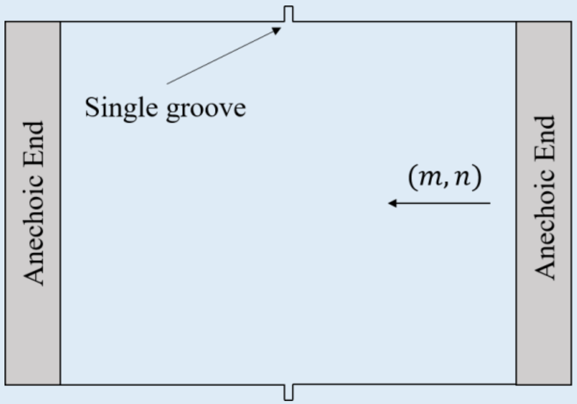
OTR acoustic casing treatment (Bozak, R. F. et al., 2018)

NUMERICAL APPROACH

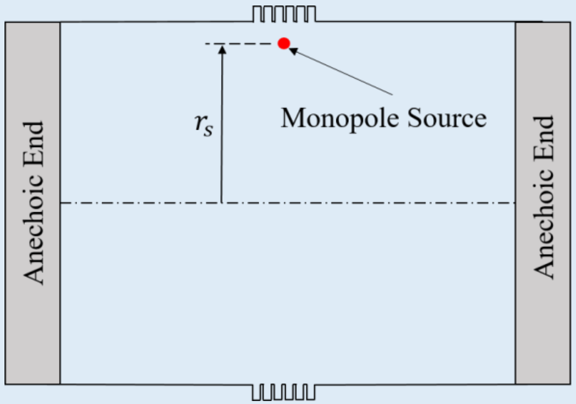
Verification of the semi-locally reacting lined groove model

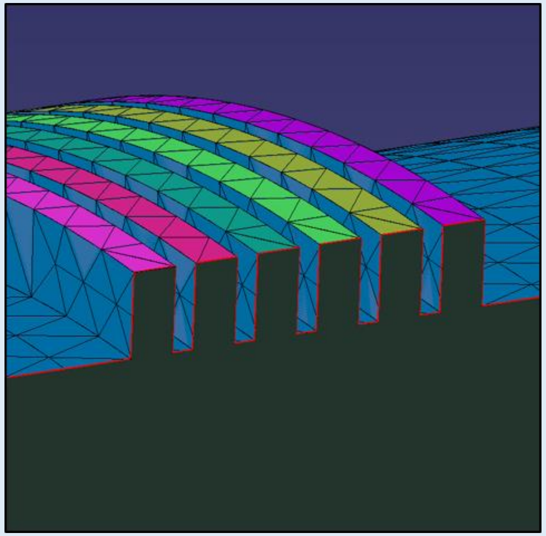
- *FEM Software*: LMS Virtual.Lab (Secondment at SIEMENS PML)
- *Objetives:*
  1. Improve the understanding of the acoustic response of acoustically treated semi-locally reacting grooves
  2. Provide a reference solution to cross-verify with the analytical impedance model
- *Cases:*

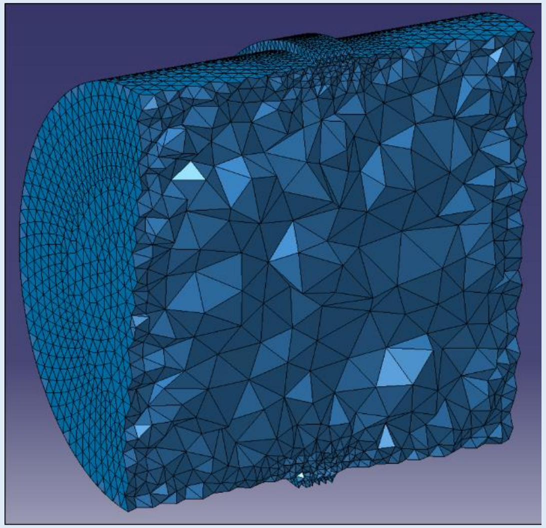
Single groove with incident duct modes



Multiple grooves excited by a monopole source

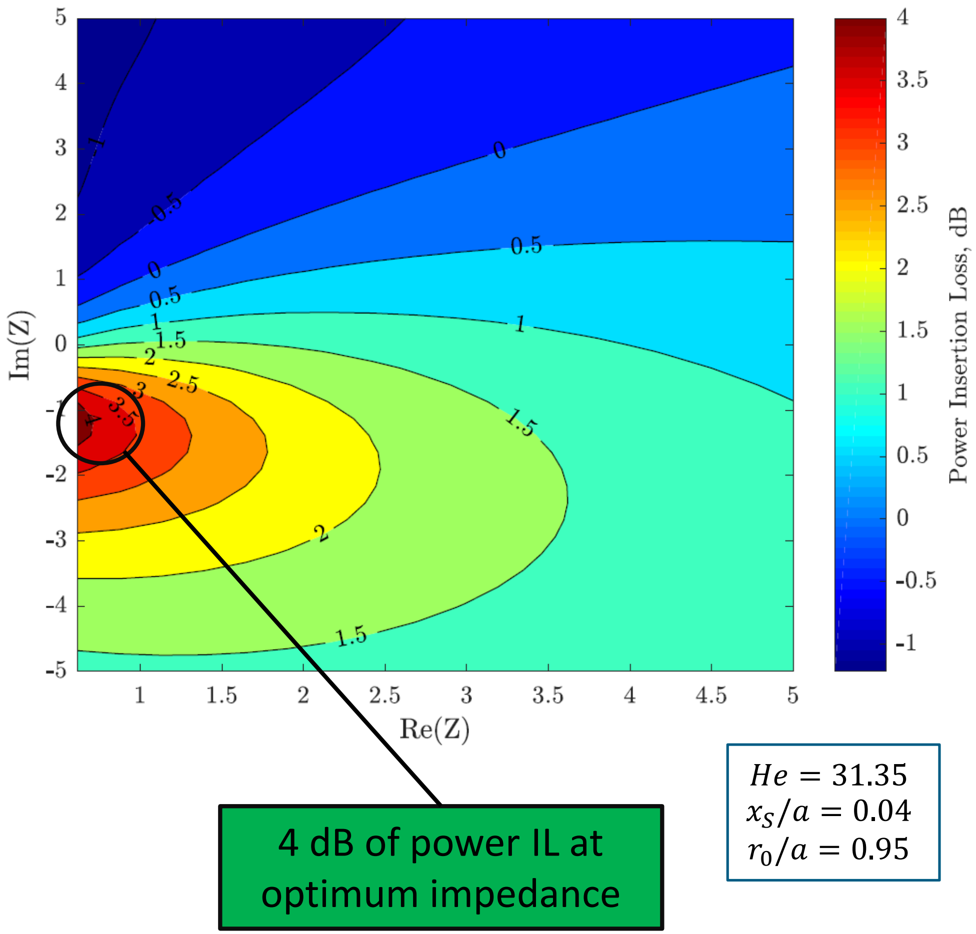






Preliminary Results

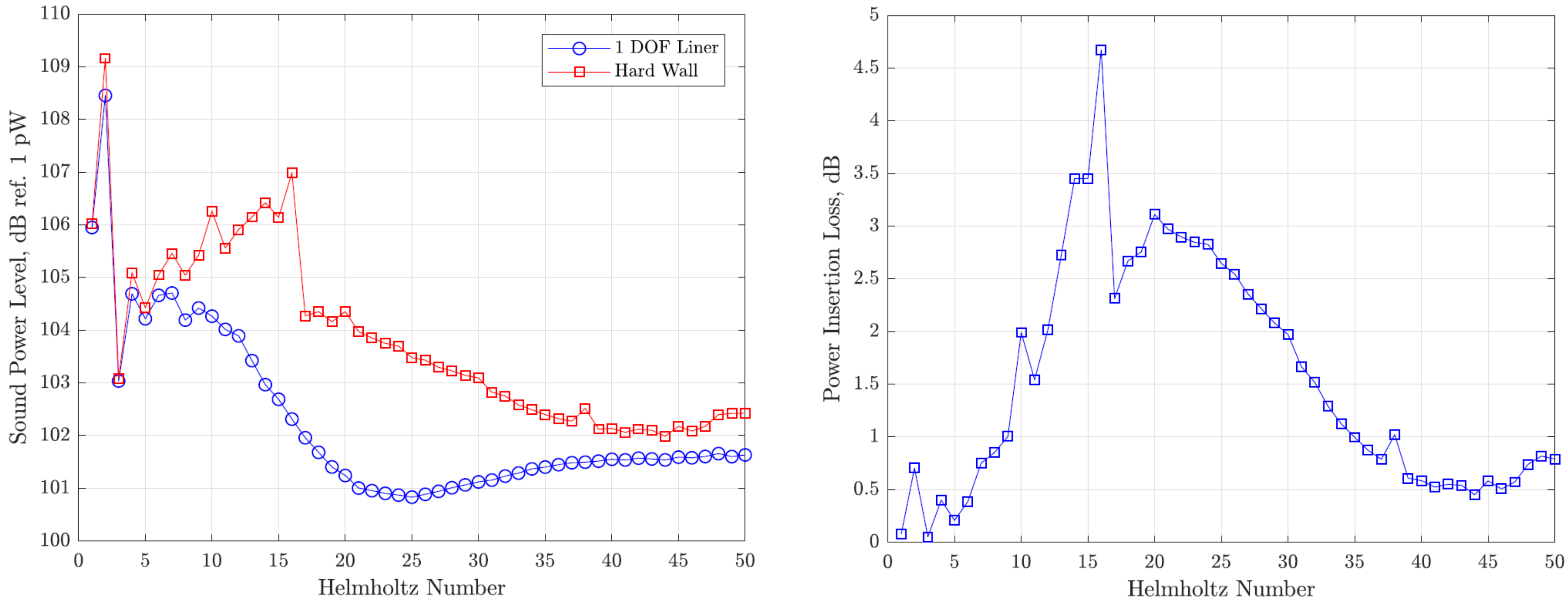
OTR Performance Estimates – Green/SINF



$He = 31.35$
$x_S/a = 0.04$
$r_0/a = 0.95$

Preliminary Results

OTR Performance Estimates – Green/SINF



$$Z(\omega) = R_f + j\left(k\frac{t+d}{\sigma} - \cot(kh)\right)$$

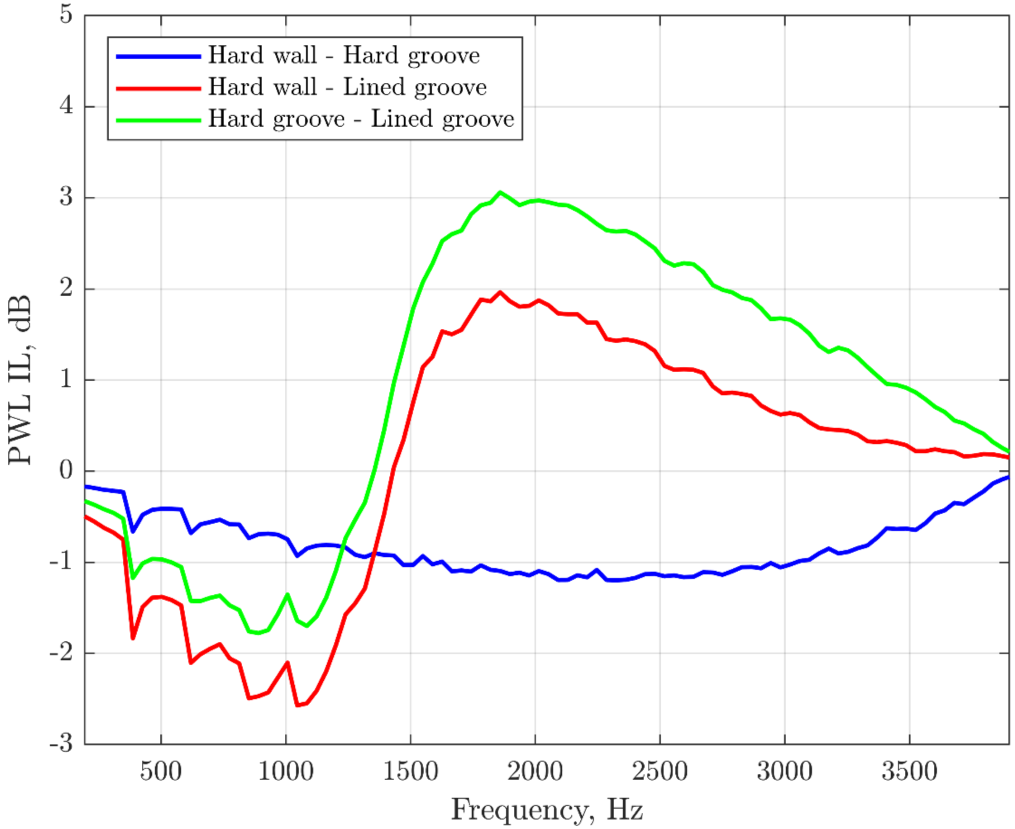
(SDOF cavity liner)

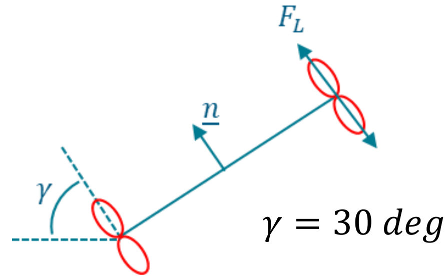
$x_S/a = 0.04$
$r_0/a = 0.95$

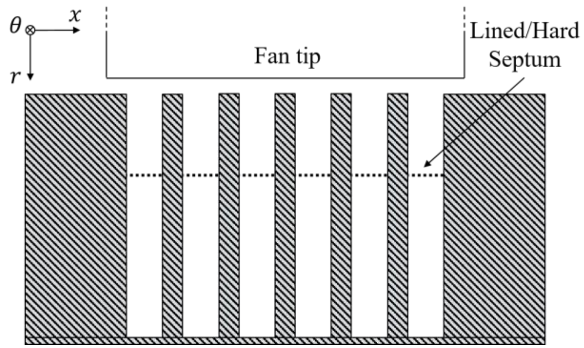
Preliminary Results

OTR NASA Estimates – PWL Insertion Loss

$COR = 5$
$r_0/a = 0.95$
$M = 0.0$







	Groove Effect	Treatment Effect	Total Effect
In-duct Sound Power Level (dB)	$\Delta W_{grooves}$	$\Delta W_{treatment}$	ΔW_{total}
Forward Propagating Modes	– 1.6dB	– 1-2dB	– 2.6-3.6dB
Co-rotating Forward Propagating Modes	– 1.7dB	– 1.8-2.9dB	– 3.5-4.6dB
Circumferential Groove Noise	+ 7.6dB	– 1.5-5dB	+ 2.6-6.1dB

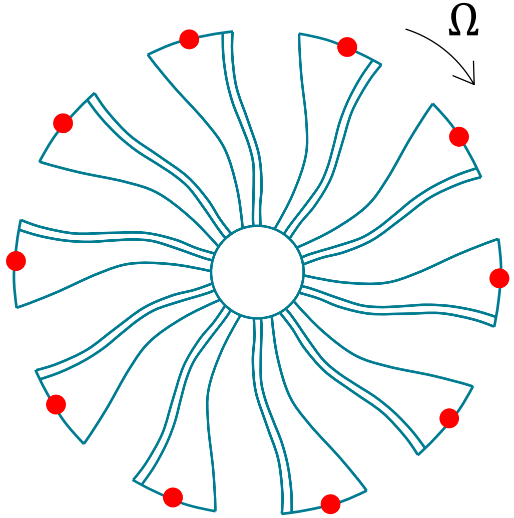
Bozak, R. F. et al., 2018

Conclusions

- ***OTR Performance Estimates – Green/SINF***
  - A point monopole source in design case provide a broadband power IL of ∼4 dB, with significant attenuation over a wide range of source excitation frequencies.
- ***Verification of the semi-locally reacting lined groove model***
  - Preliminary comparisons of the numerical simulations of the acoustically treated grooves and the results obtained with the analytical impedance model show a satisfactory agreement.
- ***OTR NASA Estimates***
  - The predicted acoustic power attenuation or insertion loss is found to be within the same range as the experimental results, i.e. 2.5 - 3.5 dB (PWL).

Future work

- ***Green/SINF Development – inclusion of:***
    - System of rotating point sources.
    - Swirl in the fan section – solid body rotation
- ***Green/FINF Development***
    - Finite length duct within a hard wall duct, the source/s placed within the lined region.
- ***Numerical Verification***
    - Further investigation on 'back-reaction' effects using LMS Virtual.Lab.
    - Obtain reference solutions to cross-verify with the analytical models.
- ***Experimental Validation***
    - Validation of the analytical results with NASA published results.
    - Validation tests at ECL : assessment of the performance of an acoustic liner in terms of reducing tip noise of an aerofoil over a flat surface.

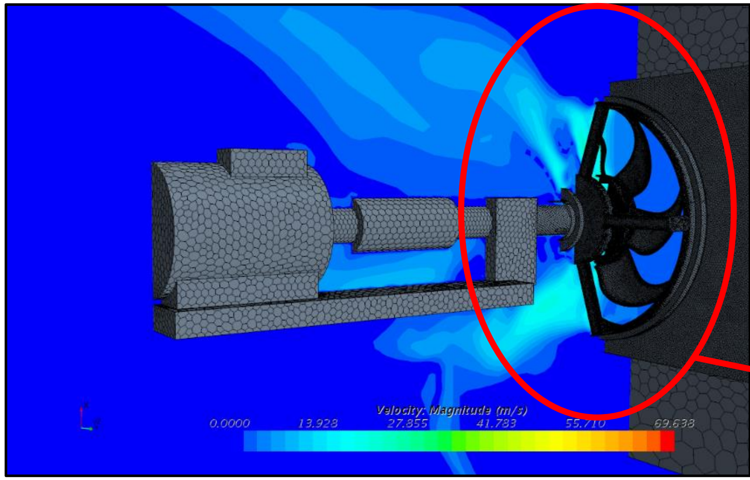


Bozak, R. F. et al., 2018

PhD Projects

Aerospace

Automotive



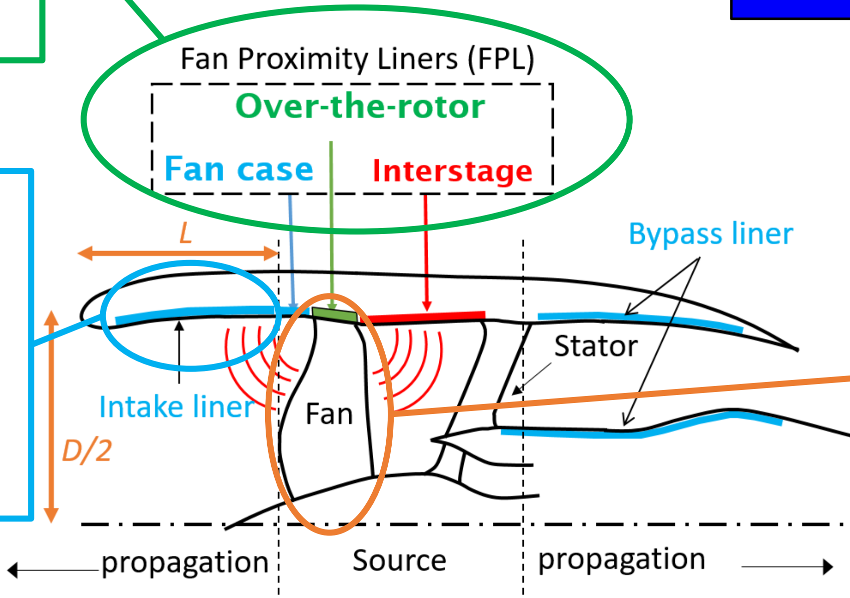
Fan Proximity Liner Modelling

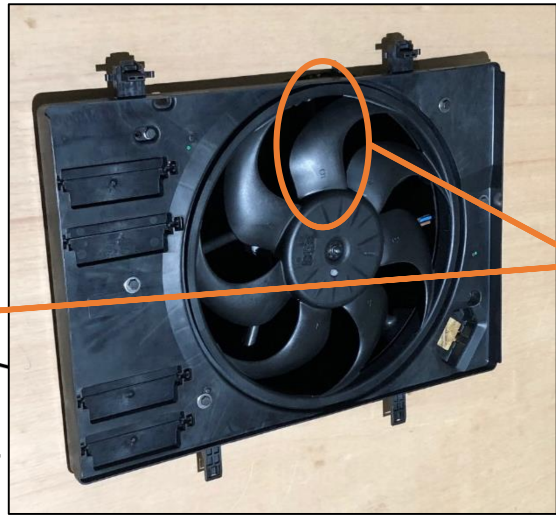
ESR: Sergi Palleja-Cabre

University of Southampton Institute of Sound and Vibration Research

Low-Speed Cooling Fan Noise Modelling

ESR: Alessandro Zarri





FEM Modelling of non-locally reacting liners

ESR: Chai

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CFD-CAA analysis & optimization methods

ESR: Morteza Monfaredi

National Technical University of Athens

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

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Domain Decomposition Methods for modeling of acoustic liners

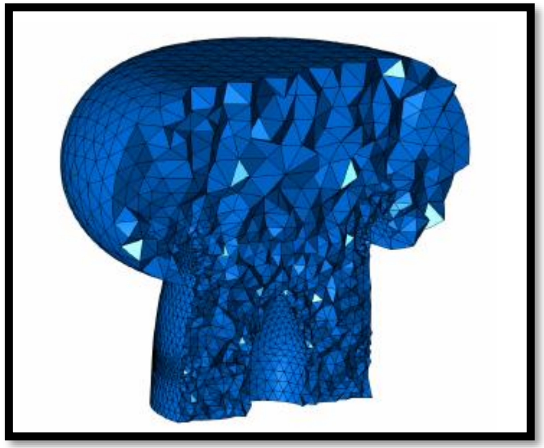
Chaitanya Sanghavi, ESR-14

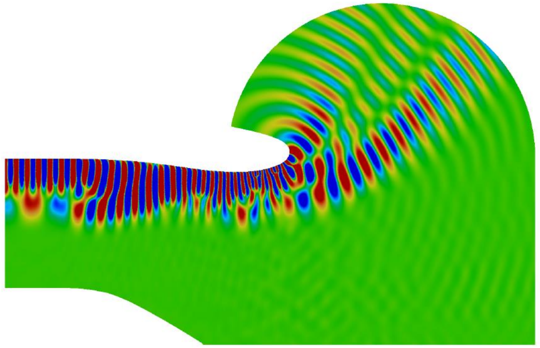
Hadrien Bériot, Gwénaël Gabard, Olivier Dazel

M24 Smart Answer Meeting, Leuven, 20th February 2019

H2020 MARIE SKŁODOWSKA-CURIE ACTIONS

Context





- Focus on the noise mitigation at the turbofan inlet.
- Modeling of non-locally reacting liners is computationally expensive.
- Modeling in the nacelle can be approximated using LPE or Helmholtz eqn.

- At 2BPF, and kR=128, the **computational time is 5h30min,** for sideline configuration.

FEM

Introduction to Finite element method (FEM)

What is FEM ??

- The computational domain is divided into **small geometric elements** like triangles, rectangles, cubes, etc.
- In each element the pressure field is computed by using **some basis functions**.

The example of a plane wave propagating in 1D in the positive X – direction is shown.
Helmholtz number = 5

FEM

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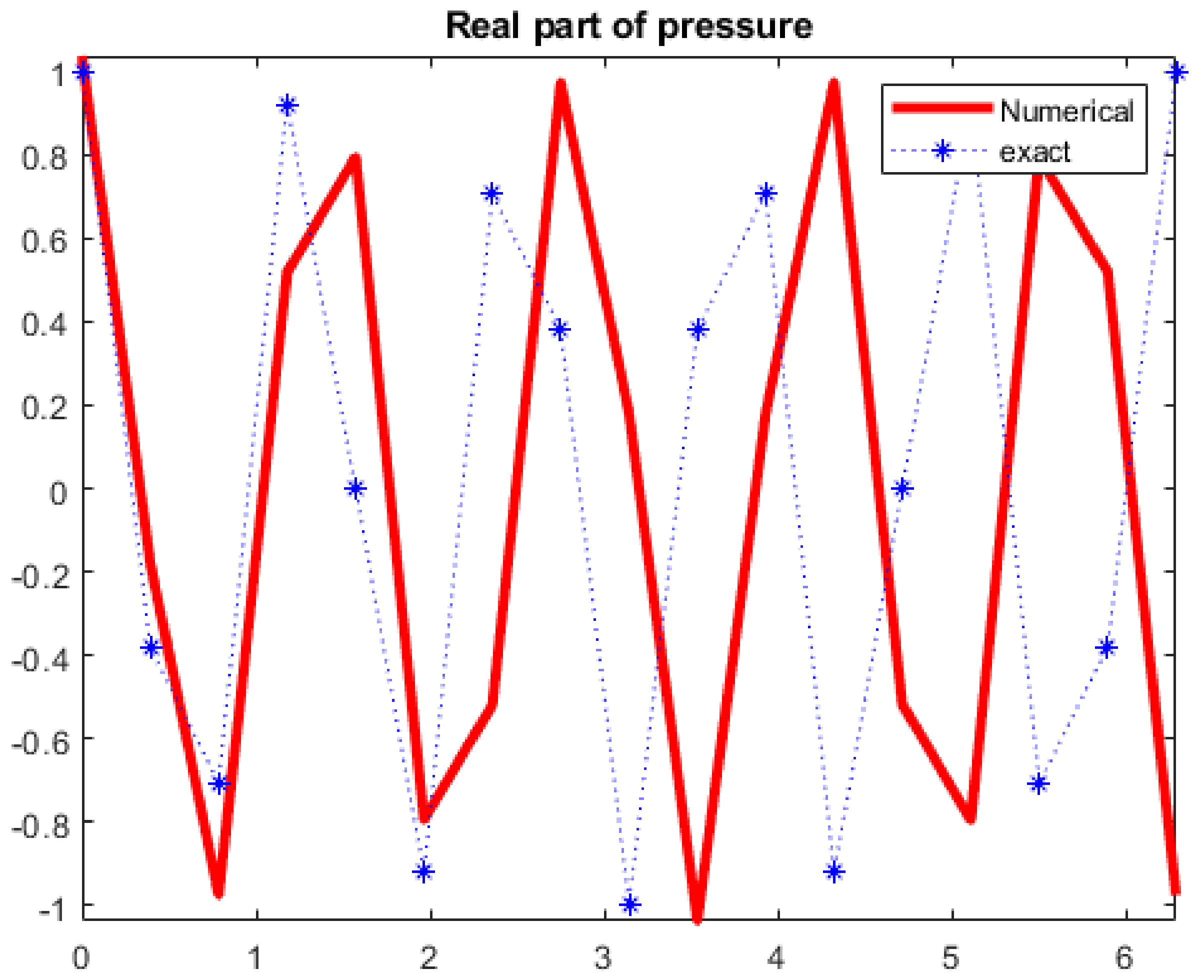

16 elements

FEM

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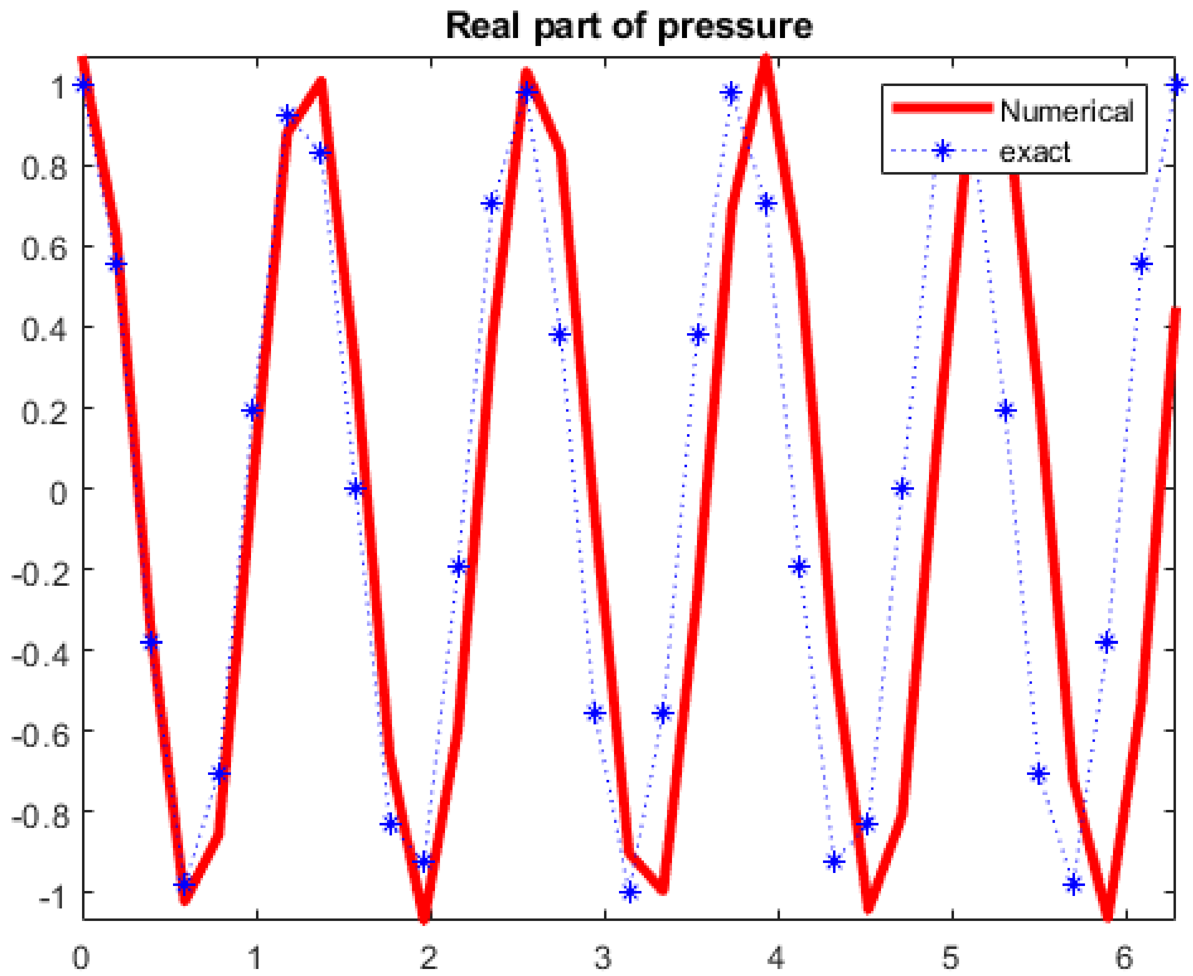

32 elements

FEM

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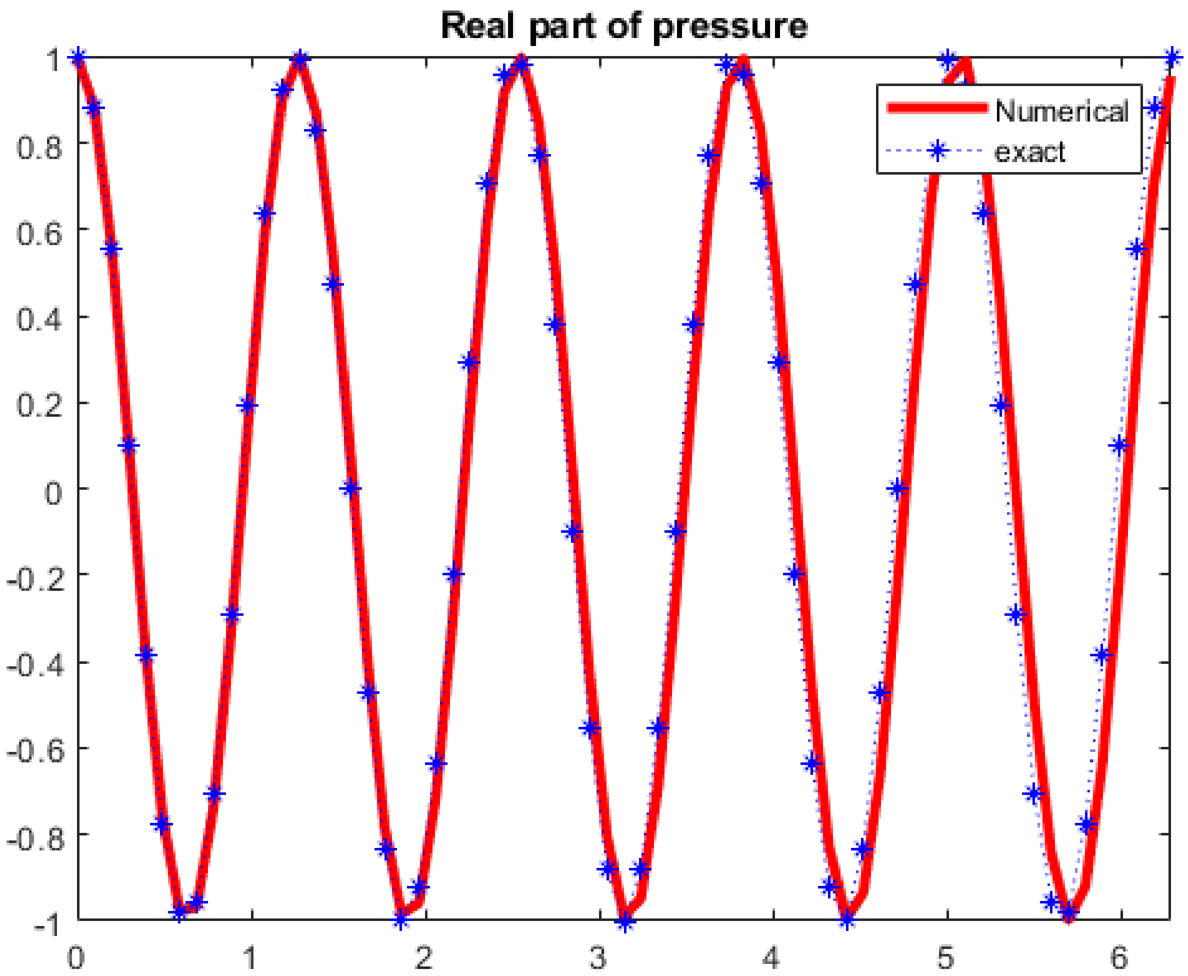

64 elements

FEM

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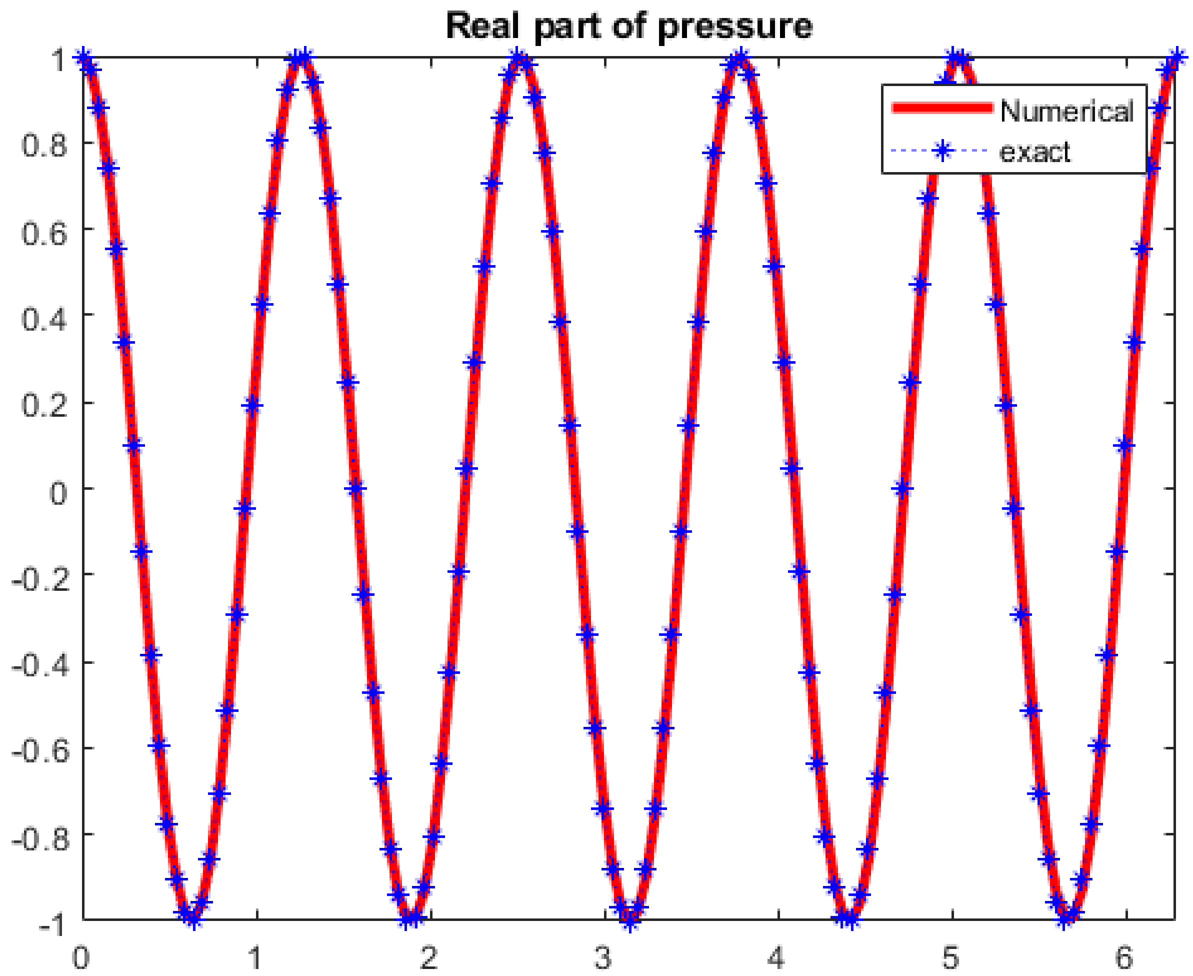
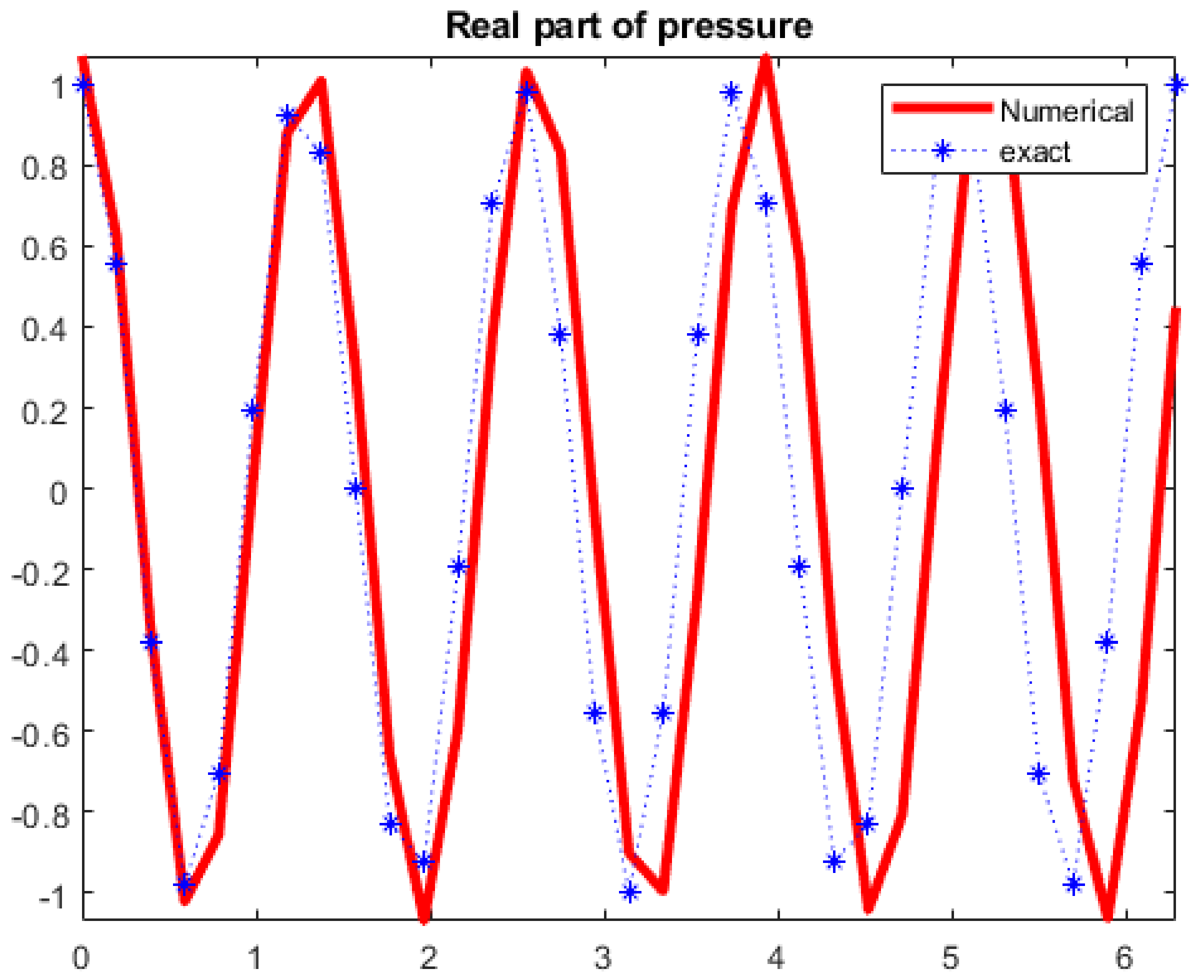


128 elements

- We need to **increase the number of points** to improve the results
- This is classical FEM.

Higher order FEM



$p = 1$, 32 elements

We keep the same number of elements, but increase "p"

Higher order FEM

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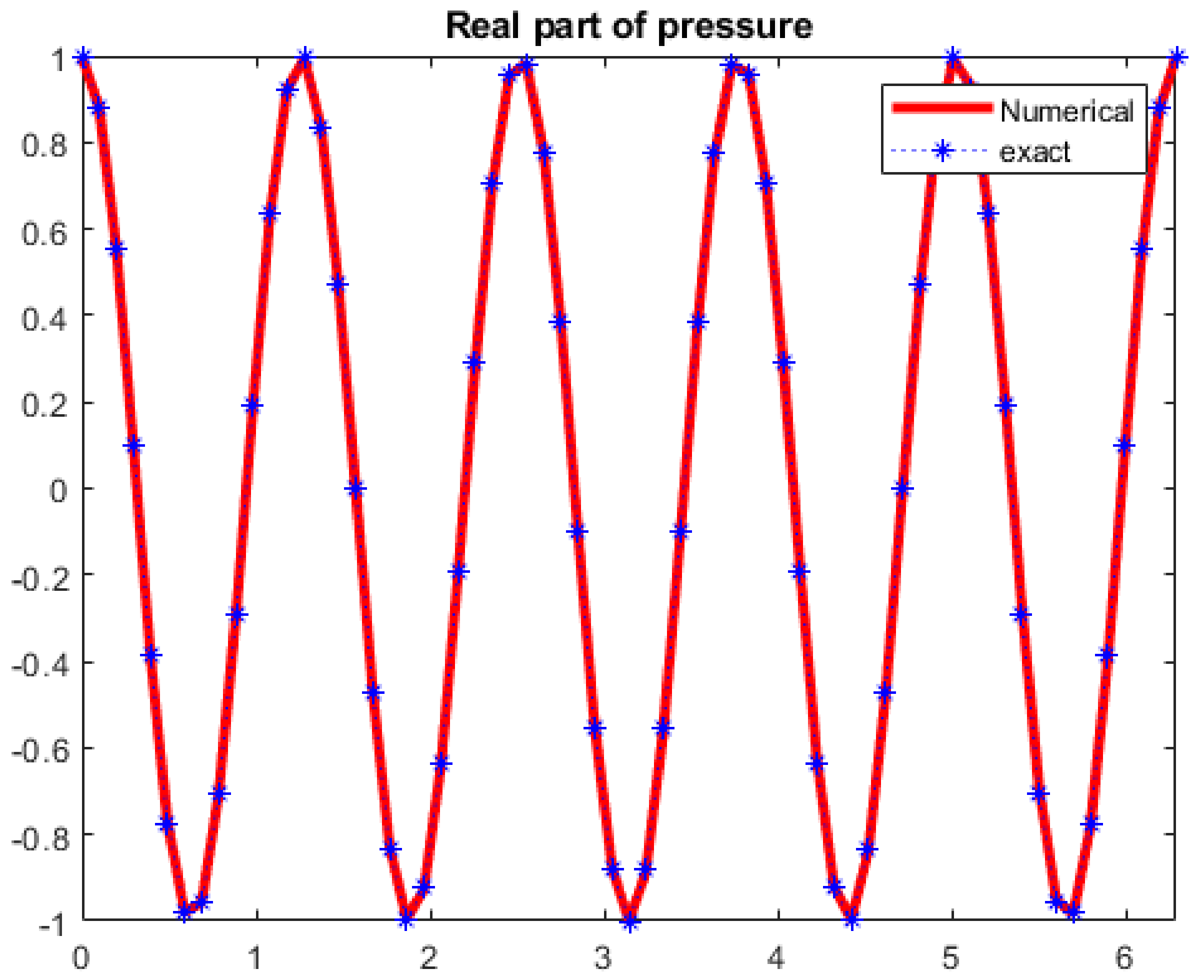

$p = 2$, 32 elements

Higher order FEM

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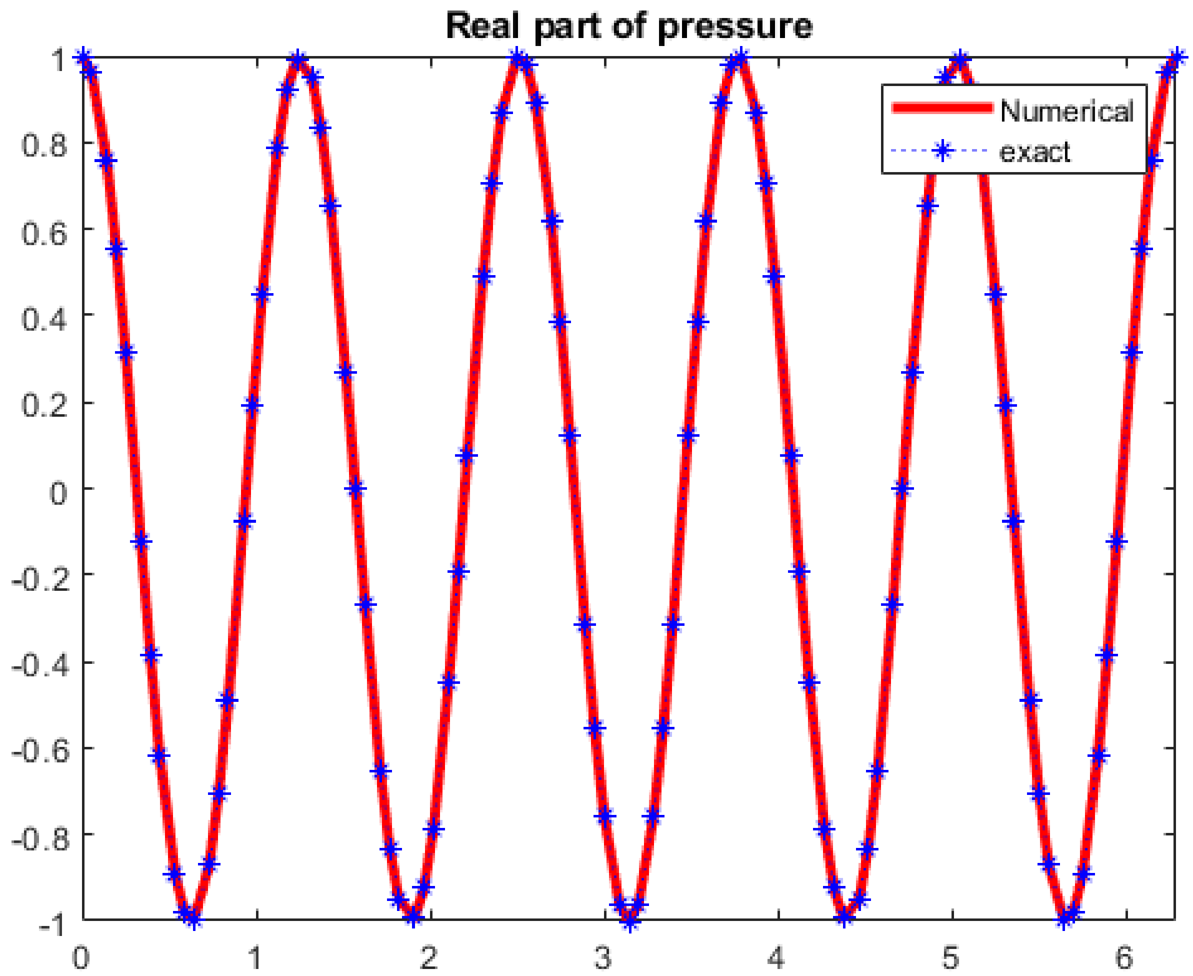
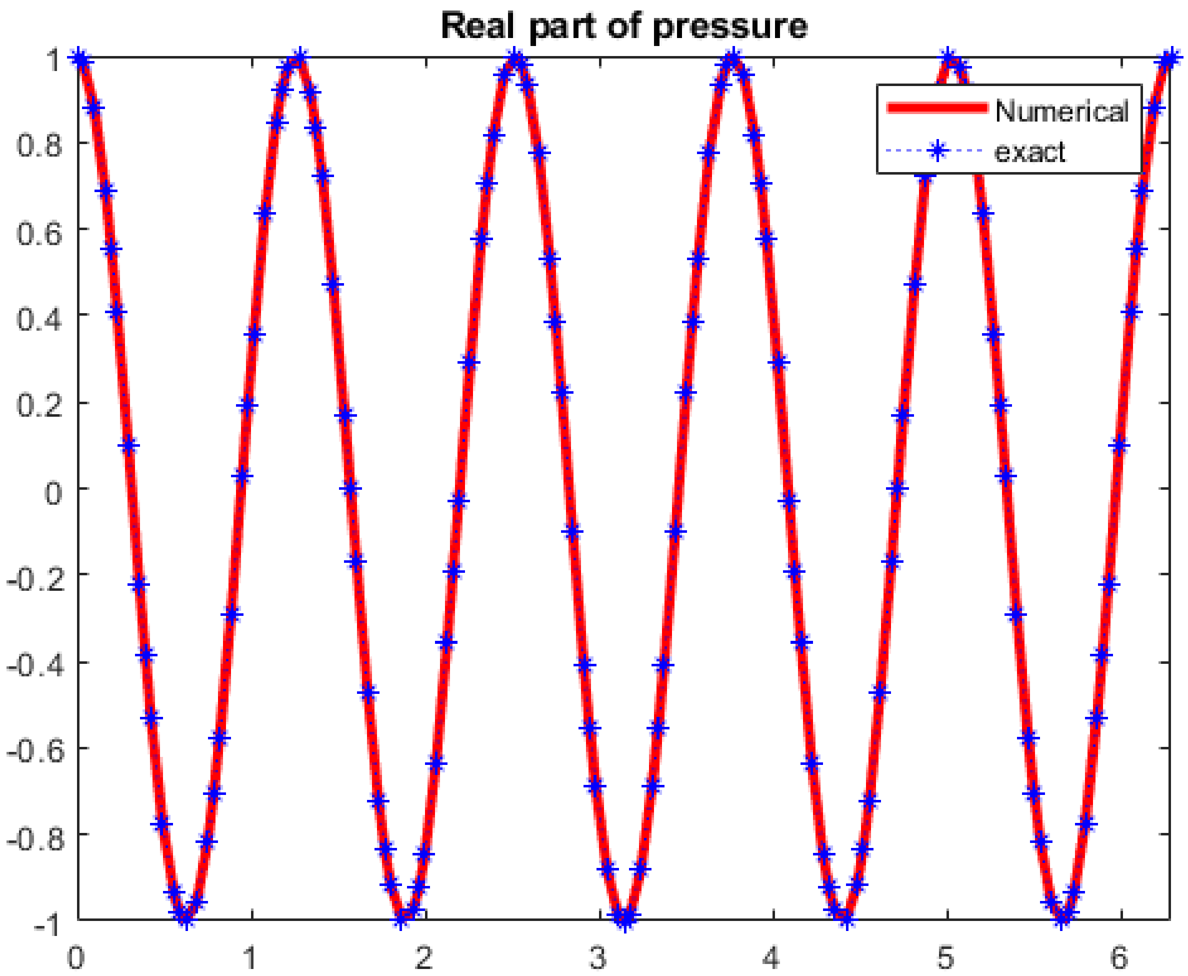


$p = 3$, 32 elements

Higher order FEM



$p = 4$, 32 elements

- Just with 32 elements with can get very good accuracy.
- Referred to as $\boldsymbol{p}$**FEM**.

Higher order FEM

Higher order FEM method

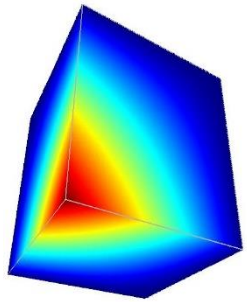
- Allows to use one mesh for a range of frequencies
- Static condensation
  - Removes bubble shape functions
  - Improves the conditioning

- Increases assembly time for the system

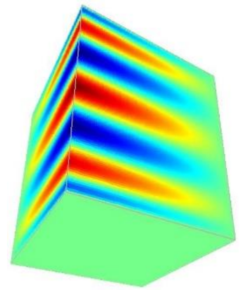
Options to choose in higher order FEM:

- Nodal based (Lagrange)
- Hierarchic (Integrated Legendre)
  - Ensures optimal conditioning of the stiffness matrix
  - basis of order $p + 1$ built on simple correction

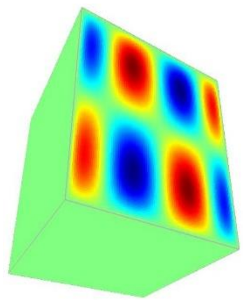
of the basis of order p;



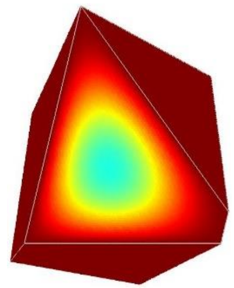
Vertex function



Edge function



Face function



Bubble function

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Background

Higher order FEM method

- Adaptive Higher order FEM (FEMAO) [1]
- Anisotropic Higher order FEM (FEMA2O) [2]

- These provides drastic improvements over the fixed higher order FEM.

- But even with FEMA2O, it **requires large computational time** for one simulation.
- These simulations need to be run 100's to 1000's of times for liner optimization.
- We propose to use domain decomposition methods (DDM) to tackle this problem

[1] Beriot, H. *et. al.* "Efficient implementation of high-order finite elements for Helmholtz problems," International Journal for Numerical Methods in Engineering, Vol. 106, No. 3, 2016, pp. 213-240.
[2] Gabard.,G., *et. al., "*An Adaptive, High-Order Finite-Element Method for Convected Acoustics." American Institute of Aeronautics and Astronautics, 2018.

Background

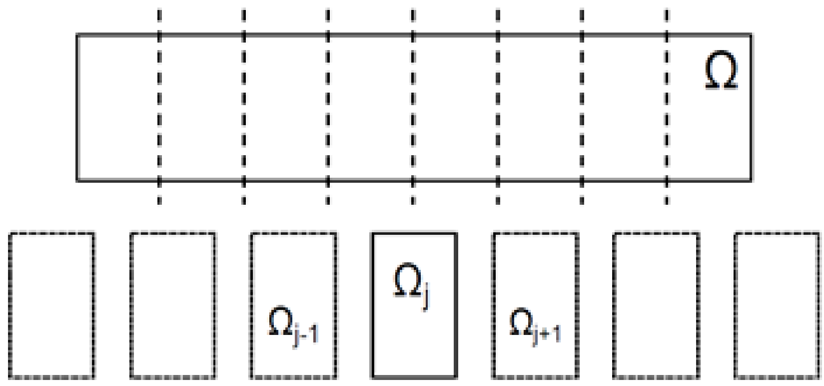
Domain Decomposition Methods

We propose to use **non-overlapping FETI** methods.

What is **FETI** ??

Finite Element Tearing and Interconnect

- Division of the numerical domain into smaller sub-domains (**Tearing**)
- Compute partial solutions in each subdomain (**Finite Element**)
- Glue the solutions back to get the final solution (**Interconnect**)



Suited for parallel computing.

Objectives

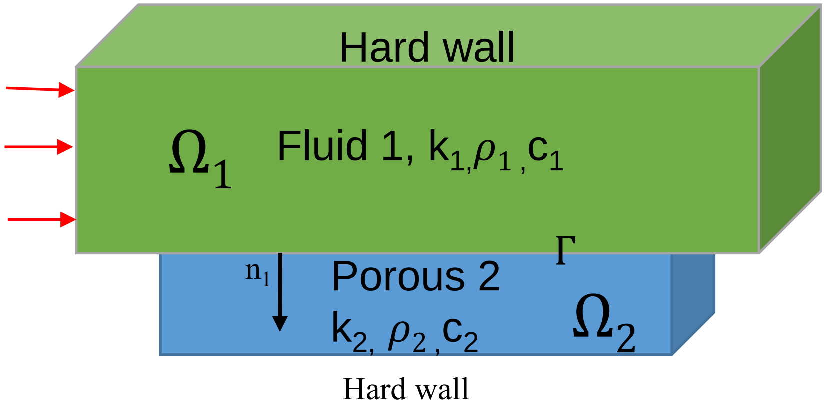
- Examine / Compare the state of art FETI methods using p FEM.
- Extend FETI methods to non-local liners
- Improve the optimization workflow for liner modeling
  - reduce CPU, memory costs
  - reduce the computational time
- Extend FETI methods to non-local liners with flow. (LPE)
- Apply the methodology on realistic nacelle intakes.

Methodology

Siemens PLM Software

- ➢ FETI-2LM (two LM for coupling.)
- ➢ FETI-H (1 LM for coupling)
- Porous material is modeled as a fluid with freq. dependent properties.
- Fluid 1 and 2 are governed by Helmholtz equation.

FETI-2LM Interface conditions:



$k_2(\omega)$, $\rho_2(\omega)$, $c_2(\omega)$ are complex and frequency dependent.

$$p_1 = p_2 \,, vn_1 = -vn_2$$

$$\frac{\partial p_1}{\partial n_1} + ik_1 p_1 = -\frac{\rho_1}{\rho_2}\frac{\partial p_2}{\partial n_2} + ik_1 p_2 \; on \; \Gamma \ldots (1)$$

$$\frac{\partial p_2}{\partial n_2} + ik_2 p_2 = -\frac{\rho_2}{\rho_1}\frac{\partial p_1}{\partial n_1} + ik_2 p_1 \; on \; \Gamma \ldots (2)$$

Methodology

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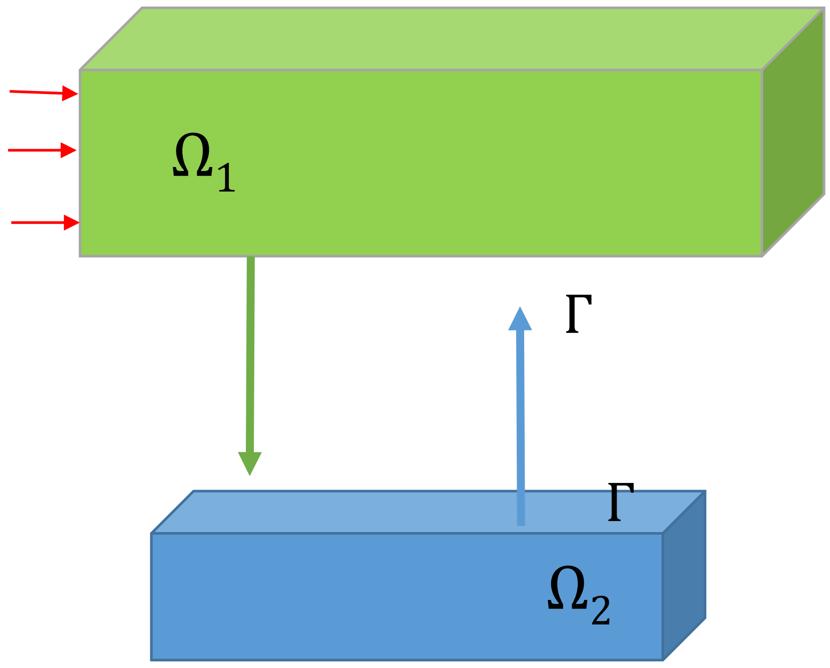
$$\frac{\partial p_1}{\partial n_1} + ik_1 p_1 = \boldsymbol{\rho_1}\ \boldsymbol{\lambda_{12}} \quad \text{on } \Gamma \ldots (3)$$

$$\frac{\partial p_2}{\partial n_2} + ik_2 p_2 = \boldsymbol{\rho_2}\ \boldsymbol{\lambda_{21}} \text{ on } \Gamma \ldots (4)$$



Resulting interface FETI-2LM problem:

$$\lambda_{12} + \lambda_{21} = i\left(\frac{k_1}{\rho_1} + \frac{k_2}{\rho_2}\right) \mathrm{p}_1 \ \text{ on } \Gamma \ldots (5)$$

$$\lambda_{12} + \lambda_{21} = i\left(\frac{k_1}{\rho_1} + \frac{k_2}{\rho_2}\right) \mathrm{p}_2 \text{ on } \Gamma \ldots (6)$$

Discretization : Higher order FEM

ORTHODIR to solve the iterative system.

Methodology

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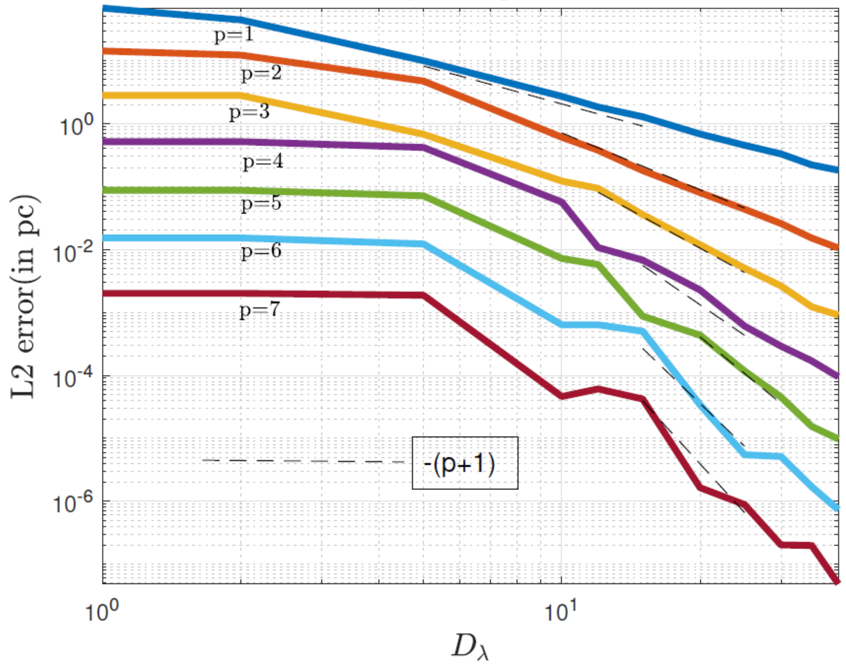
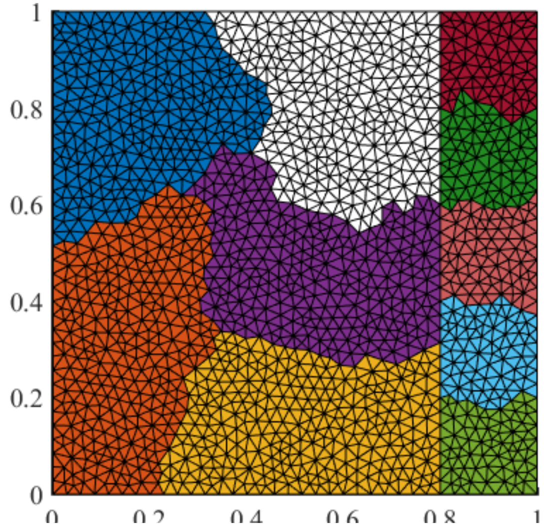
Case 1: Plane wave propagation

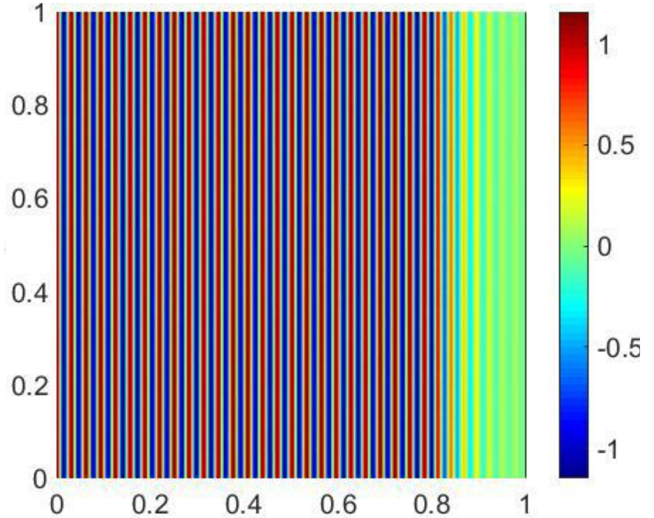


h-p convergence in 1D using p-FEM

Case 2: Kundt's tube test case



5 partitions each in fluid 1 and 2



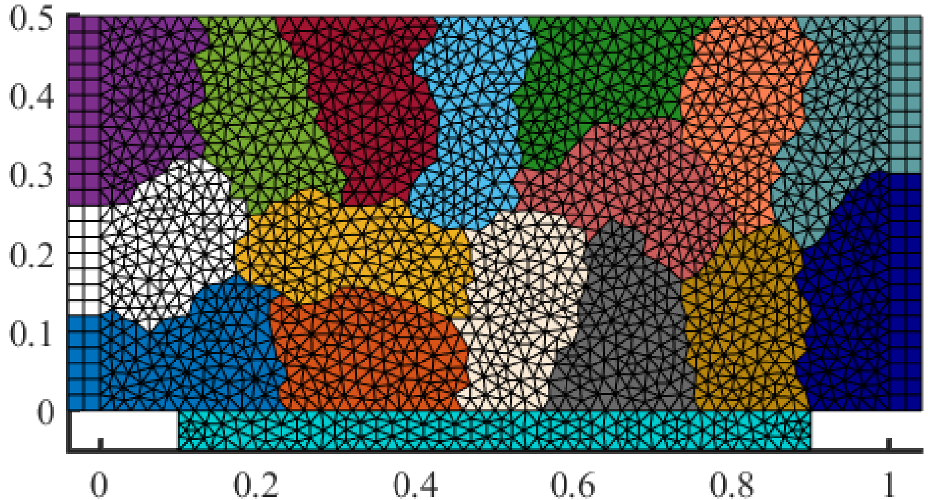
Pressure field at 7.7kHz for a plane wave

- L_2 − norm error converges as $D_\lambda^{-(p+1)}$.
- Scalability tests (w.r.t. iteration count) showed **better** performance for FETI-2LM compared to FETI-H. **No preconditioner used.**

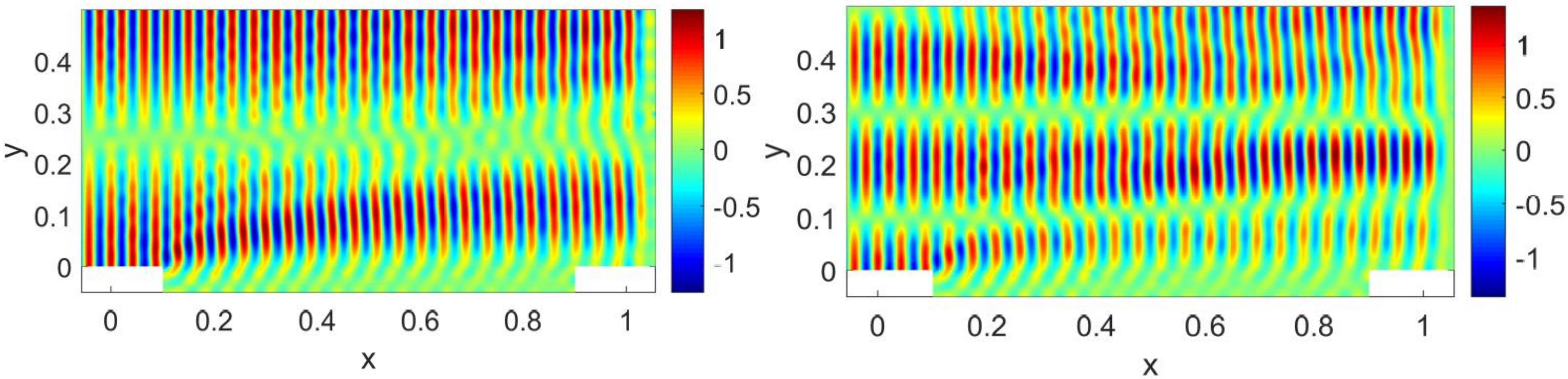
Verification

Case 3:Duct-Liner Test case

Simplified Geometry in 2D



16 partitions in duct, 1 liner medium



Mode order =2,5 at f = 8kHz using FETI-2LM, 8 partitions in duct and 1 partition in liner

Workflow

Proposed workflow at a particular frequency

Select design parameters, porosity, liner depth, etc.

↓

Save the LU factors (if first iteration) otherwise reuse them from the previous FEM calculation

↓

Solve the interface matrix iteratively for a given tolerance (Reuse the previous Krylov subspace basis)

↓

Compute the transmission loss for the design parameters chosen

Has to be run 100's of times in the optimization loop.

Workflow

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- This new optimized workflow has been verified for this simple geometry.

- The results from case 1 and case 2 are accurate up to machine precision.

- Drastic reductions in the CPU cost observed.

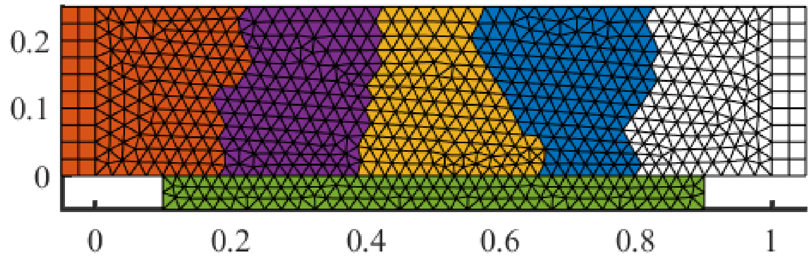
- Recycling the vectors reduced the iterations cost by a factor of 2.

- The range of parameters chosen for the liner :

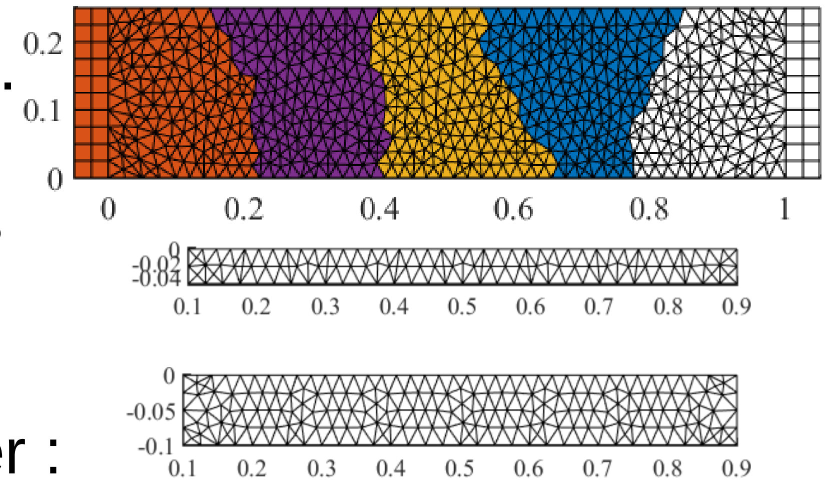
  $d = 5 - 10\ cm$

  $\phi = 2e^3\ to\ 5e^4 \frac{Ns}{m^4}$

Case 1: Classical way



Case 2: Proposed methodology

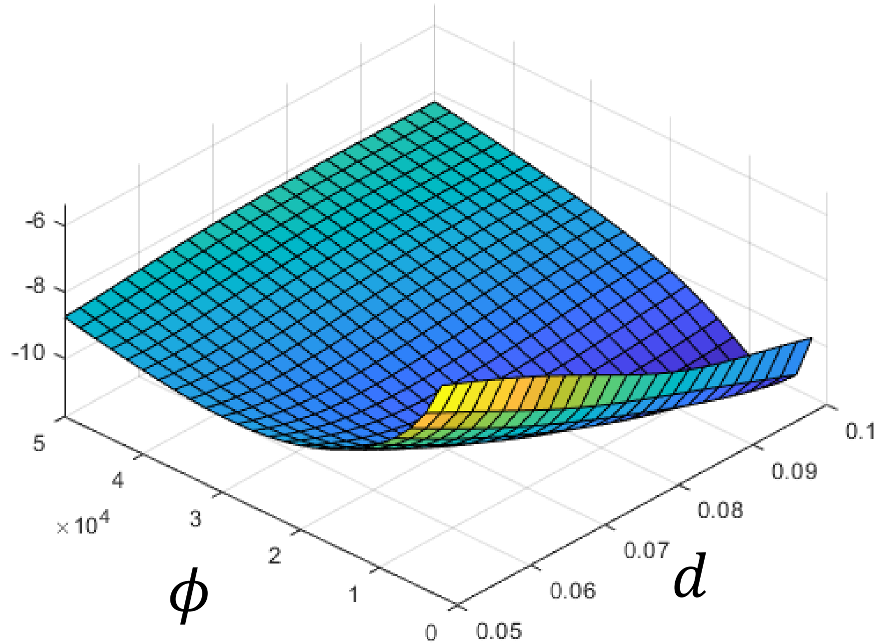


Liner 1: $d = 5$ cm, $\phi = 2e^3 \frac{Ns}{m^4}$

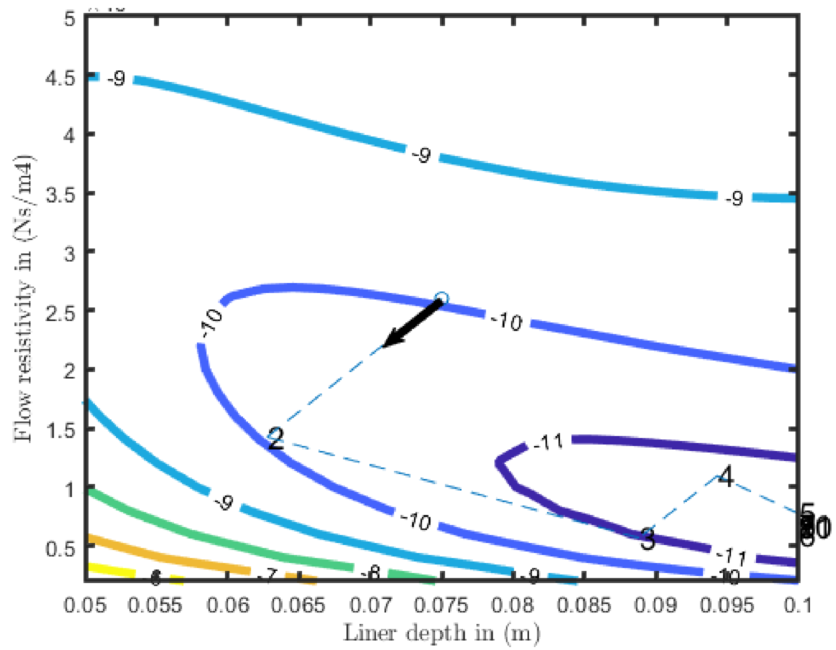
Liner 2: $d = 10$ cm, $\phi = 5e^4 \frac{Ns}{m^4}$

Preliminary results

1kHz, first mode optimization



Results from manual scan of the design space



Results from "fmincon" for optimization

- T.L. = 11.77 dB for 10cm, 6572 $\frac{Ns}{m^4}$
- **Matlab** optimization toolbox "fmincon" is used.
- Since there is only one minima, the fmincon converges irrespective of initial guess.
- The higher the liner depth, better is the attenuation in general.

Conclusion

- The **FETI-2LM DDM** was found to be more efficient in the absence of a global preconditioner.
- The optimization workflow has been implemented and verified in 2D in the case of no flow.
- Automatic local optimization tools have been tested for simplified geometries in 2D.
- The savings in the LU factor provide **drastic reductions** in **CPU costs**.
- The current recycling strategies **reduce the number of iterations** by 50%.

Future work

- More efficient recycling strategies to improve the performance of the proposed workflow.
- Extend the current workflow including mean flow effects in 3D.
- Application to a realistic test case using optimization tools in 3D.
- **Generic and a black box tool, easy to use** which can be integrated in any optimization workflow.

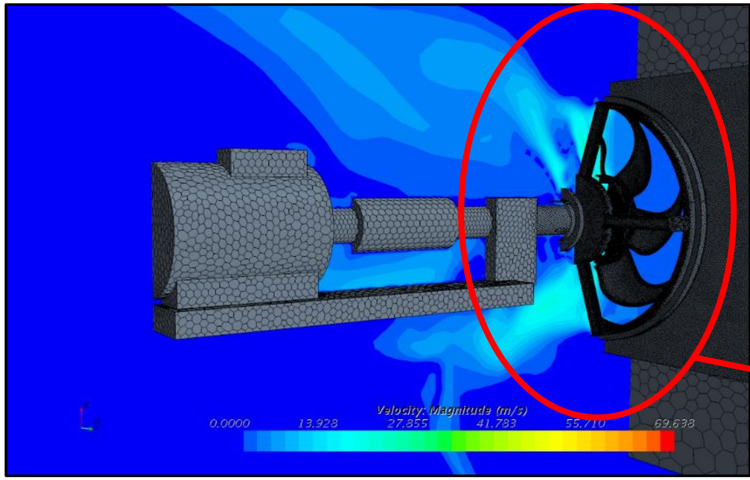
Smart ANSWER

PhD Projects

UNIVERSITY OF Southampton
Institute of Sound and Vibration Research

Aerospace

Automotive



Fan Proximity Liner Modelling

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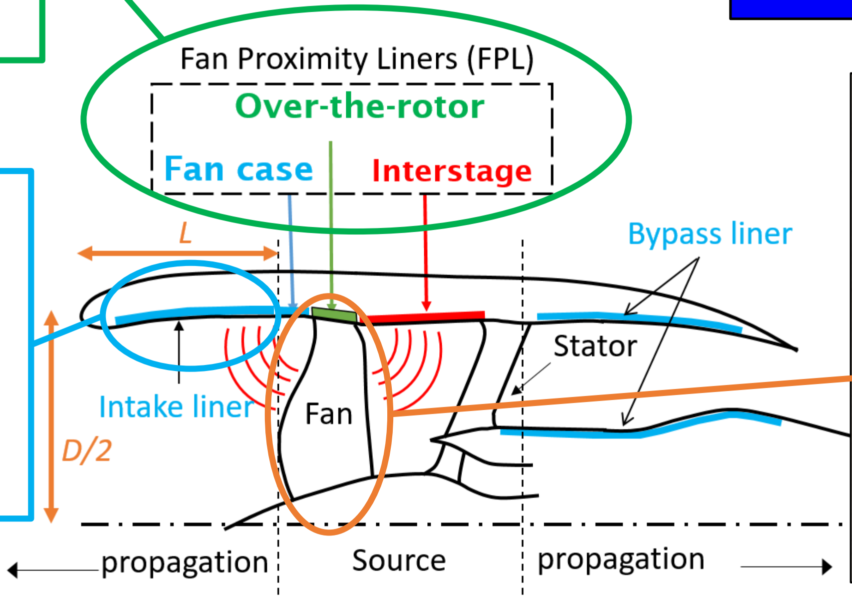
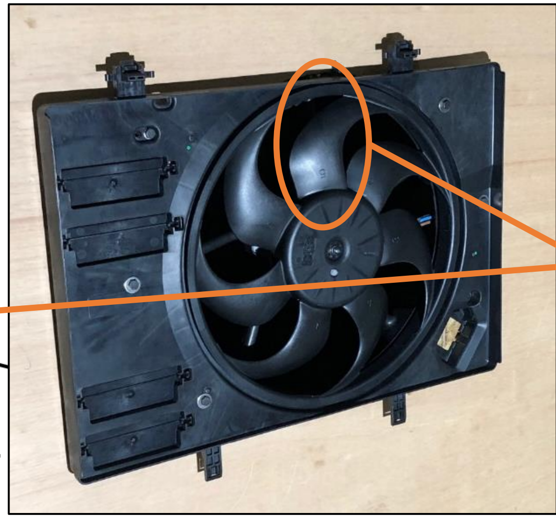
UNIVERSITY OF Southampton
Institute of Sound and Vibration Research

Low-Speed Cooling Fan Noise Modelling

ESR: Alessandro Zarri





FEM Modelling of non-locally reacting liners

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CFD-CAA analysis & optimization methods

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National Technical University of Athens

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

National Technical University of Athens

CFD-CAA analysis & optimization methods, with industrial applications

ESR 13: Morteza Monfaredi *Supervisor: K. Giannakoglou*

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Outline

- Hybrid Methods
- Validation of Hybrid solver
- Adjoint Methods
- Continuous Adjoint formulation
- Background
- Optimization results
- Next Steps

Hybrid Methods

The overall acoustic problem is broken down into a set of coupled sub-problems, addressed using a numerical method that is customized to the dominant physics occurring at this stage.

•Development of a CAA tool based on Ffowcs Williams & Hawkings (FW-H) analogy and coupling with a GPU-enabled compressible CFD solver .

•Development of the (continuous) adjoint to the coupled CFD-CAA model.

FW-H analogy (permeable version)

$$H(f)c_o^2\rho'(\mathbf{y},\omega) = -\oint_{f=0} F_i(\xi,\omega)\frac{\partial G(\mathbf{y};\xi)}{\partial \xi_i}\,\mathrm{d}l - \oint_{f=0} \mathrm{i}\omega Q(\xi,\omega)G(\mathbf{y};\xi)\,\mathrm{d}l - \int_{f>0} T_{ij}(\xi,\omega)H(f)\frac{\partial^2 G(\mathbf{y};\xi)}{\partial\xi_i\partial\xi_j}\mathrm{d}\xi.$$

$$F_i = (P_{ij} + \rho u_i(u_j - v_j))\frac{\partial f}{\partial x_i}$$

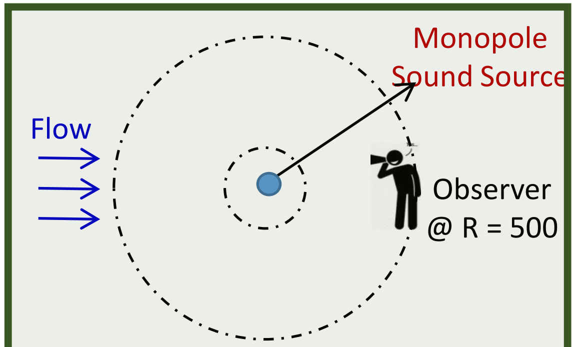
$$Q_i = (p_o v_i + \rho(u_i - v_i))\frac{\partial f}{\partial x_i}$$

$$T_{ij} = \rho u_i u_j + P_{ij} - c_o^2\rho'\delta_{ij},$$

Validation of Hybrid solver

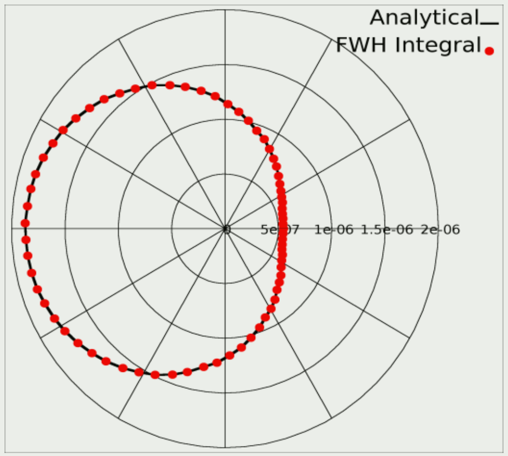
National Technical University of Athens

Monopole in flow

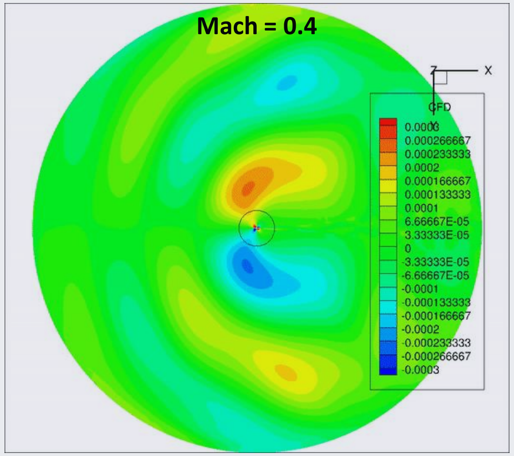


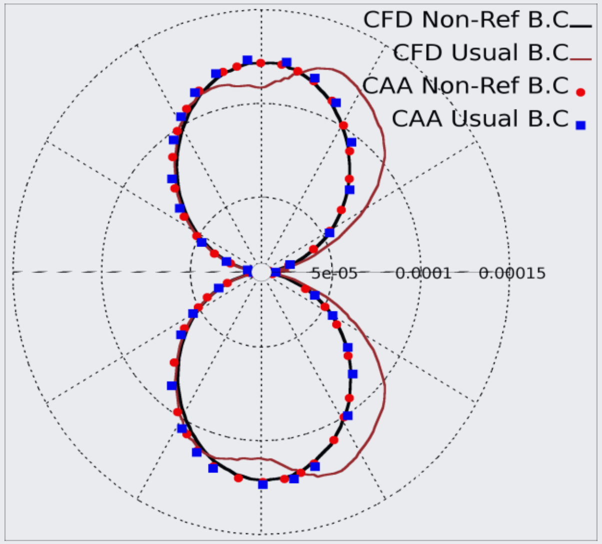
$$\phi(x,y,t) = A\frac{i}{4\beta}\exp^{i(\omega t + Mkx/\beta^2)} H_o^{(2)}\left(\frac{k}{\beta^2}\sqrt{x^2+\beta^2 y^2}\right)$$

$$p' = -\rho_o(\partial\phi/\partial t + U_o\partial\phi/\partial x),\ u' = \nabla\phi$$



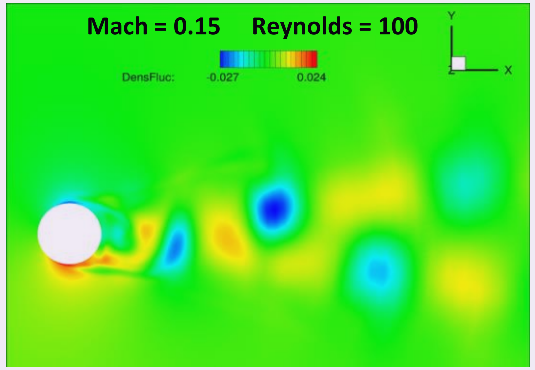
Pitching Airfoil NACA12in inviscid fluid



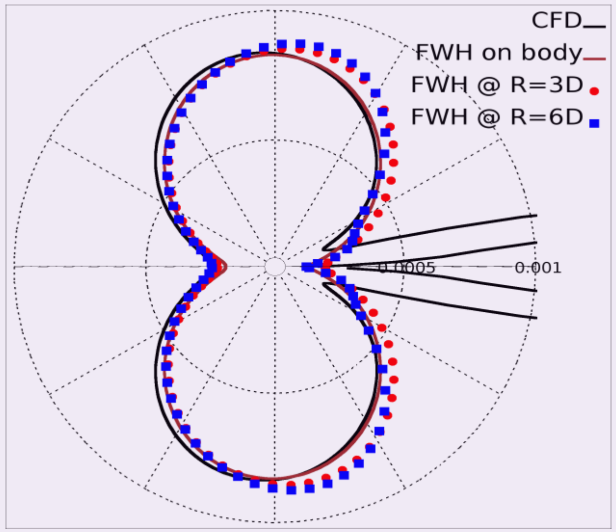


Navier–Stokes characteristic boundary conditions (NSCBC)

Laminar Vortex shedding Cylinder

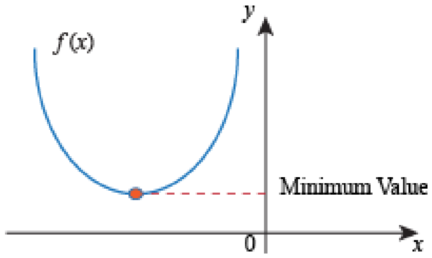


Khalighi Y, Mani A, Ham F, Moin P. Prediction of sound generated by complex flows at low Mach numbers. AIAA journal. 2010 Feb;48(2):306-16.



Adjoint Method

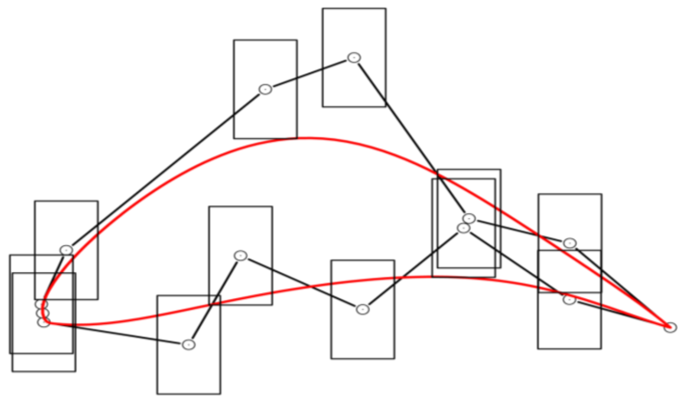
- Find the minimum of f(x).



- But, analytic expressions are not known in the computational world !!
- To optimize an Objective Function with respect to a Design Variable we need the gradient.
- Efficiency of GBMs depends on the method used to compute objective function (J) gradients.
- Finite Difference method:

$$\frac{\delta J(b)}{\delta b_n} = \frac{J(b_1,.....,b_n+\varepsilon,....,b_N) - J(b_1,.....,b_n-\varepsilon,....,b_N)}{2\varepsilon}$$

$2 \times N$ RUN!!!



Continuous adjoint Formulation:

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- Adjoint methods can tell you from a **single run** how you should change a geometry to improve it, **independent** from the number of design variables.

- Continuous adjoint formulation:

Primal equation : $\vec{R}(\vec{u},\vec{b}) = 0$

Objective function : $J(\vec{u},\vec{b})$

$$J_{aug} = J + \int_{\Omega} \vec{\psi}\vec{R} \; d\Omega \xrightarrow{Differentiation} \frac{\delta J_{Aug}}{\delta b_n} = \int_{\Omega} \left[(.....) \frac{\partial \vec{u}}{\partial b_n} + (.....) \right] d\Omega$$

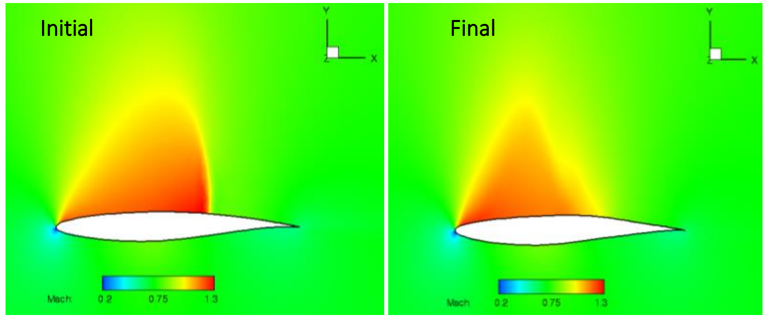
Adjoint equation ← (.....) $\frac{\partial \vec{u}}{\partial b_n}$

(.....) → Adjoint B.C & Sensitivities

- Field adjoint equations, their boundary conditions and the final expression of the gradients (sensitivity derivative) are derived by differentiating the augmented function

- Adjoint solves backward in time (saving result in unsteady problems).

Adjoint method for aeroacoustic:



RAE airfoil, Drag minimization

- Adjoint methods are Widely used in aerodynamic shape optimization.
- relatively new in the field of aeroacoustic optimization .
- **Discrete Adjoint using Algorithmic Differentiation**
  - Rumpfkeil et al (2010). **URANS/FW-H** -(blunt trailing edge in turbulent flow).
  - Zhou et al (2015 - now). **URANS/FW-H**-(nviscid pitching airfoil, laminar and turbulent vortex shedding cylinder, rod airfoil, jet flap interaction noise).
  - Zhou et al (2019). **RANS-SNG**(Direct method, broadband noise minimization).
- **Continuous Adjoint**
  - Economon et al (2012). FW-H formulation in the wave equation form, solved using a FEM. Needs cumbersome derivations of new adjoint boundary conditions at the interface between the CFD and CAA. (inviscid pitching airfoil)
  - NTUA (2015). Steady flow model was used and a turbulence-based surrogate objective functions-(side mirror).
  - Kapellos. Incompressible flow models and the Kirchhoff integral.

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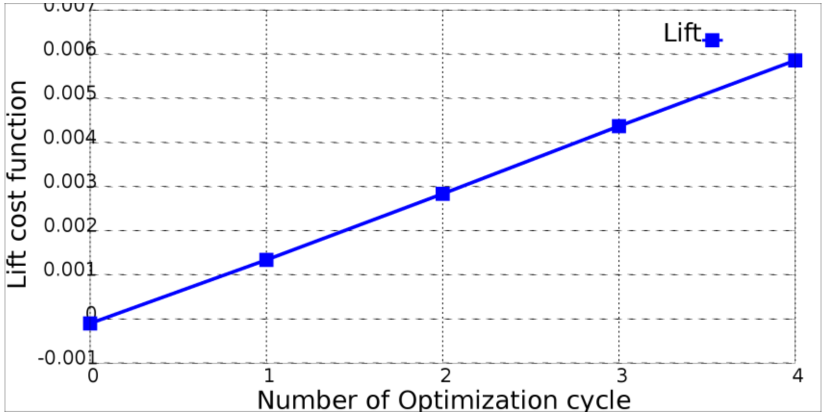
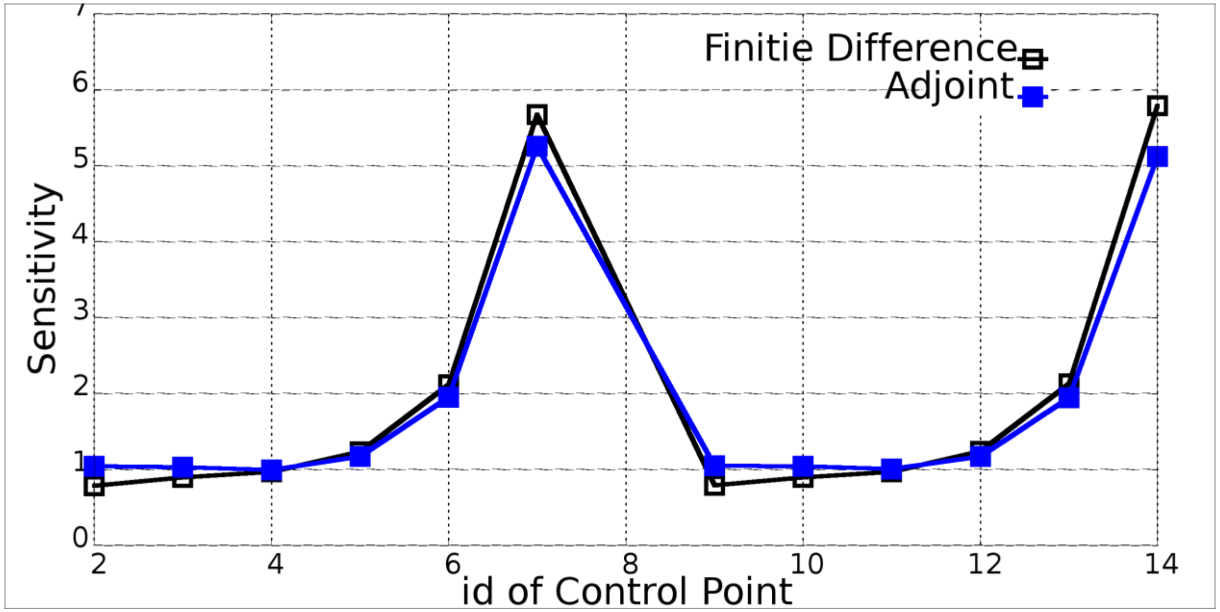
Lift Optimization

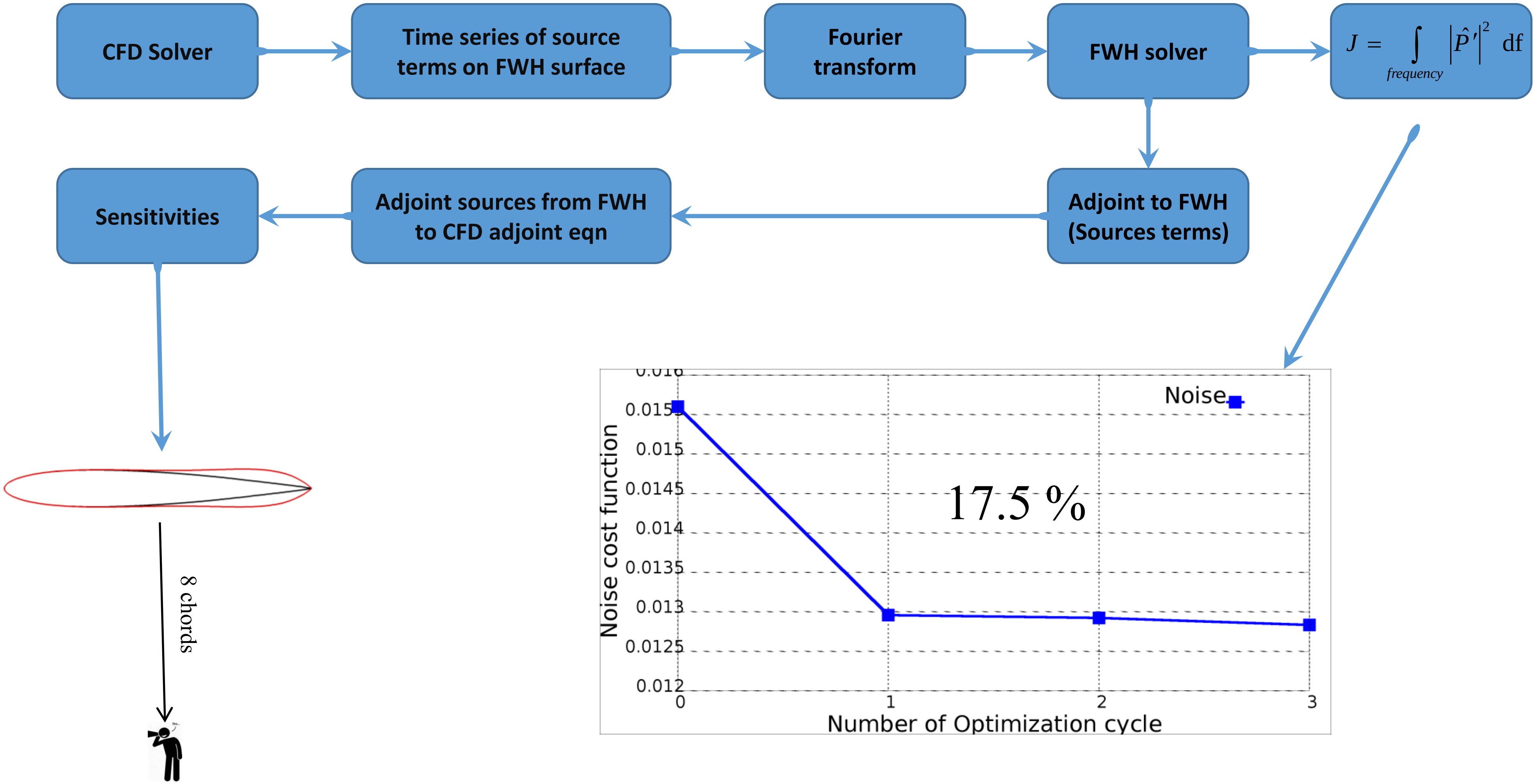
- Mach = 0.6
- Amplitude = 2.44 degrees
- Mean angle of attack = 0
- Period = 0.114
- 40 time steps per period
- 2D
- Unstructured
- 51000 nodes
- 202 nodes on airfoil
- 201 nodes on far field





Optimization results

Noise Optimization



Optimization results

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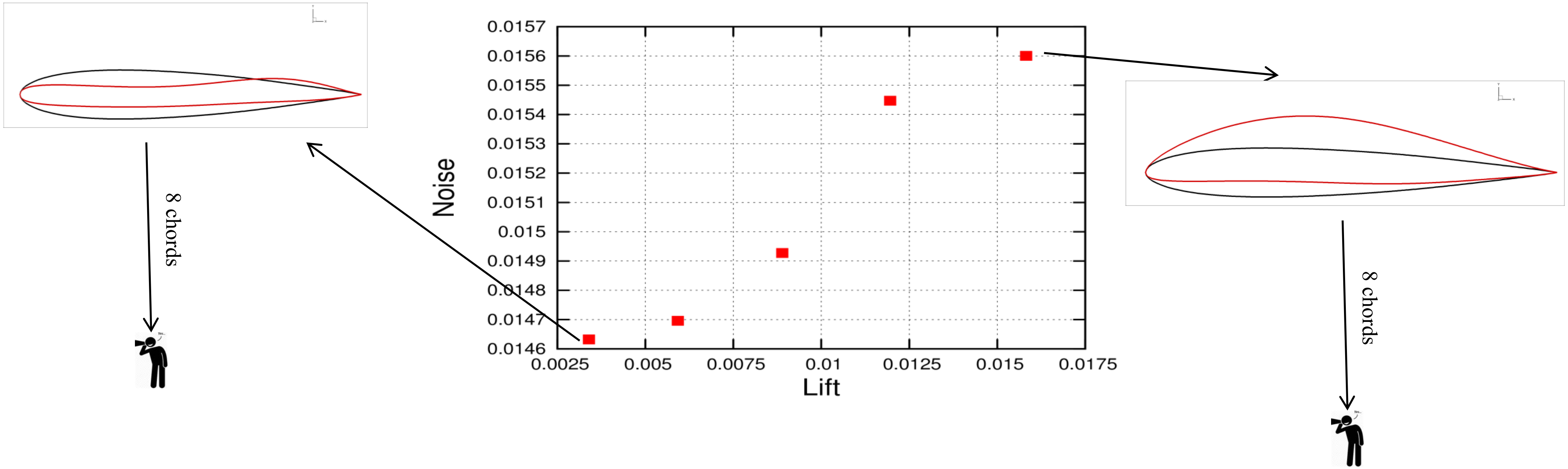
Noise Optimization

In-house software (EASY) – Evolutionary algorithm



Next Steps

- Validate the sensitivities for inviscid case.
- Including constraints.
- Run the code for the laminar vortex shedding cylinder.
- Inclusion of turbulent cases.

Overall conclusions

Low-Speed Cooling Fan Noise Modelling

ESR: Alessandro Zarri

- A low-order prediction methodology has been applied to model the self-noise emitted by a low-speed cooling fan.

FEM Modelling of non-locally reacting liners

ESR: Chaitanya Sanghavi

Siemens PLM Software

SIEMENS

A generic, robust, easy to use tool for modeling liners in the initial design phase.

Fan Proximity Liner Modelling

ESR: Sergi Palleja-Cabre

UNIVERSITY OF Southampton
Institute of Sound and Vibration Research

- OTR analytical liner models can yield a peak PWL insertion loss of ~4 dB, with a significant broadband IL over a wide range of frequencies.

CFD-CAA analysis & optimization methods

ESR: Morteza Monfaredi

National Technical University of Athens

- A shape optimization frame-work for noise reduction based on the continuous adjoint method has been developed.

Smart ANSWER

Thank you for your attention

HORIZON 2020 — MARIE CURIE ACTIONS

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