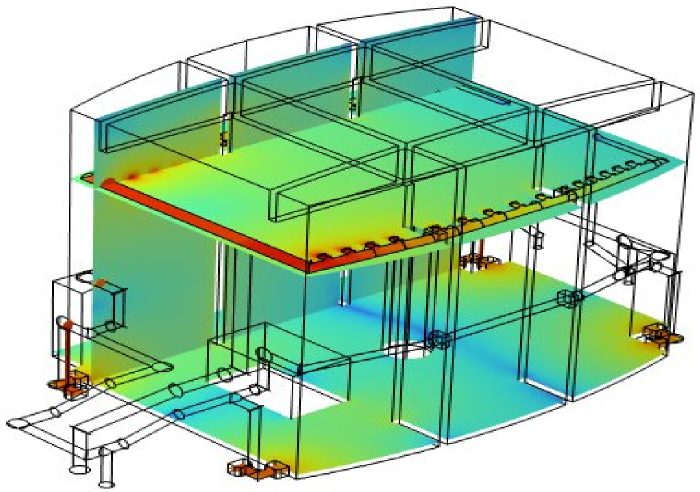
Acoustic noise in the gravitational wave detector Virgo.

Research actions at LAUM



F. Gautier, L. Maurin, M. Brun, S. Terrien

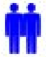
Collaborations

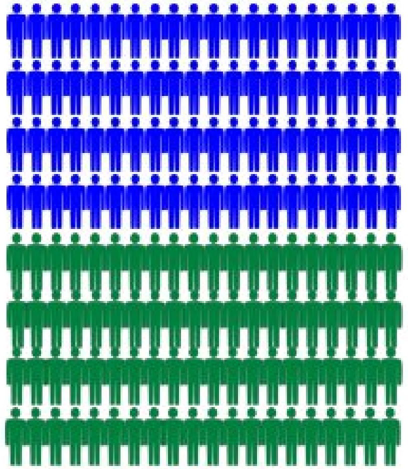
- M. Barsuglia (DR CNRS, laboratoire APC, AstroParticules et Cosmologie, UMR CNRS, Paris)
- D.Fiorucci (lecturer, INRC, Italian National Research Council, Consorzio RFX, Padua)
- I. Fiori, M. Tringali, F. Paoletti (EGO, European Gravitational Observatory, Cascina)

LABORATOIRE D'ACOUSTIQUE DE L'UNIVERSITÉ DU MANS



→ Joint unit CNRS - Le Mans Université


1980


2024

170 people

60 faculty (11 CNRS)

20 technical staff

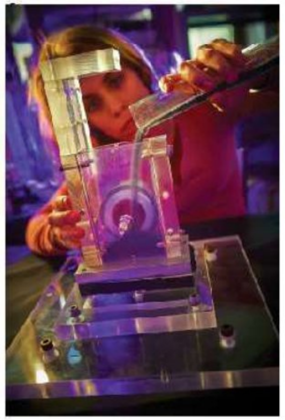
common budget

shared equipment

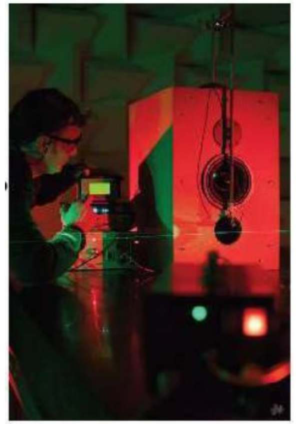
~500 students in acoustics

3 teams

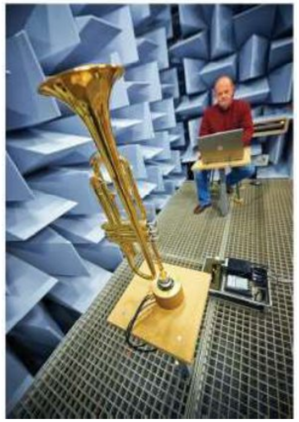
Material



Transducers

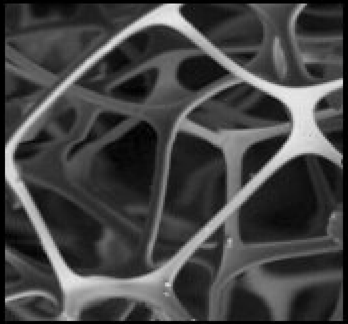


Guided waves
and structures

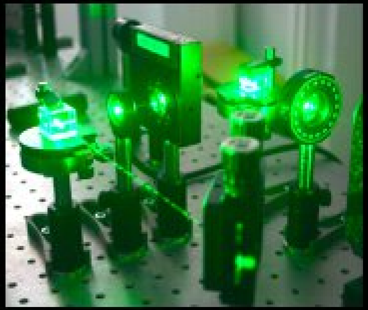


Acoustics @LAUM

Musical acoustics

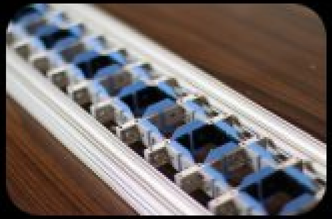


Porous absorbing materials



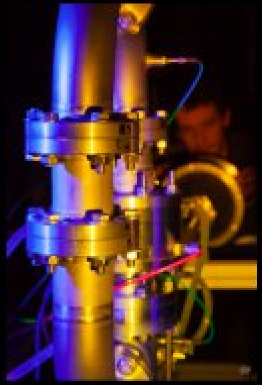
Laser ultrasonics

Granular materials

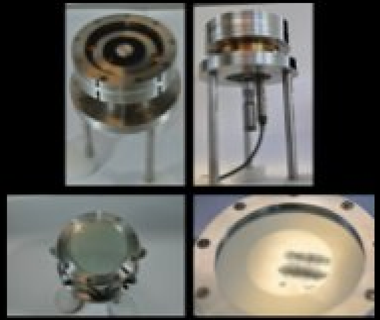


Acoustic and elastic metamaterials

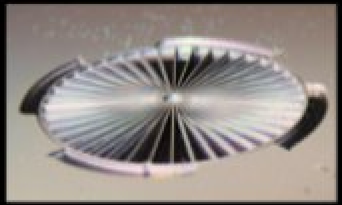
Ultrasonic characterization



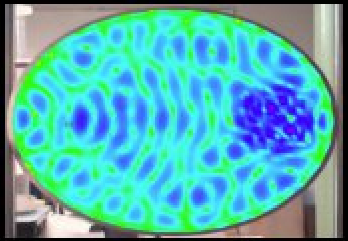
Thermo-acoustics



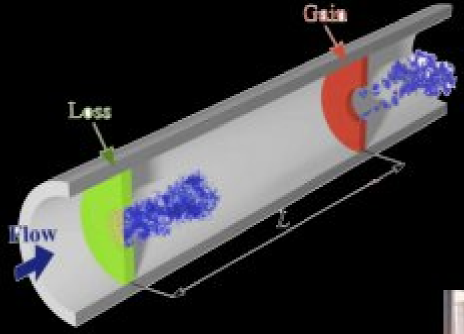
Acoustic micro-systems



Acoustic transducers



Vibro-acoustics

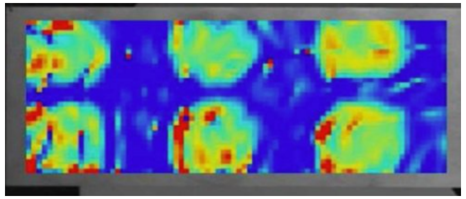


Aero-acoustics

LAUM : Research activities in Vibroacoustics

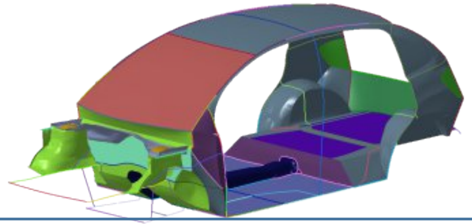
Inverse problems

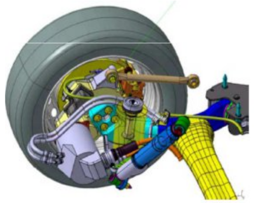
- Acoustic imaging
  Near field holography and beam forming
- Source identification
- Identification of effective material properties
- Defaults identification.



Vibroacoustic modelling

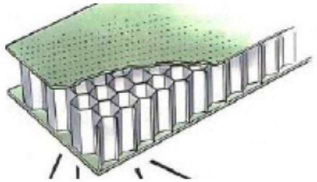
- Squeak and rattle noise
- Numerical modelling
- Mechanical junctions

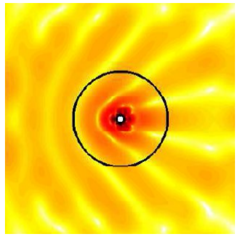




Vibration control

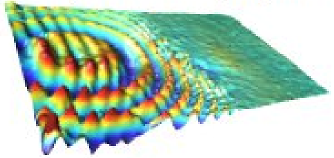
- Periodic structures
- Damping using added granular media
- Microperforated panel
- Gradient of properties (ABH effect)





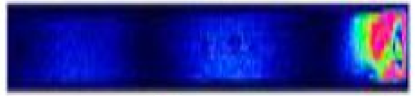
Multi-modal combined imaging

Laser vibrometer
➡ dynamical properties

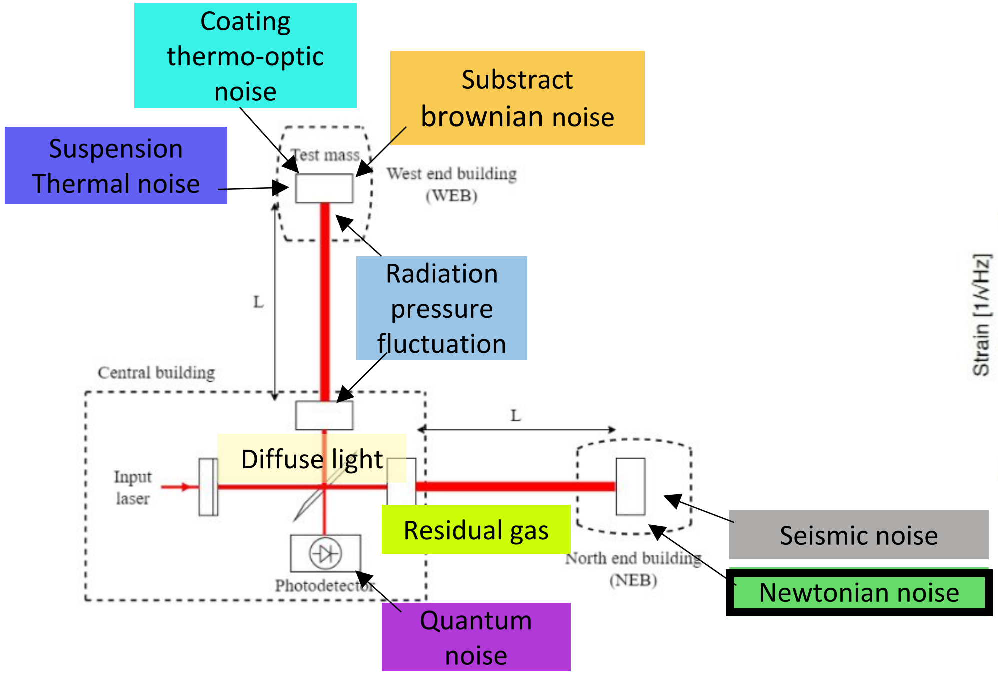


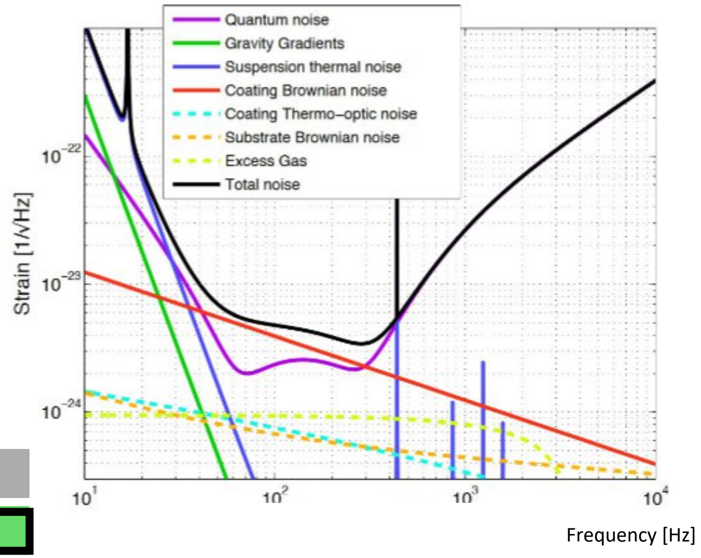
Microphone antenna
➡ sound radiation

Infrared camera
➡ structural damping



Acoustic Newtonian Noise (NN)

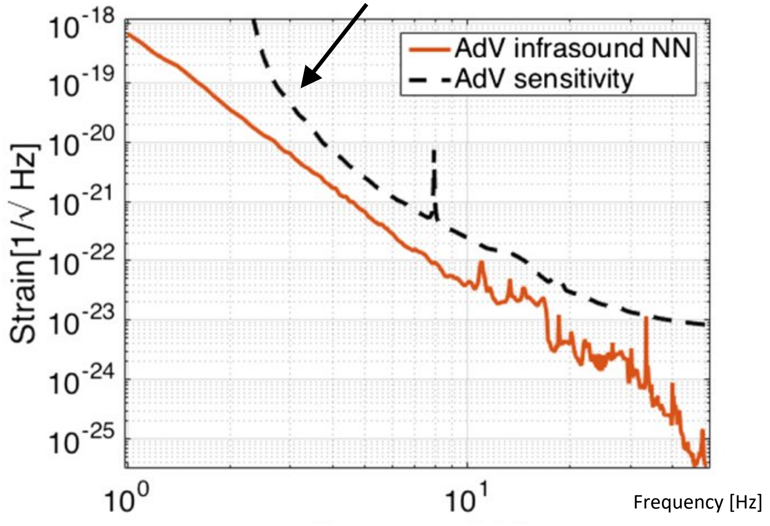




Noise Budget from

T. Accadia et al. VIR-0128A-12, 2012

Target sensitivity of Advanced Virgo (2018)



NN estimate from

D. Fiorucci et al. Phys. Rev. D, 97, 2018.

Newtonian noise is caused by mass density fluctuation, which is proportional to acoustic pressure

is a fundamental limit for gravitational astronomy as It can not be shielded

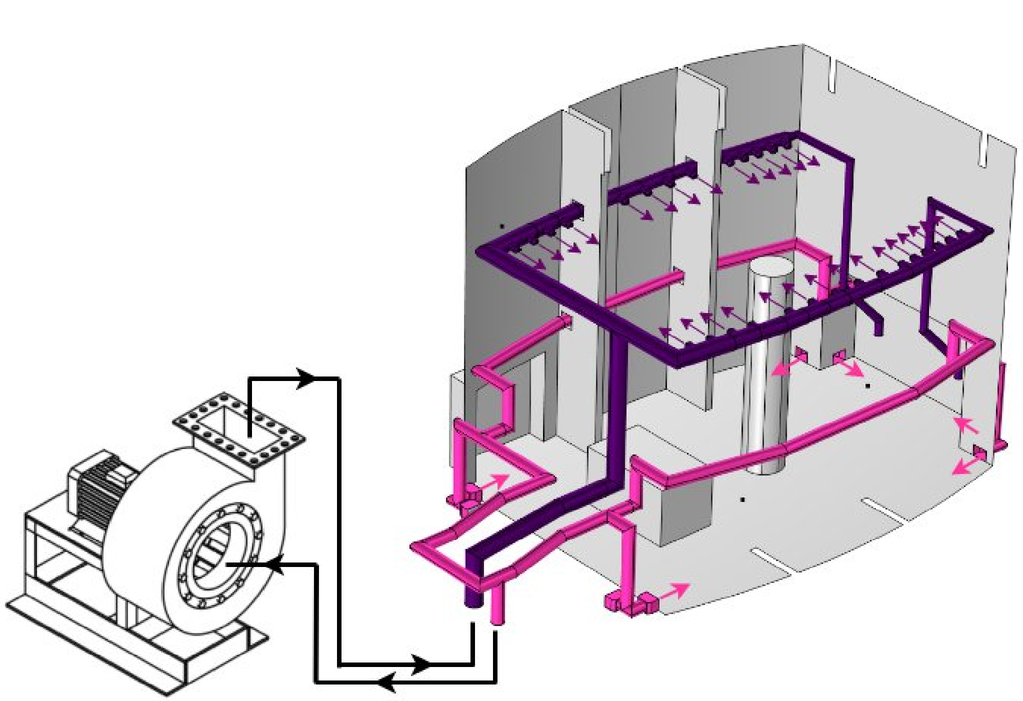
$$\delta\rho = \frac{\rho_0}{\gamma p_0}\delta p$$

Density fluctuation

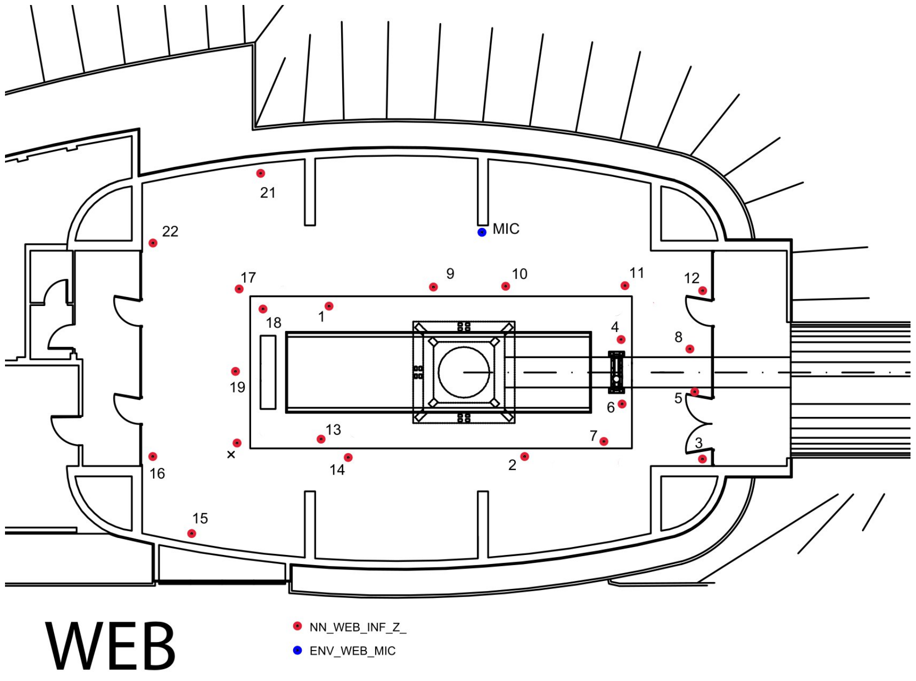
Acoustic pressure

Context

- Goal: analysis of the Newtonian noise due to acoustic noise in experimental halls
  - methodology for the modelling
  - estimate of the NN level
  - rules for the design

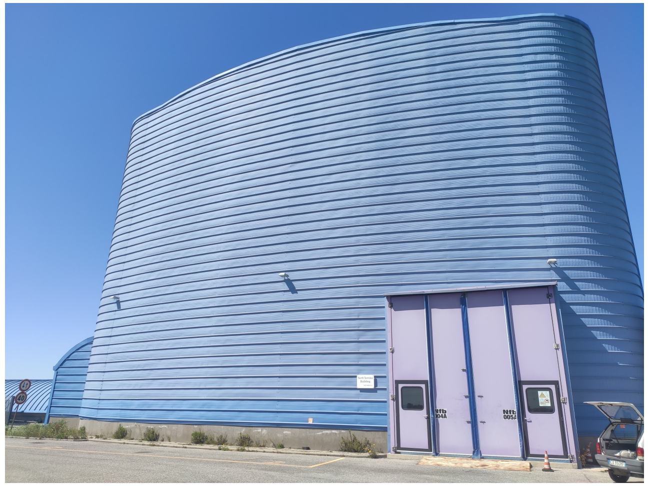


HVAC (heating ventilation and air conditioning) = Main acoustic source

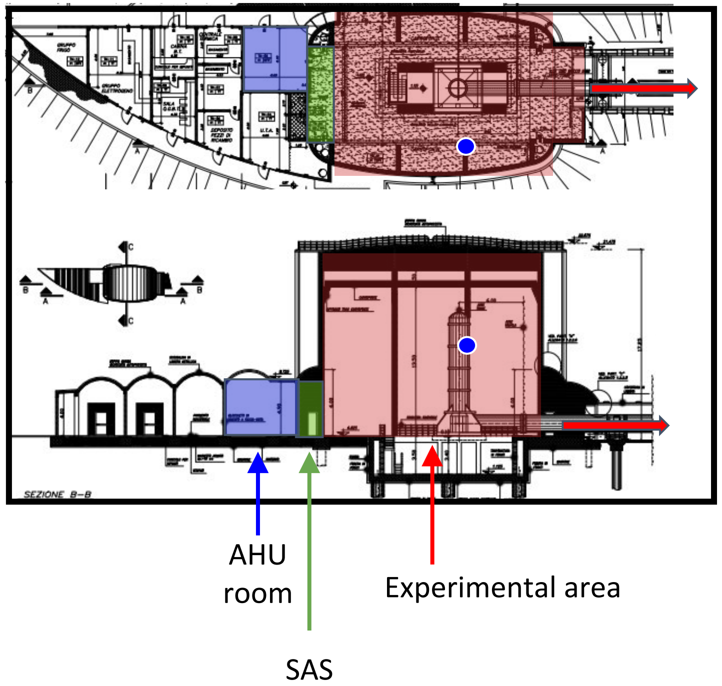


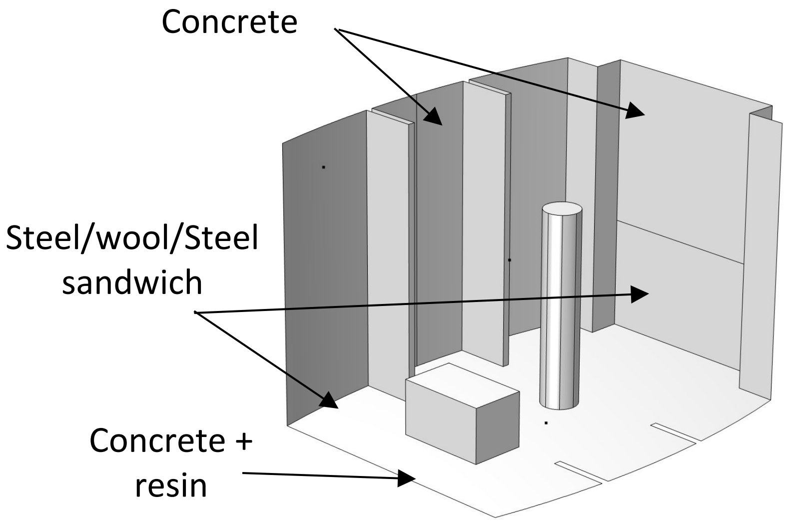
Array of infrasonic microphones in the WEB

Room acoustic characteristics (TR60, f_s, α)

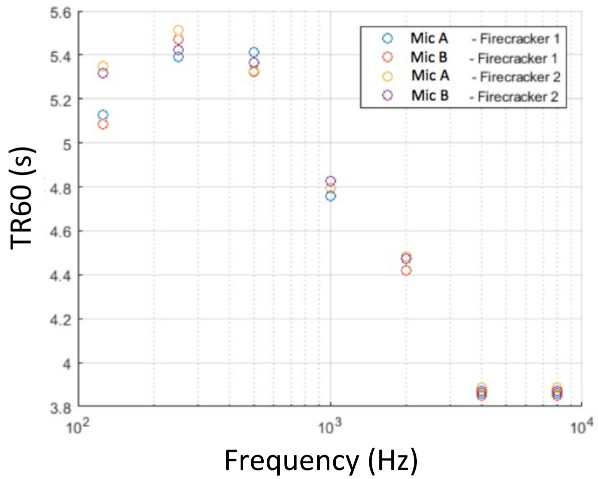


North End Building





M. Falxa et al, 2018* => acoustic characterization



$$TR60 = 0.161 \frac{V}{\sum_i^n S_i \alpha_i}$$

$$F_s = 2000\sqrt{\frac{T_{60}}{V}} \; ^{*}$$

Room volume

Reverberation time
TR60 = 4.7 s

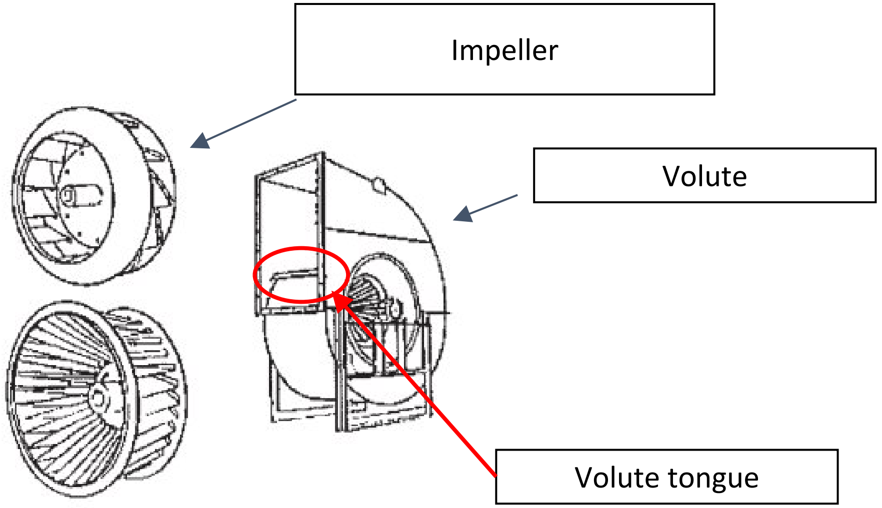
Schroeder frequency
Fs = 50 Hz
⇒ Modal acoustics if f < 50Hz

Average absorption coefficient
α = 0.097

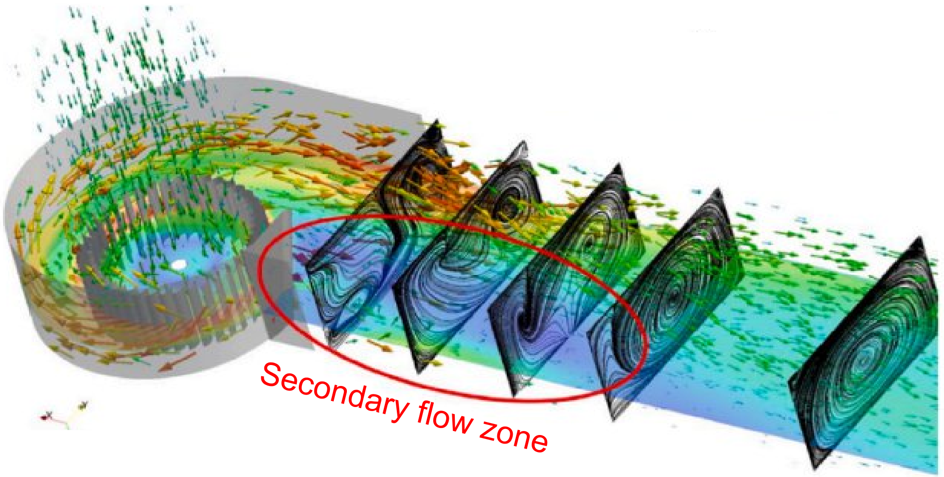
*VIR-0673A-18

HVAC acoustic source

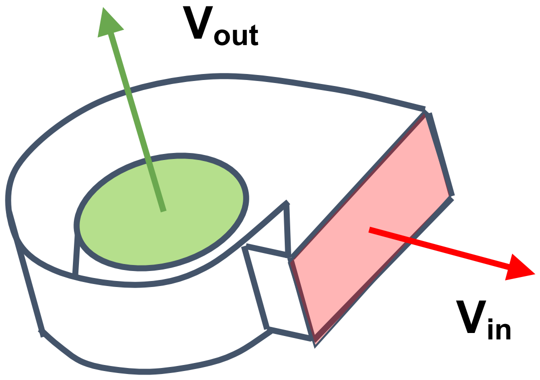
Source of problems is a reverse blade centrifugal fan located in the technical area



Complex aeroacoustic behavior
=> Set of equivalent acoustic pistons

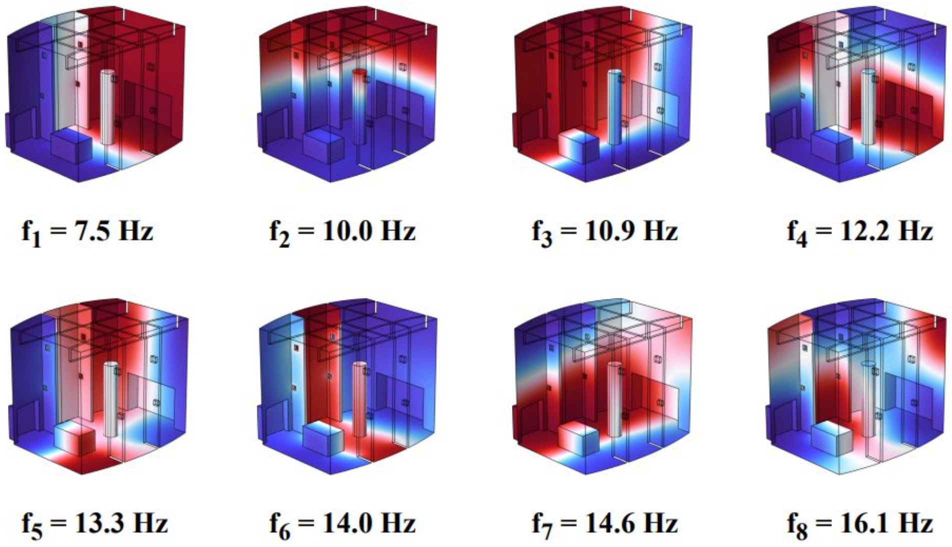


≡

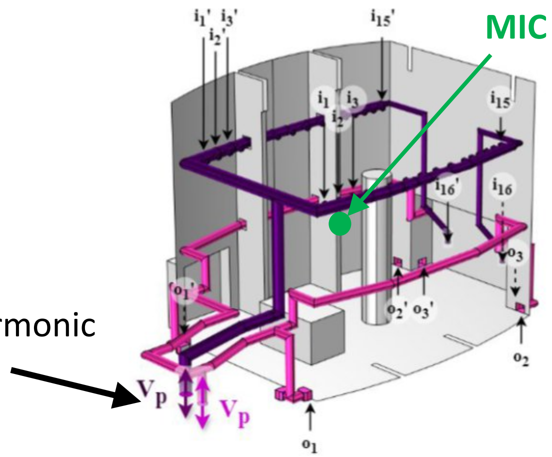


*B. Jiang et al, Journal of Building Engineering, 2023

Acoustic field modelling

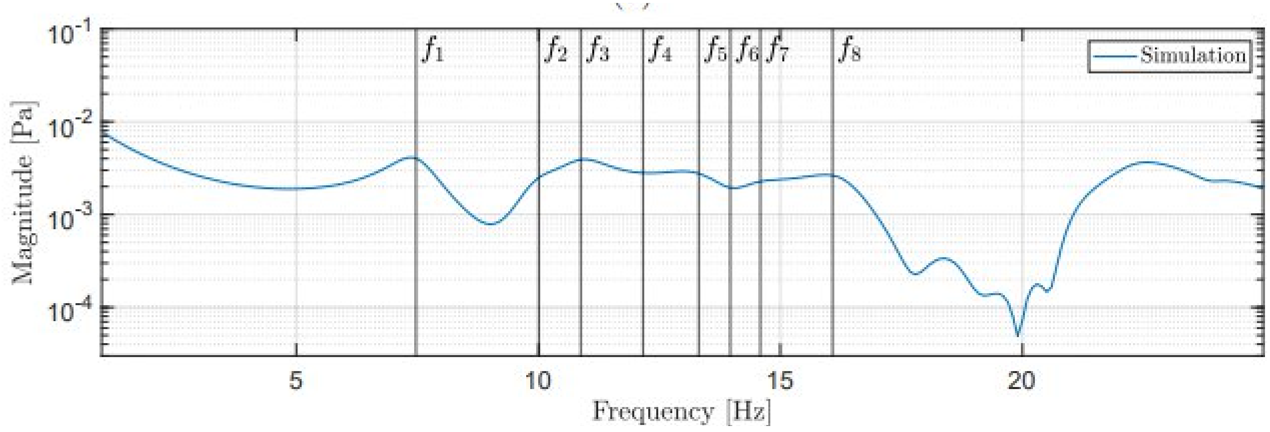


Modal analysis of the terminal building experimental hall

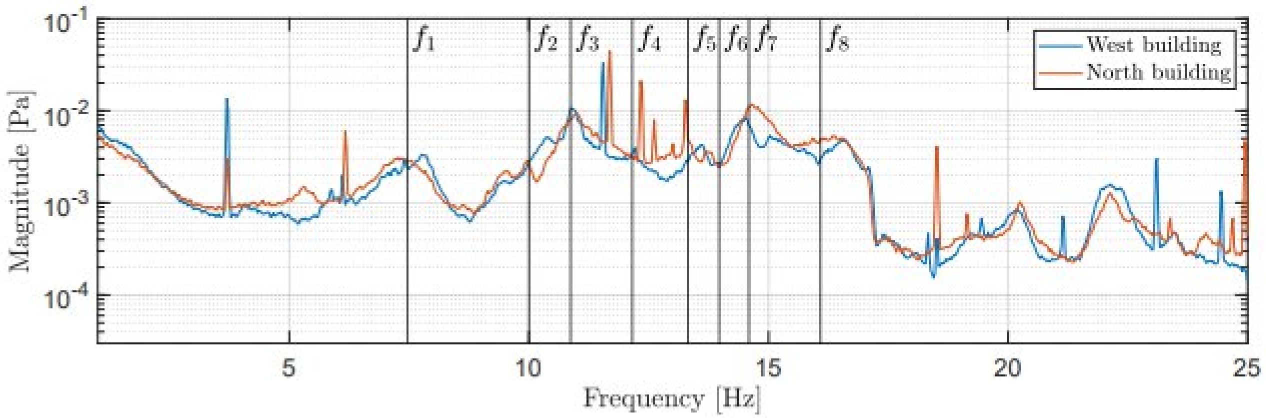


Planar harmonic pistons

Simulated acoustic pressure including room absorption at **MIC** ($\alpha = 10\%$)



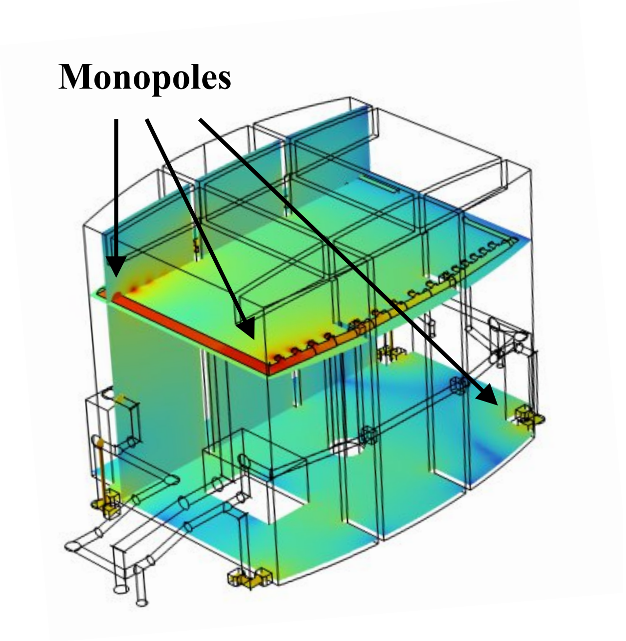
Measured acoustic pressure at **MIC**



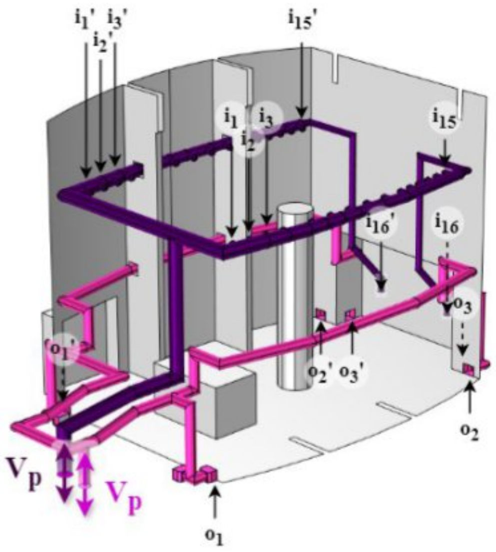
- RMS error between simulation and all microphones of the array ~9.8%

Simplifying the model => Monopolar approximation of the inlets/outlets acoustic radiation

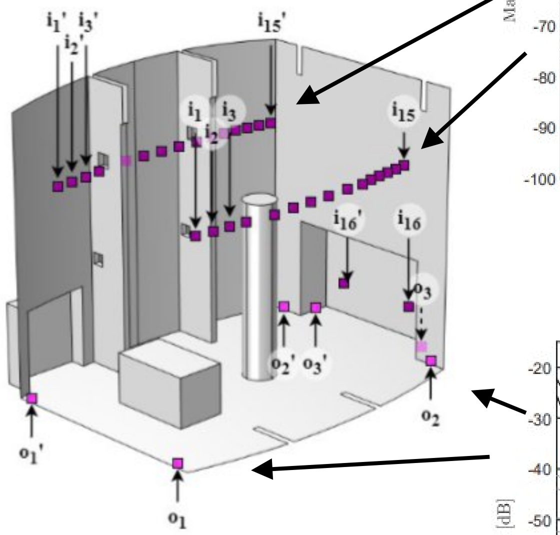
HVAC = collection of acoustic monopoles.



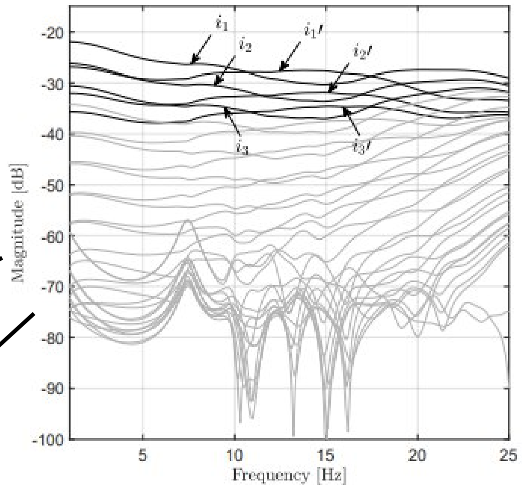
Acoustic field resulting from the radiation of the ducts' terminations



Inlets and outlets duct networks

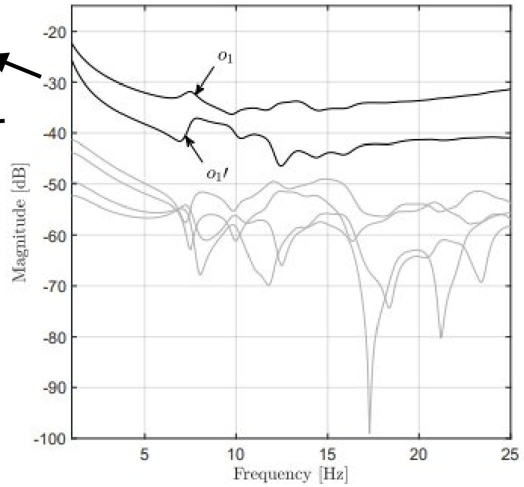


Simplified geometry with monopoles only



Inlets acoustic flow

Inlets :
6 dominant monopoles



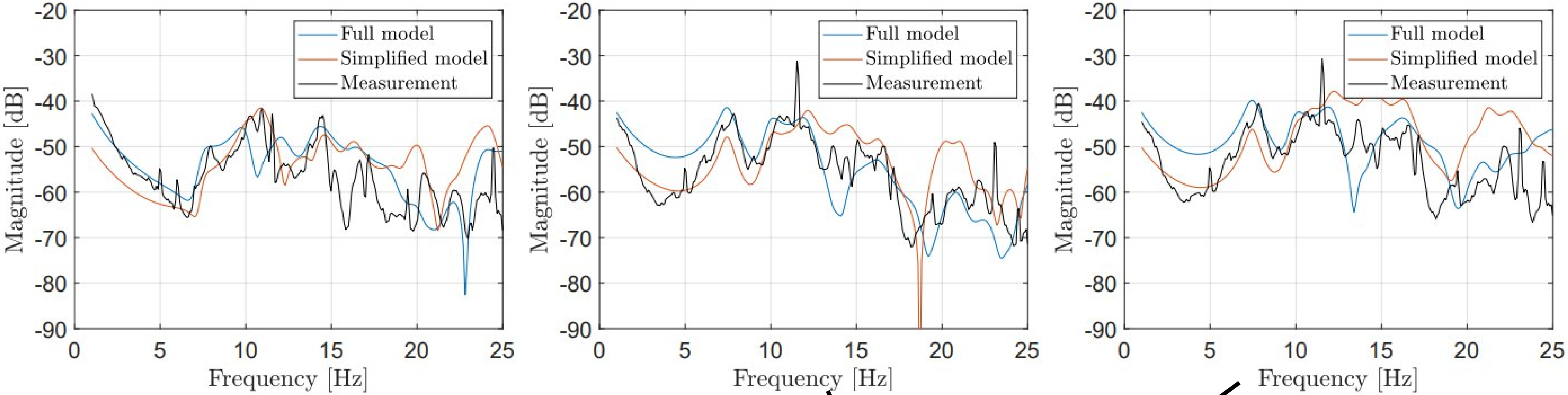
Outlets acoustic flow

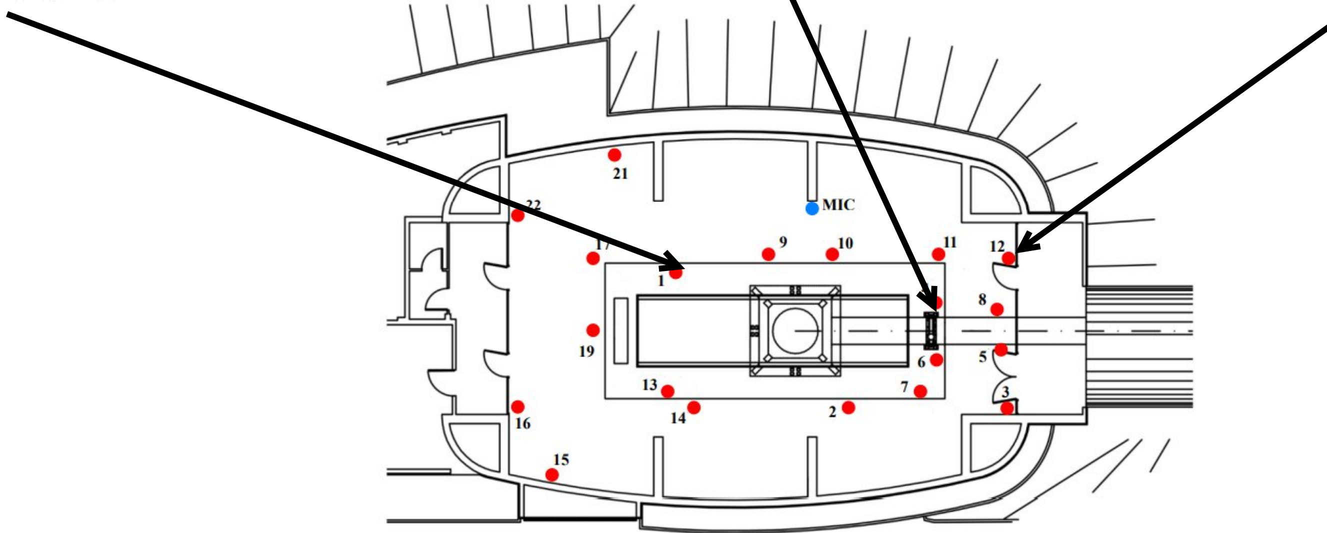
Outlets
2 dominant monopoles

2 models :

- Full model (computationally expensive)
- Simplified model (low cost, easier parametric study)

Simplified and full models versus measurements





- Key Parameters for the simplified model
    - → Fan rotation speed
    - → Number of equivalent sources
    - → Wall absorption

Gravity field expanded over a functional basis

Acoustic field

- Density fluctuation: $$\delta\rho = \frac{\rho_0}{\gamma p_0}\delta p$$

Modal basis

- Pressure $$\delta p(\vec{r},\omega) = \sum_n A_n(\omega)\phi_n(\vec{r})$$

$$A_n = \frac{\sum_i Q_i \phi_n(\vec{r_i})}{\Lambda_n(k_n^2 - k^2)}$$

Gravity field

- Potential: $$\delta\Phi(\vec{r},\omega) = -G\int \frac{\delta\rho(\vec{r'},\omega)}{|\vec{r'}-\vec{r}|} dV(\vec{r'})$$
- Gravity field: $$\vec{g}(\vec{r},\omega) = -\vec{\nabla}\Phi(\vec{r},\omega)$$

Functional basis

$$\delta\vec{g}(\vec{r},\omega) = -\sum_n B_n(\omega)\vec{\nabla}\psi_n(\vec{r})$$

$$B_n(\omega) = \frac{G\rho_0}{\gamma p_0}A_n(\omega)$$

$$\psi_n(\vec{r}) = \int_V \frac{\phi_n(\vec{r'})}{|\vec{r'}-\vec{r}|} dV(\vec{r'})$$

Modal basis for $\delta p(\vec{r},\omega)$ / functional basis for $\delta \Phi(\vec{r},\omega)$

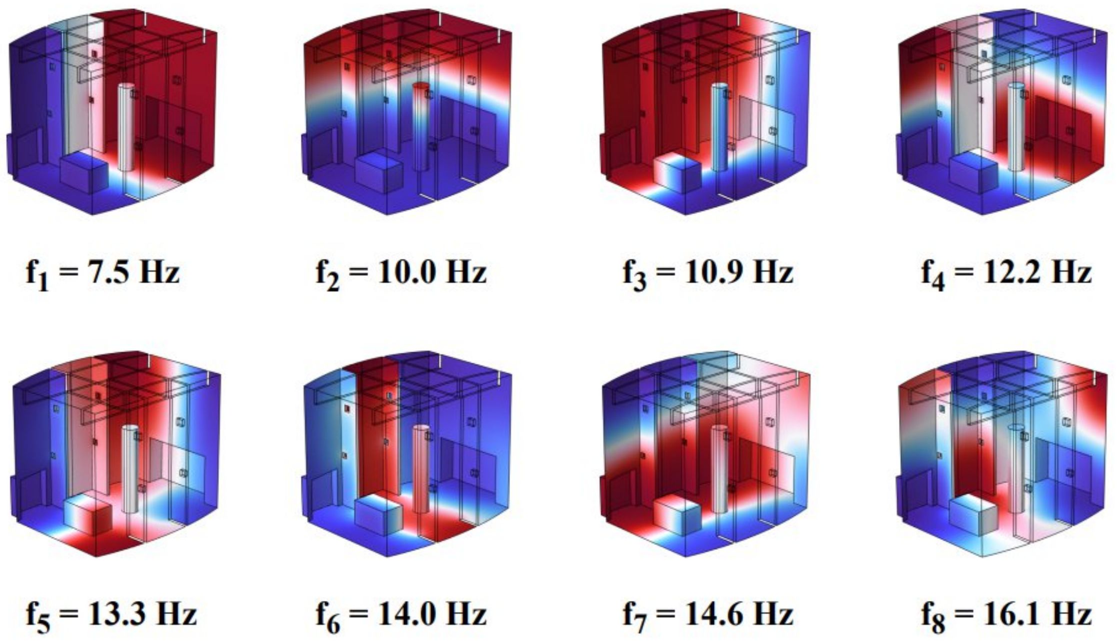
Acoustic field

$$\delta p(\vec{r},\omega) = \sum_n A_n(\omega)\phi_n(\vec{r})$$

Potential of gravity field

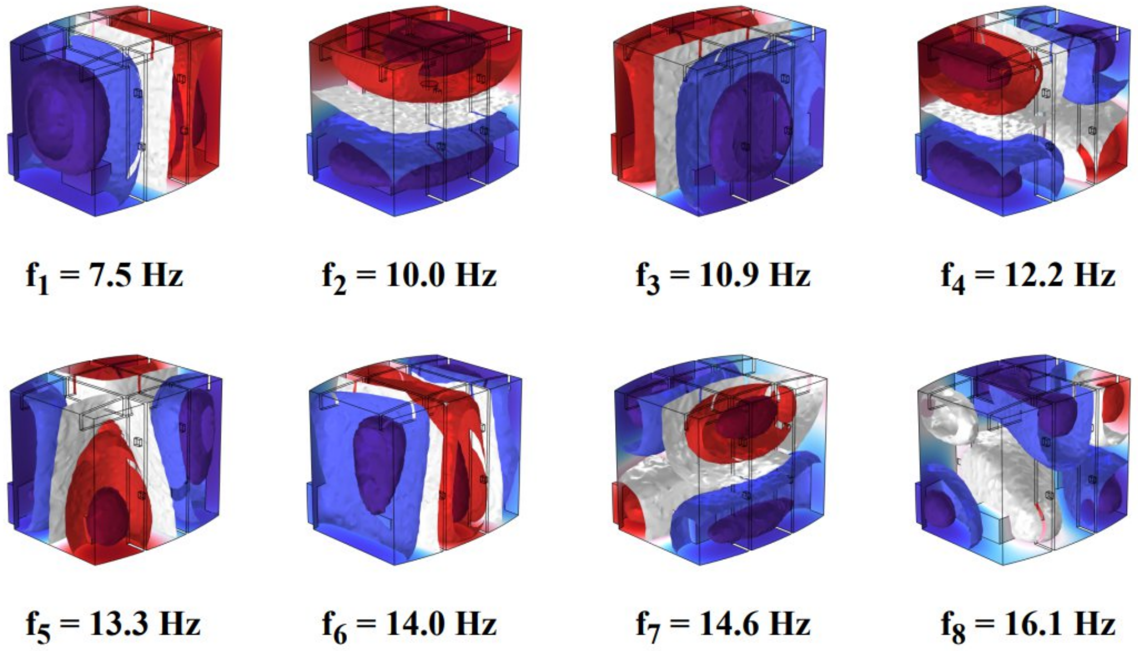
$$\delta \Phi(\vec{r},\omega) = \sum_n B_n(\omega)\psi_n(\vec{r})$$

Modal basis



ϕn Function

Functional basis



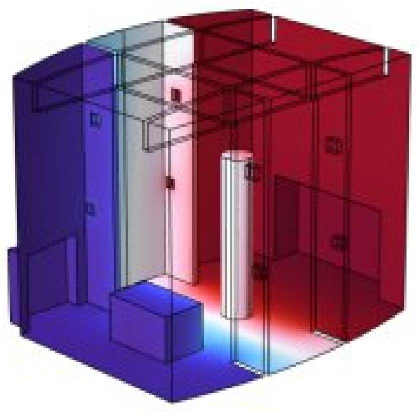
Ψn Function

Modal basis for $\delta p(\vec{r},\omega)$ / functional basis for $\delta\vec{g}(\vec{r},\omega)$

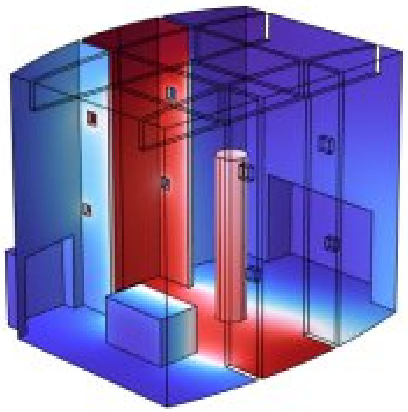
Acoustic field

$$\delta p(\vec{r},\omega) = \sum_n A_n(\omega)\phi_n(\vec{r})$$

Modal basis



$f_1 = 7.5$ Hz



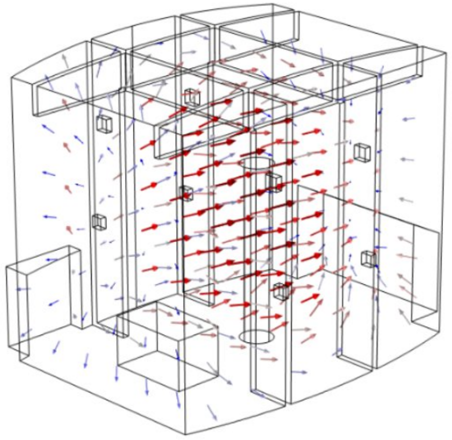
$f_6 = 14.0$ Hz

ϕn Function

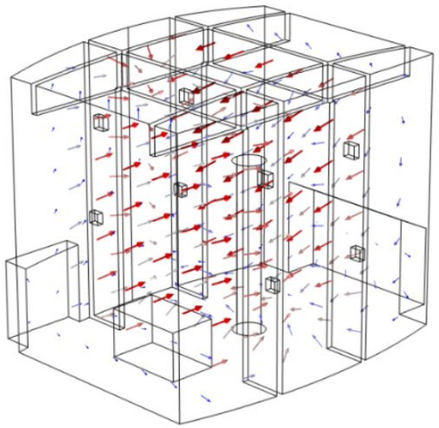
Gravity field

$$\delta\vec{g}(\vec{r},\omega) = -\sum_n B_n(\omega)\vec{\nabla}\psi_n(\vec{r})$$

Functionnal basis



$f_1 = 7.5$ Hz



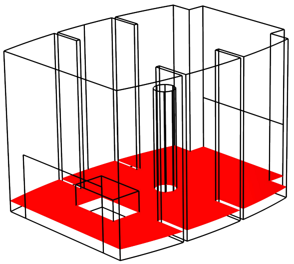
$f_6 = 14.0$ Hz

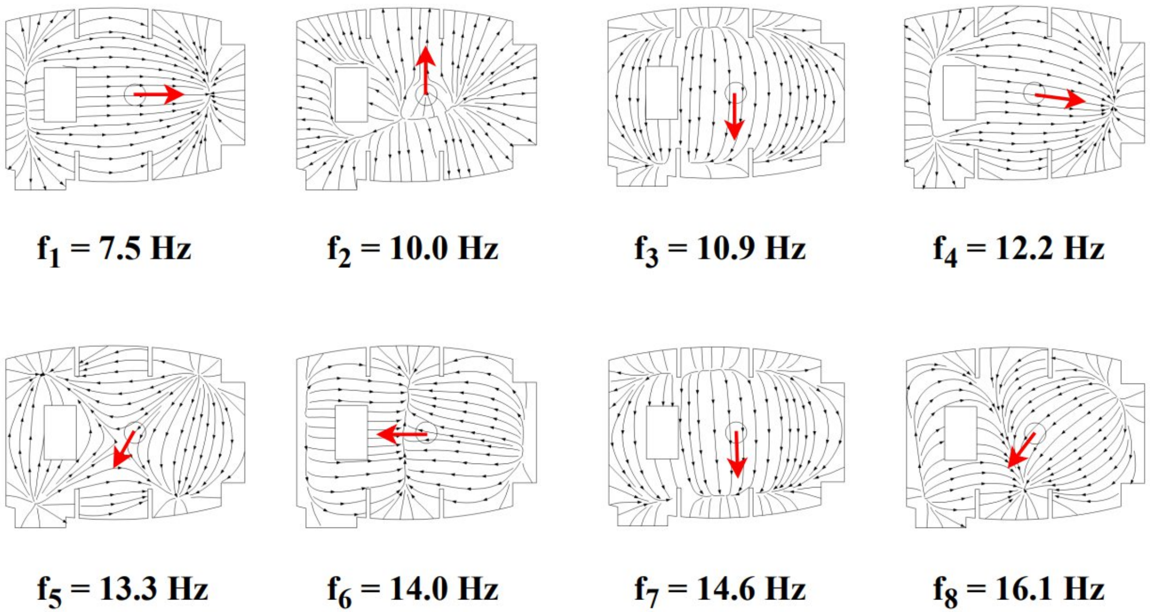
$\vec{\nabla}\Psi n$ Function

Estimating the Newtonian noise from the simplified acoustic model

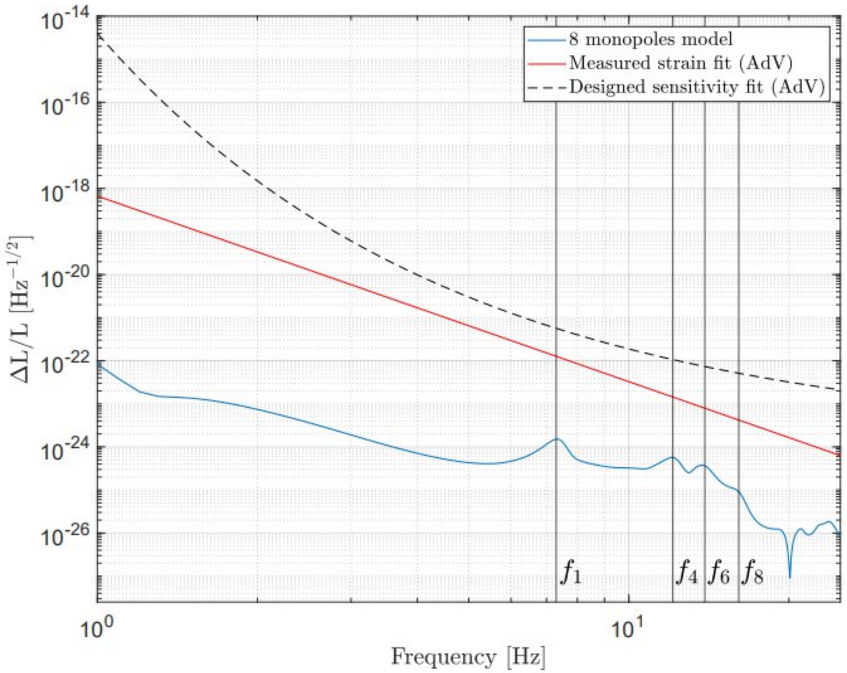
- Impact of the Newtonian noise on the suspended test mass

$$\frac{\Delta L}{L} = -\frac{g_x(\omega)}{L\omega^2}$$





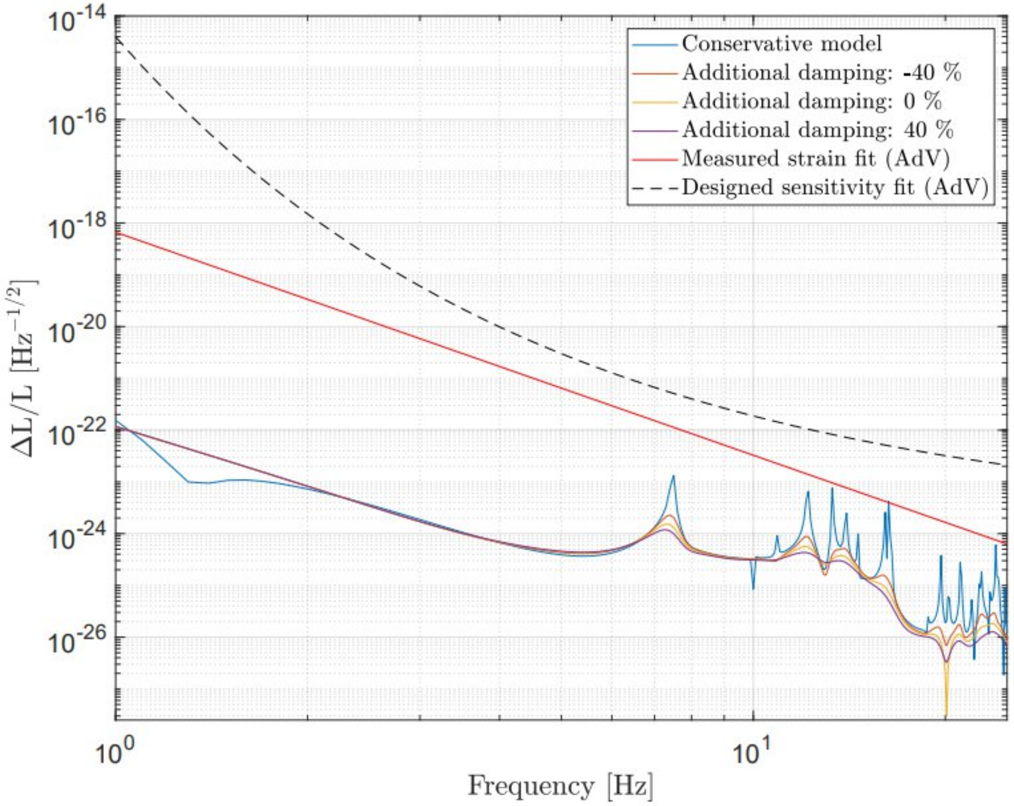
Streamlines for the gravity field in the room in the 2D cross-section at one meter from the ground.



NN estimate

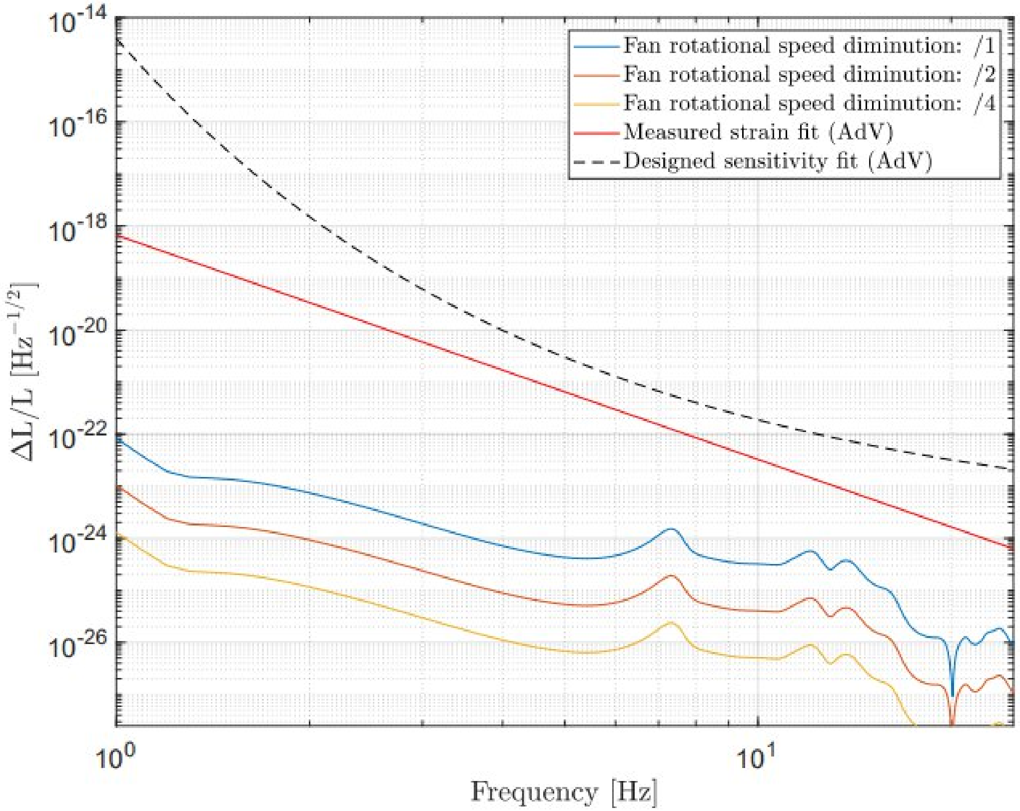
Propositions to limit the Newtonian noise

- Absorption of the experiment hall walls.



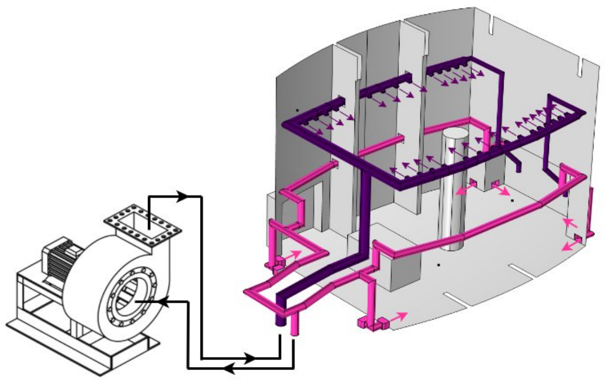
Simulating different absorption coefficients throught the damping ξ_n.

- Rotational speed of the fan from the HVAC.

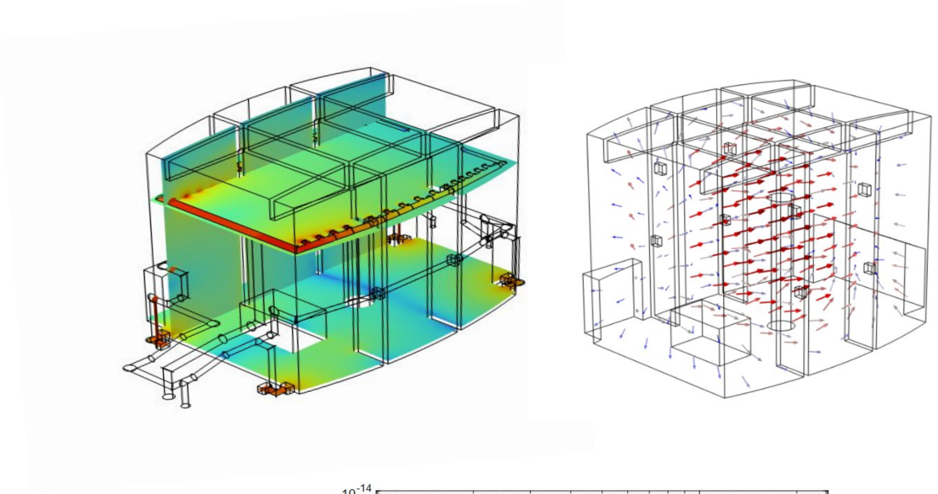


Acoustic pressure level generated by rotating fan follows a power law $P \sim \Omega^n$
In this plot, n = 3

Concluding remarks

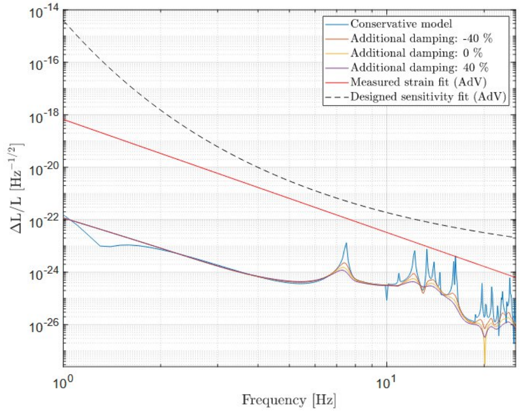


- Acoustics in the Virgo Terminal buildings
  - Dominant role of the HVAC (Air Conditionning system)
  - Acoustic pressure field is well described by a modal approach (f<30Hz)
  - In situ measurement validate the modal description.
  - Spectra and also spatial organisation are correctly represented



- Estimate of the newtonian noise from acoustic origin is a direct consequence
  Structure of the gravity field is described using a functional basis.

- Rules for the design
  - Fan rotation speed as low as possible (thermal insulation)
  - Acoustic Absorption could be pertinent but very difficult below 30 Hz
  - Inlets and outlets should be located on acoustic nodes of the first modes
  - Importance of leaks effect at low frequency
  - Locations with minimal NN



- Applications of Acoustic (+vibration !) modelling
  Transfer Path analysis - identification of technical noises - Acoustic/vibration budget
  NN from building vibration origin ?
  Scattered light noise ?
  PhD of L. Maurin (12/2024- 12 /2027)
  Possible application of the methodology to the caverns of ET