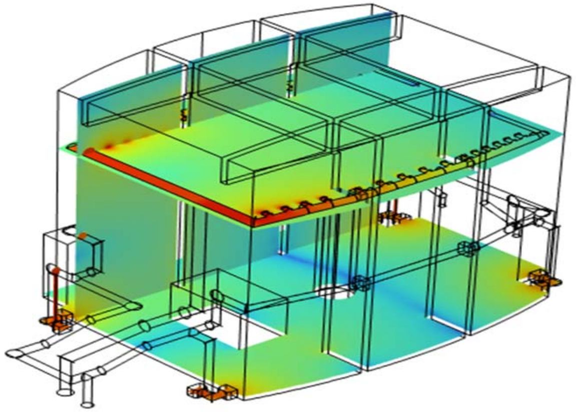
Acoustic noise in the Virgo gravitational wave detector

Laum research actions

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



Collaborations

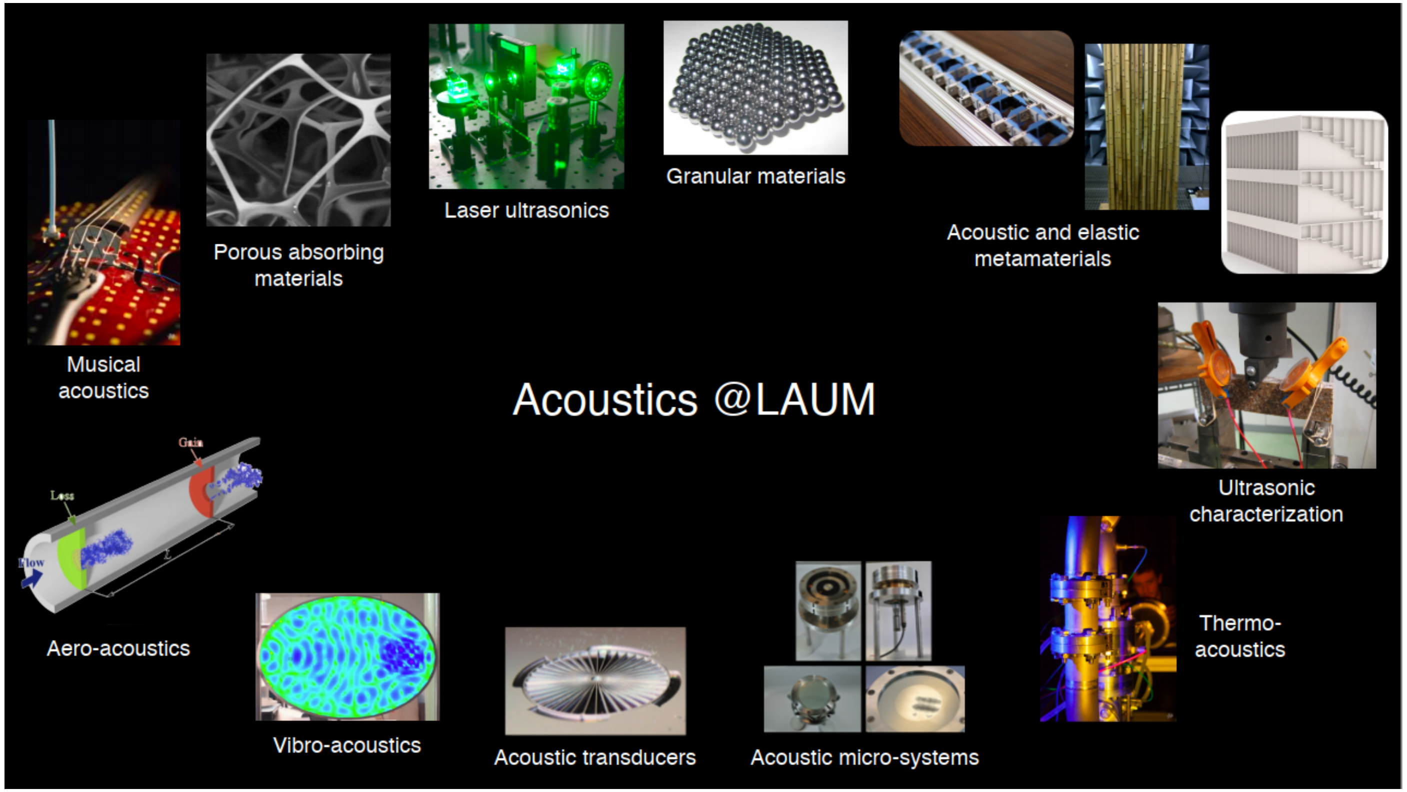
- **M. Barsuglia** (laboratoire APC, AstroParticules et Cosmologie, UMR CNRS, Paris)
- **D.Fiorucci** (INRC, Italian National Research Council, Consorzio RFX, Padua)
- **I. Fiori, M. Tringali, F. Paoletti, R. Passaquieti** (EGO, European Gravitational Observatory, Cascina)

Workshop Virgo/ET, 04-06 mars 2024, Institut Fresnel, Marseille

LAUM Laboratoire d'Acoustique
Le Mans Université · CNRS - UMR 6613

Laum = Research Lab in Acoustics
Joint Unit CNRS – Le Mans Université
170 people :
60 academics, 11 CNRS, 20 technical staff

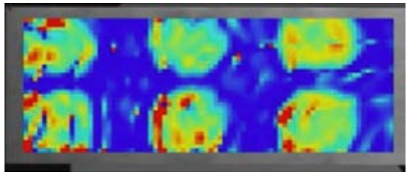
500 students per year in Acoustics
Licence, Master, Engineering school



Research activities in Vibroacoustics at LAUM

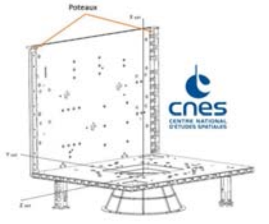
Inverse problems

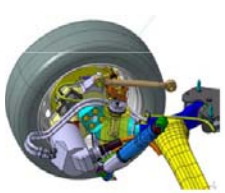
- Acoustic imaging
  Near field holography and beam forming
- Source identification
- Identification of effective material properties
- Defaults identification.



Vibroacoustic modelling

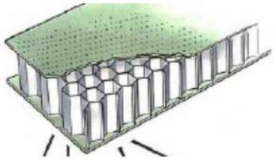
- Squeak and rattle noise
- Numerical modelling
- Mechanical junctions

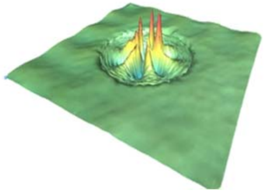




Vibration control

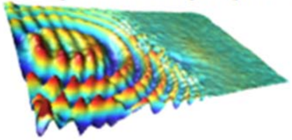
- Periodic structures
- Damping using added granular media
- Microperforated panel
- Acoustic Black holes effect



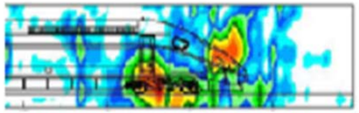


Multi-modal combined imaging

Laser vibrometer
➡ dynamical properties



Microphone antenna
➡ sound radiation



Infrared camera
➡ structural damping

Research lines related to GW in Laum

Axis 1: Noise from acoustic origine

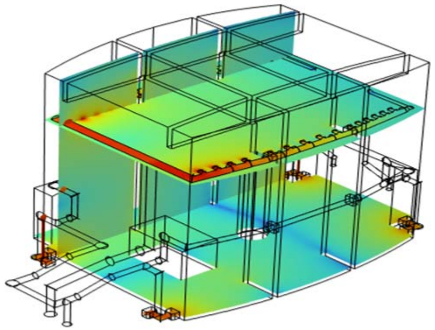
- Technical noise (HVAC,…)
- Newtonian noise
- Vibroacoustic transfer path analysis

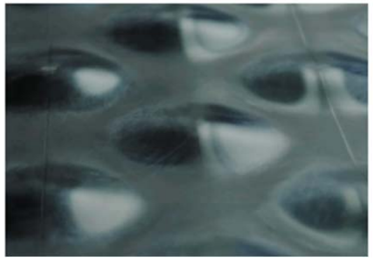
Axis 2: Analysis of acoustic noise reduction techniques

- Recommandation for sound absorption
- Recommandation for sound insulation

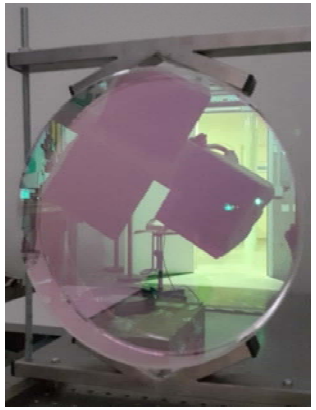
Axis 3 : Parametric instabilities

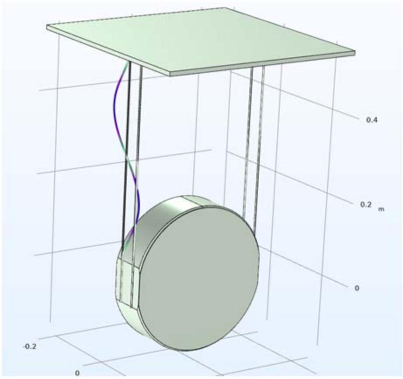
- Instability model and mirror modal analysis.
- Periodically attached masses on wires





Nov. 2022,
Convention
APC/LAUM





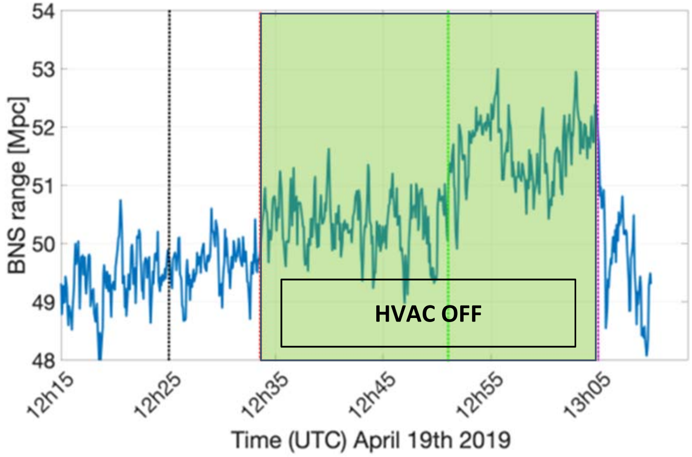
Noise from acoustic origin

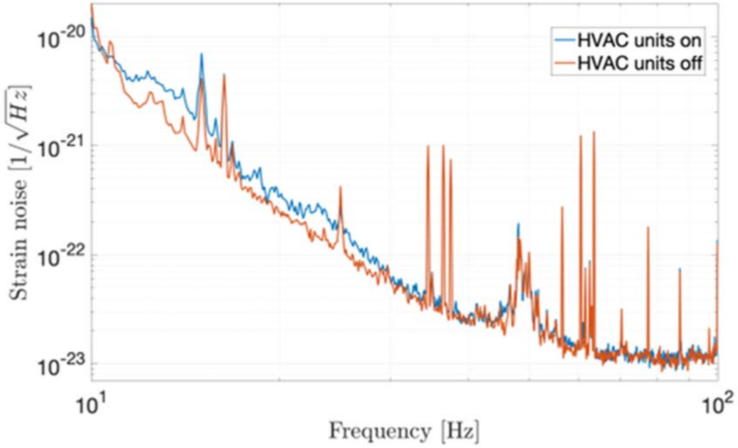
HVAC = Heating, Venting, Air Conditioning

Experimental evidence of the HVAC acoustic contribution to strain noise :

HVAC Off in 2 labs of CEB in 2019

=> **ΔL/L** ↘
BNS ↗

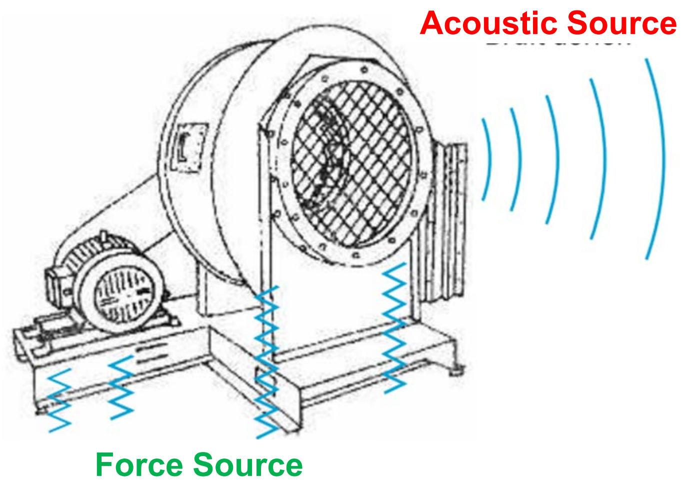


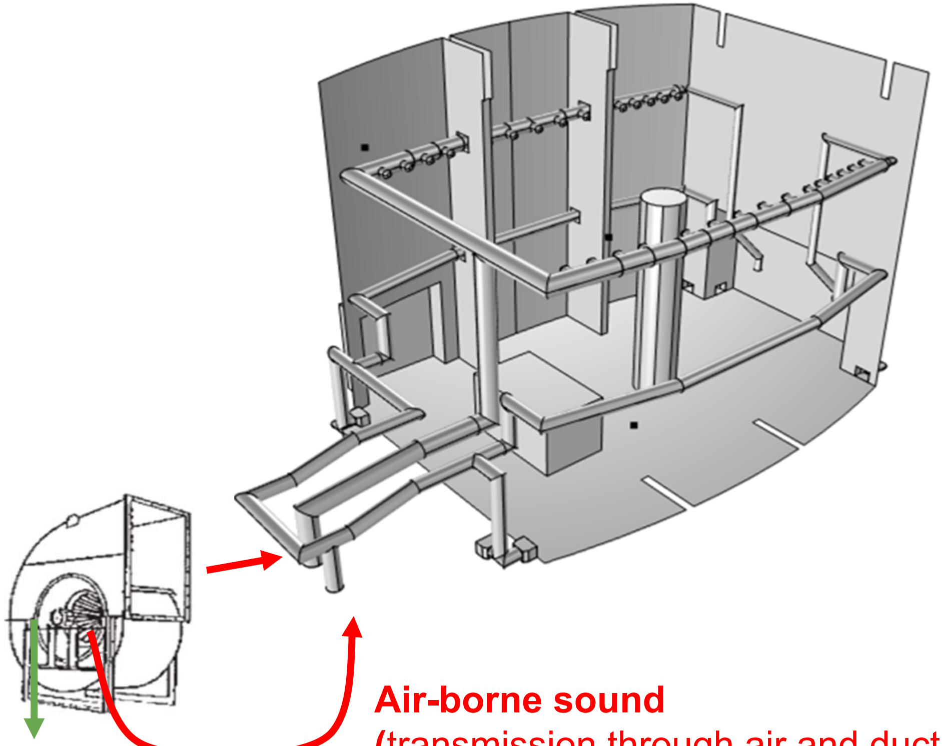


HVAC noise

- HVAC => pressure pulsation in the infrasound range => Tower or viewport vibrations => scattered light noise
  => Newtonian Noise

- Aim: modeling the noise transmission path between HVAC equipments and detector's sensitivity



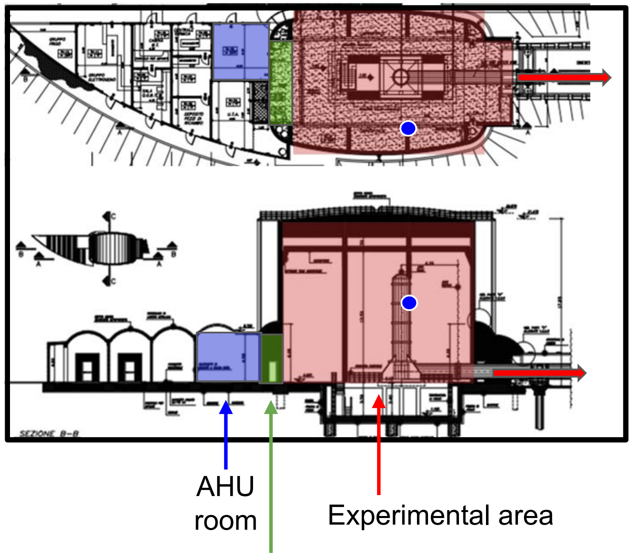


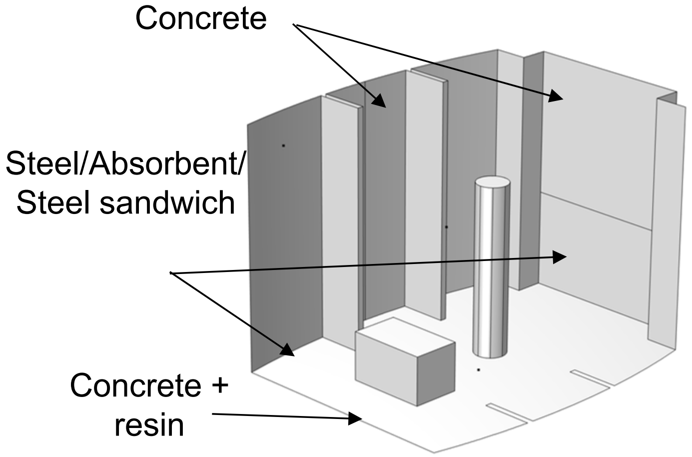
Structure-borne sound
(transmission through ground and walls)

Air-borne sound
(transmission through air and ducts)

NEB characteristics (TR60, f_s, α)

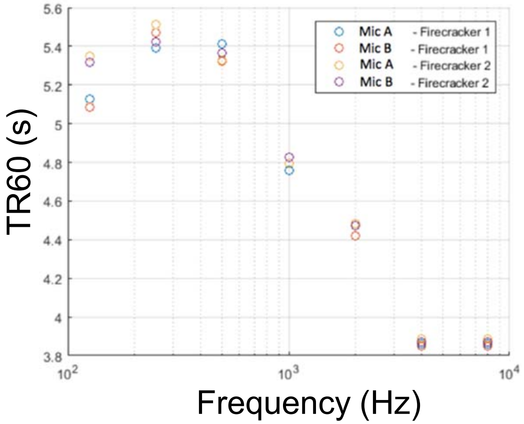
North Terminal Buildinging





Simplified geometry of the experimental area

- 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

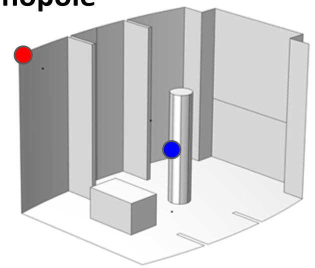
Schroeder frequency
Fs = 50 Hz
⇒ Modal acoustics if f < 50Hz

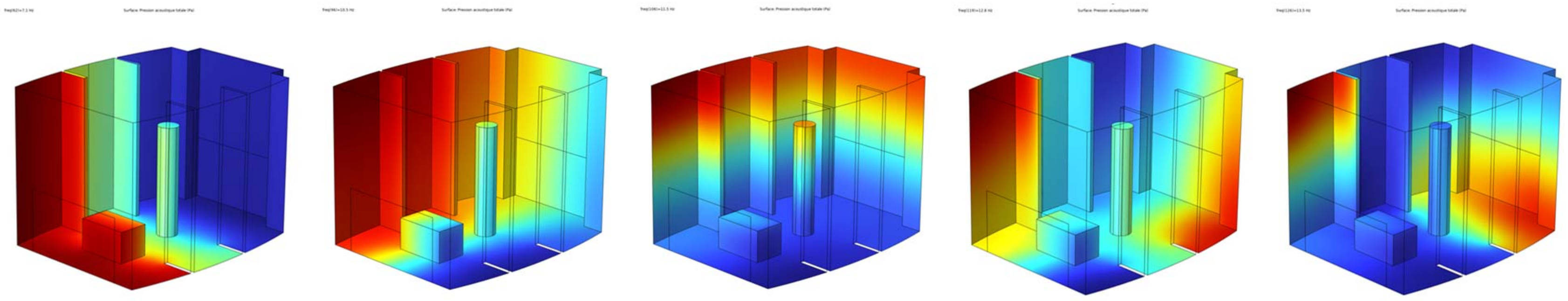
Average absorption coefficient
α =0.1

*VIR-0673A-18

Acoustic response of the NEB resulting from a single monopole placed in a corner

Monopole





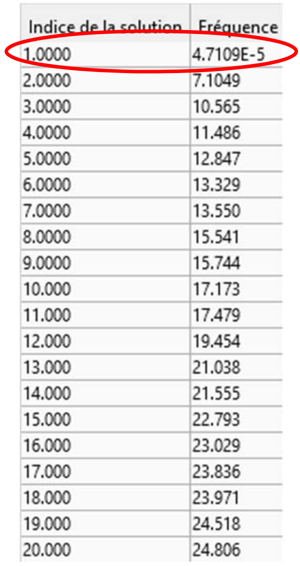
[Mode 1] 7 Hz

[2] 10.5 Hz

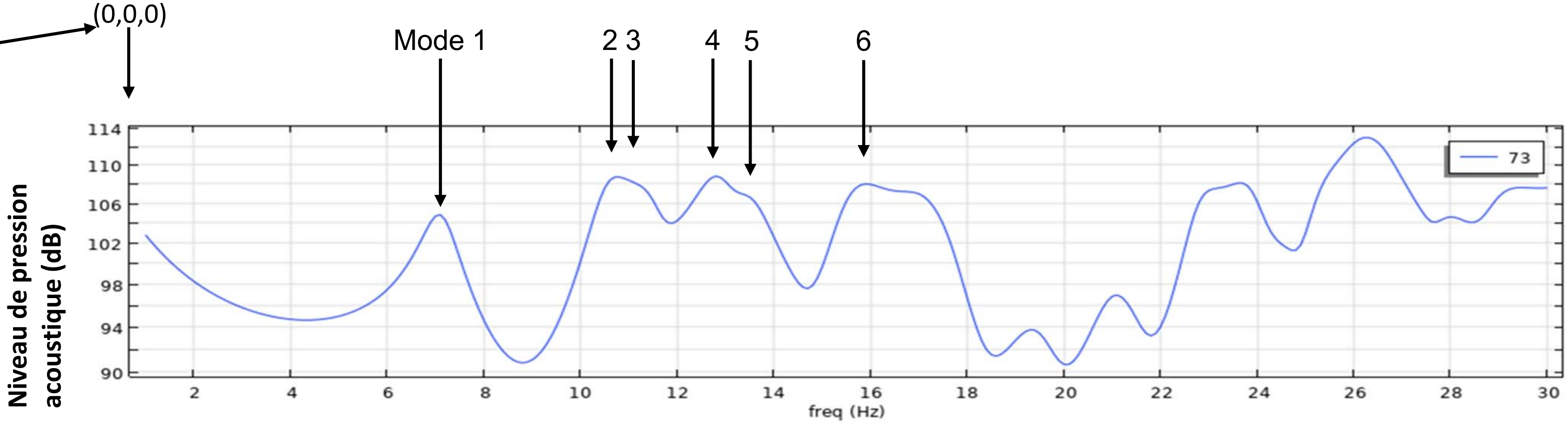
[3] 11.5 Hz

[4] 12.8 Hz

[5] 13.4 Hz

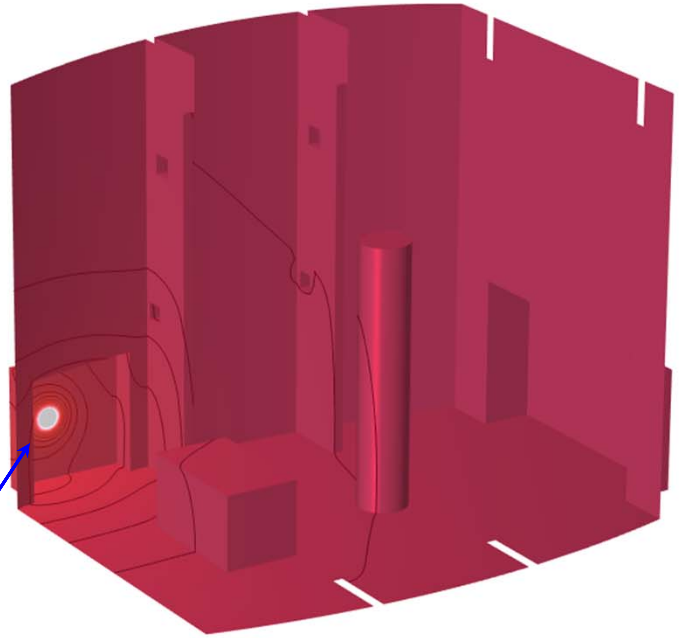


Indice de la solution	Fréquence
1.0000	4.7109E-5
2.0000	7.1049
3.0000	10.565
4.0000	11.486
5.0000	12.847
6.0000	13.329
7.0000	13.550
8.0000	15.541
9.0000	15.744
10.000	17.173
11.000	17.479
12.000	19.454
13.000	21.038
14.000	21.555
15.000	22.793
16.000	23.029
17.000	23.836
18.000	23.971
19.000	24.518
20.000	24.806



Room : 25 modes below 30 Hz

Influence of the leaks (doors, ducts, walls)



Artificial leakage representing distributed and not well identified holes in the building

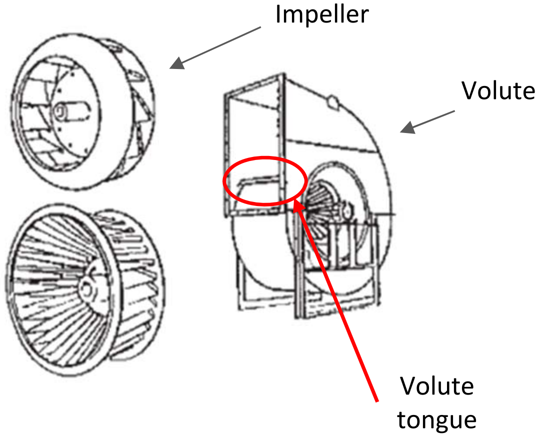
Without leaks	With leaks
5.6091E-13	0.85763
7.4368	7.5451
9.9835	10.076
10.823	10.939
12.136	12.289
13.244	13.417
13.892	13.926
14.517	14.633
16.021	16.203
16.231	16.233
16.353	16.442
18.637	18.767
19.577	19.578
20.178	20.206
21.059	21.073
21.174	21.226
21.893	21.899
22.581	22.649
22.819	22.851

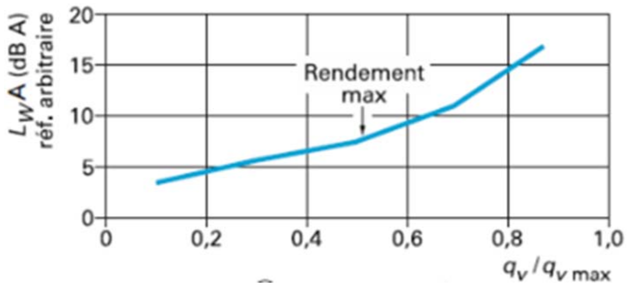
Appearance of a low frequency Helmholtz mode

A (strongly) damped acoustic mode is created by the leaks at very low frequency
Importance of the leaks at very low frequency acoustic response !

Acoustic sources equivalent to the HVAC

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



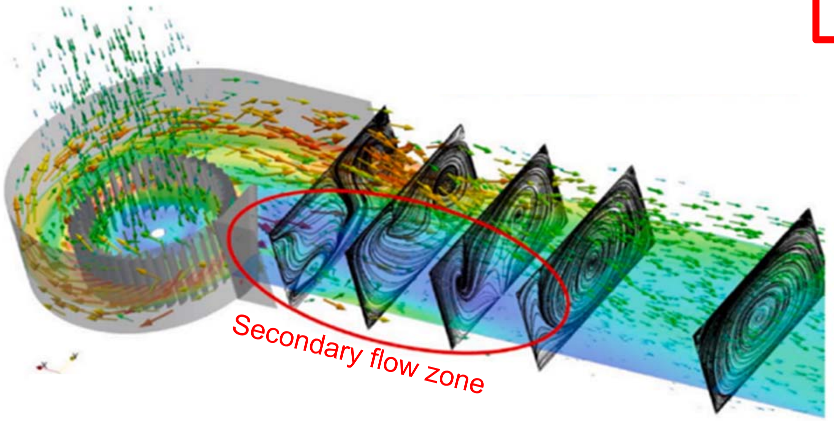


Sound level = power law of the air flow (or velocity)

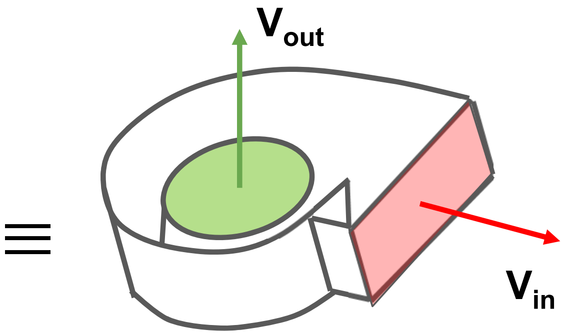
$L_p \propto u^n$ with n = 4;6;8

Aeroacoustic behavior => high complexity

=> Represented by 2 equivalent acoustic pistons (Velocities V_{out} and V_{in})



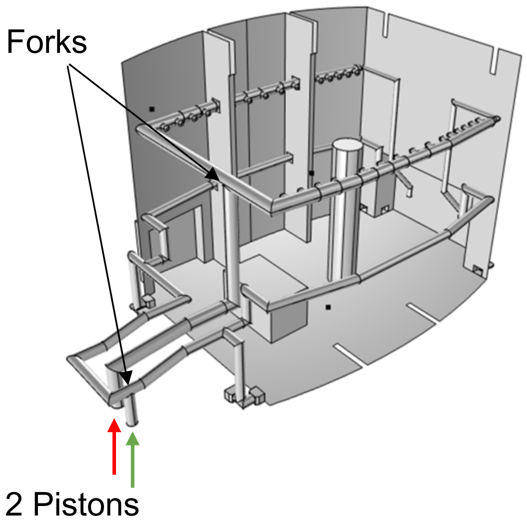
*B. Jiang et al, Journal of Building Engineering, 2023

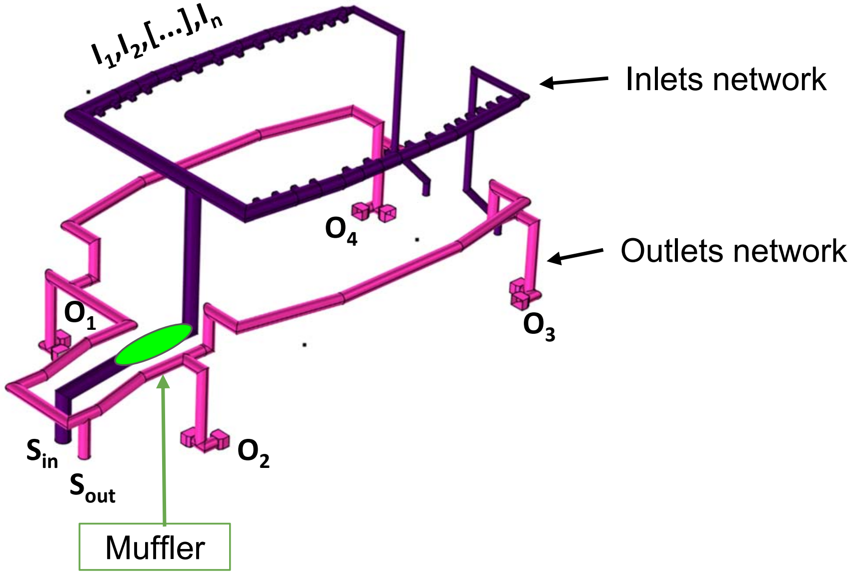


$V_{in} = V_{out} = 1$ m/s

Ducts acoustic – inlets and outlets networks

2 ducts networks
- Air inlet
- Air oulet

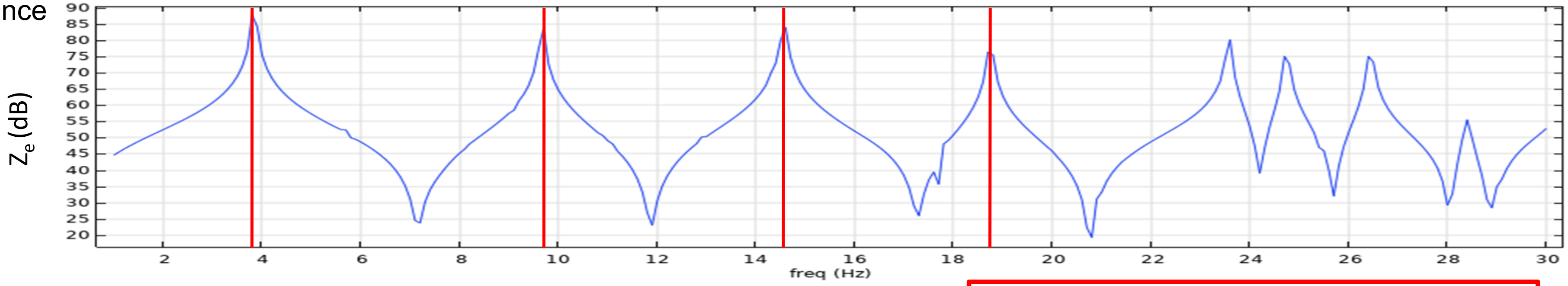




Acoustic input impedance of the Inlets network

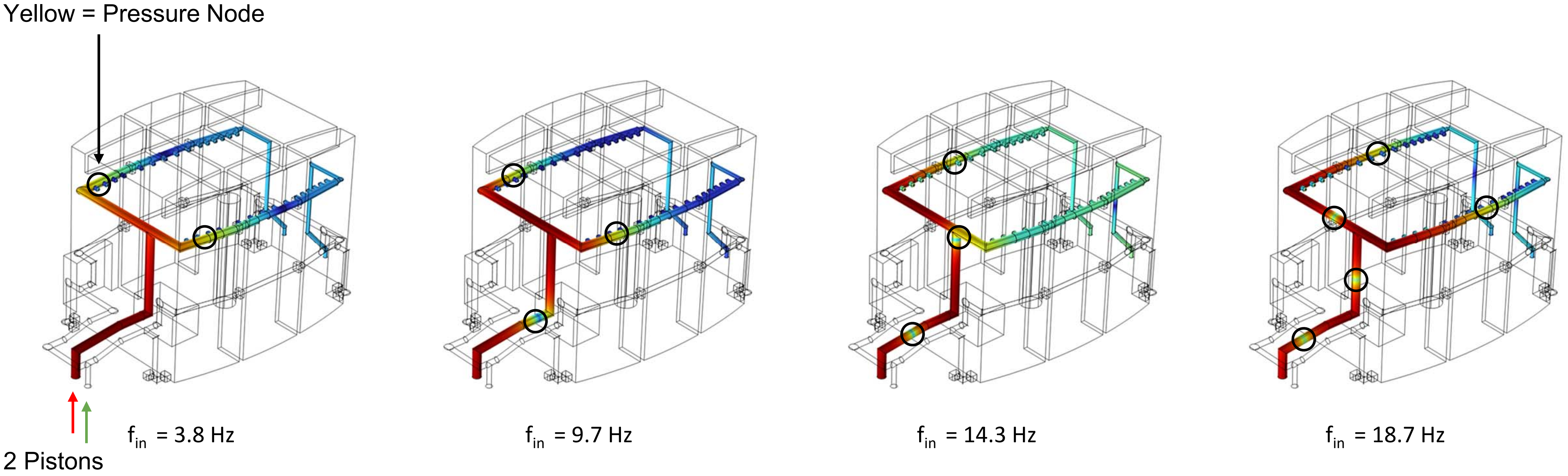
$$Z = \frac{P}{V}$$

P : acoustic pressure
V : acoustic velocity



Inlets network : 8 modes below 30 Hz

Acoustic modes of the inlets ducts


Yellow = Pressure Node

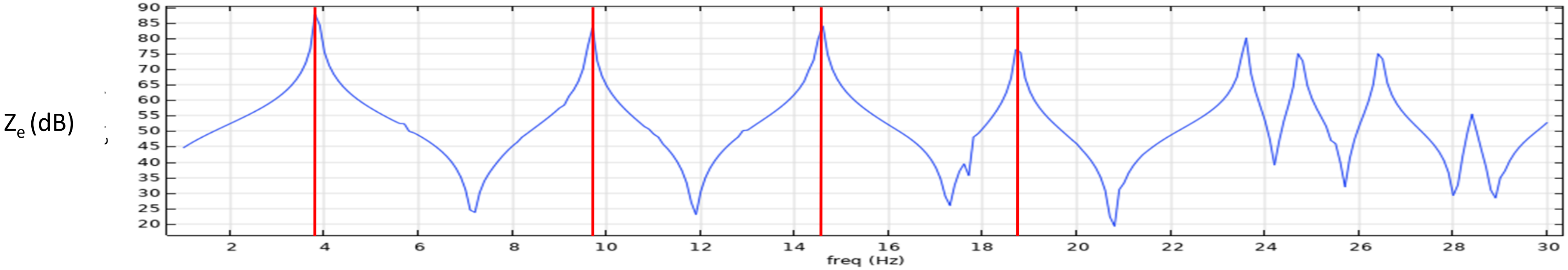
2 Pistons

f_{in} = 3.8 Hz

f_{in} = 9.7 Hz

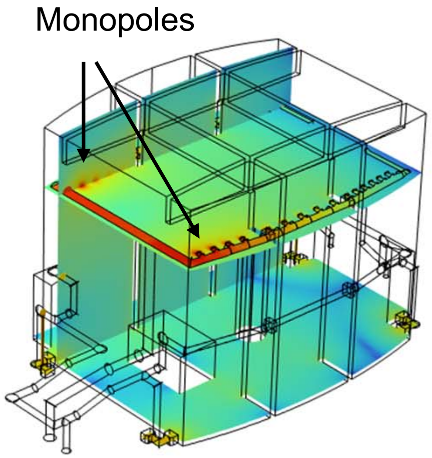
f_{in} = 14.3 Hz

f_{in} = 18.7 Hz

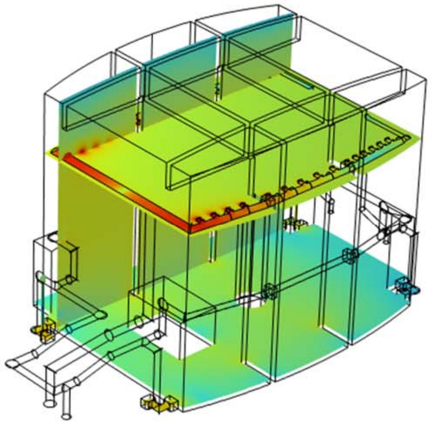


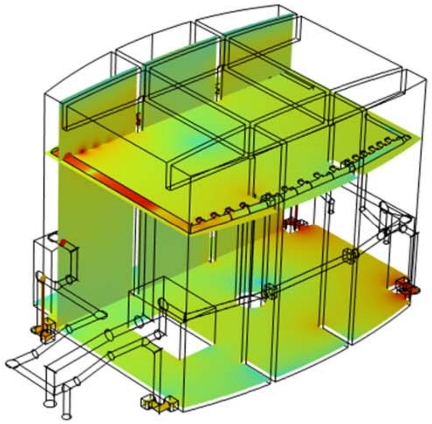
=> Duct resonances. Modal shapes characterised by internal nodes.
First mode = λ/4 mode

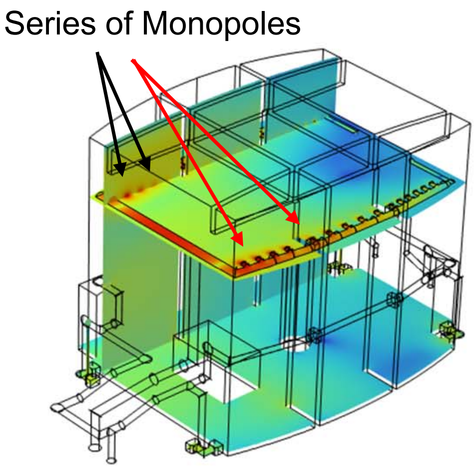
Acoustic radiation from the inlets ducts


Monopoles

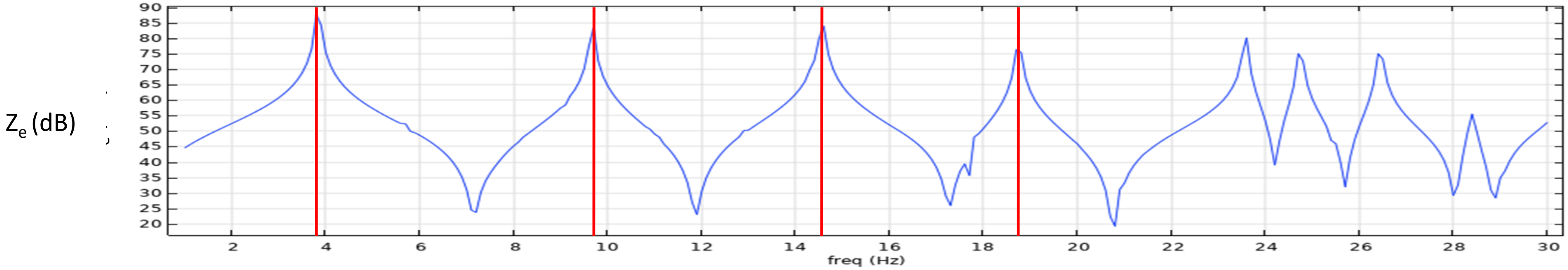
f_{in} = 3.8 Hz


f_{in} = 9.7 Hz


f_{in} = 14.3 Hz


Series of Monopoles

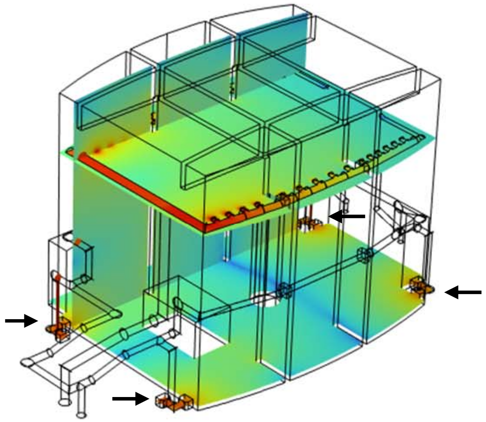
f_{in} = 18.7 Hz



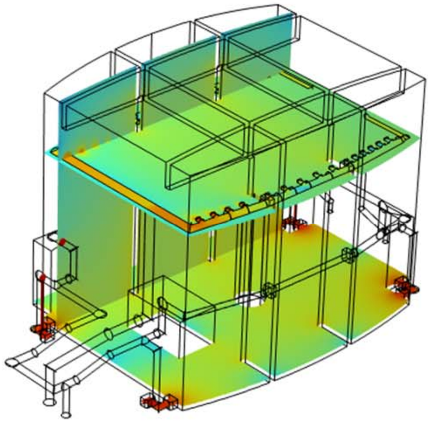
=> Inlets are equivalent to 2 series of acoustic monopoles

Acoustic radiation from the outlets ducts

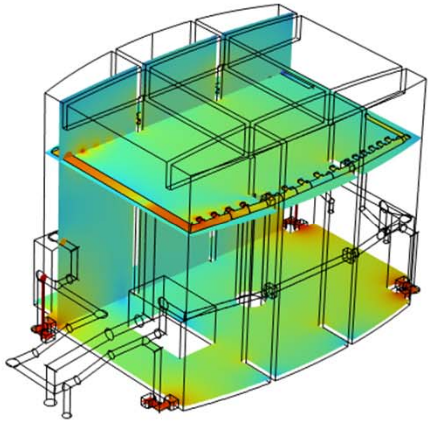
4 corners monopoles



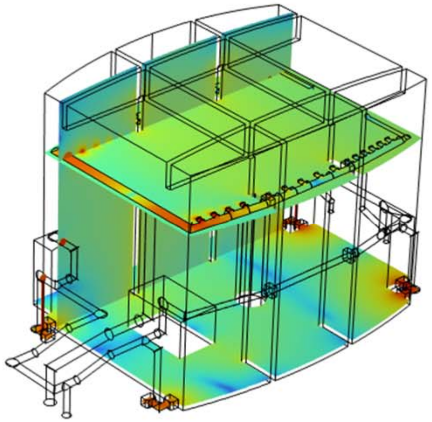
f_{out} = 3.9 Hz



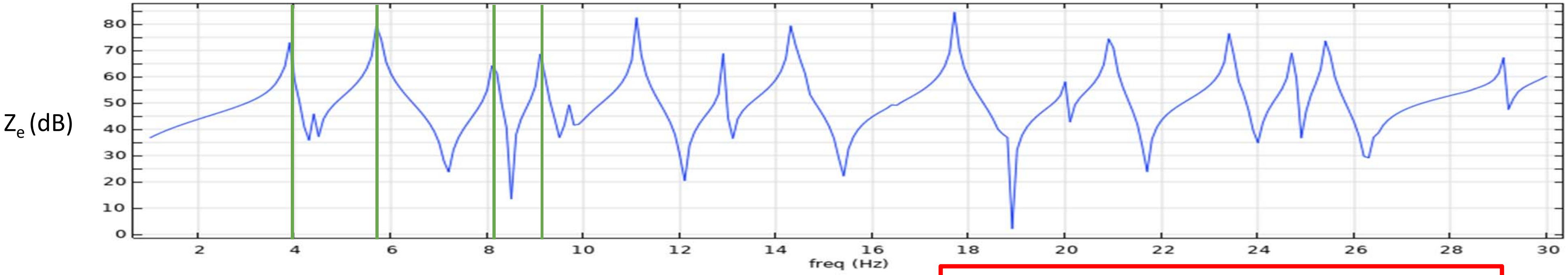
f_{out} = 5.7 Hz



f_{out} = 8.1 Hz



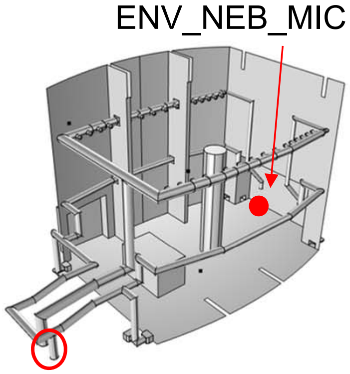
f_{out} = 9.1 Hz



=> Outlets are equivalent to 4 acoustic monopoles

Outlets network : 16 modes below 30 Hz

Simulation and measurement of the acoustic field in the NEB



Absorption coefficient of the room and ducts

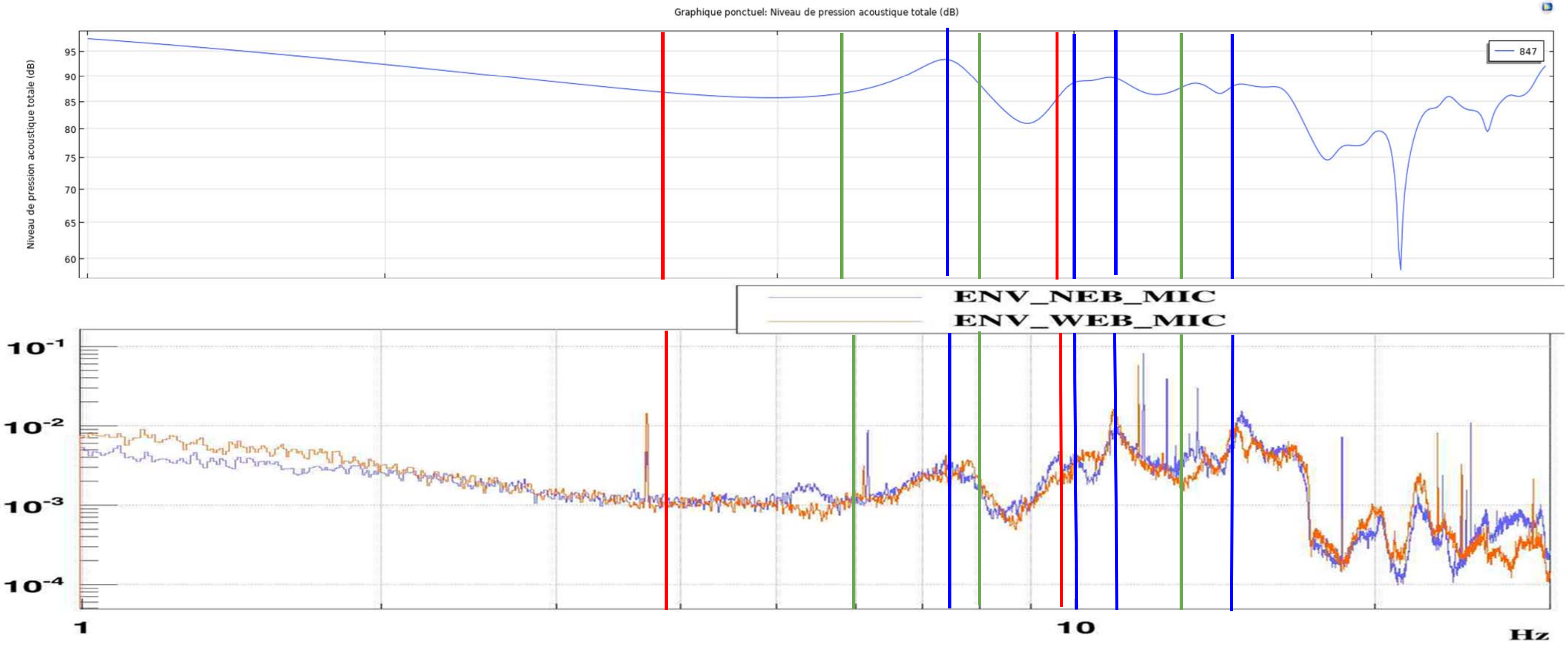
⇒ **Smooth response resulting from the modal overlap**

Inlets ducts modes
Outlets ducts modes
Room modes

α_{room}= 0.097

α_{in}= 0.09

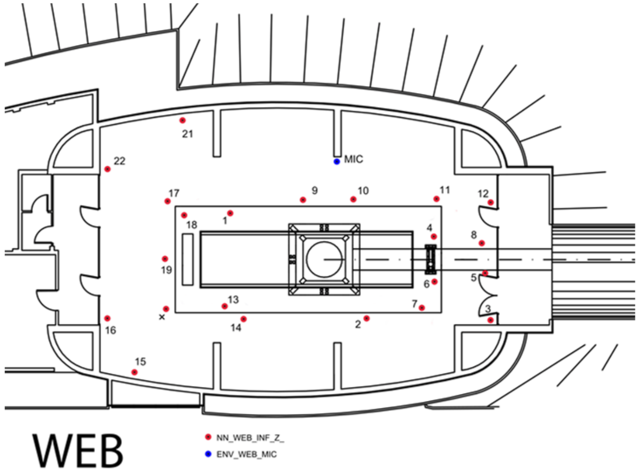
α_{out}= 0.11

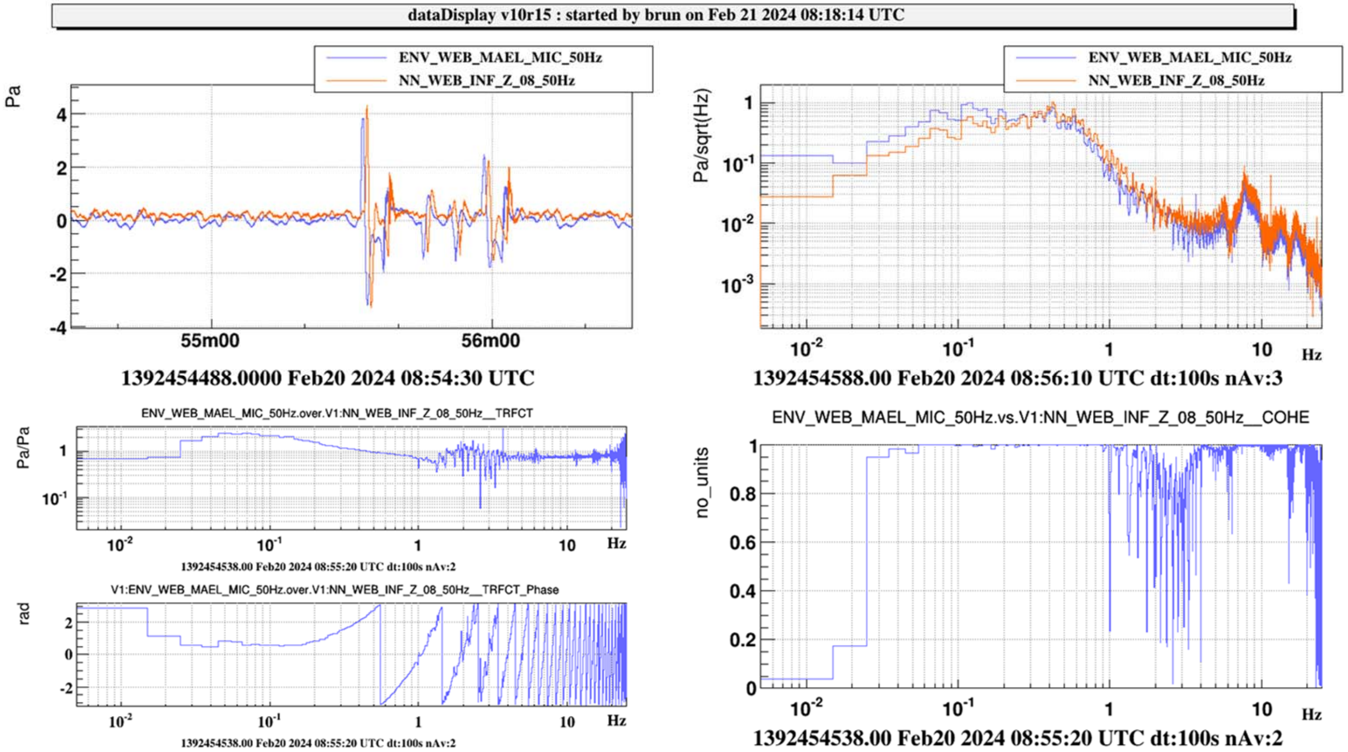


Tuning =>
$V_p = 3.10^{-3}$m/s
Piston equivalent to the fan

Acoustic model of the NEB validated

Systematic acoustic measurements in the WEB (in course)





dataDisplay v10r15 : started by brun on Feb 21 2024 08:18:14 UTC

- Microphones array by T. Bulik, M. Suchenek, University of Warsaw, Poland
- Calibration using a Bruel and Kjaer reference microphone (APC)

Application 1 : estimation of the newtonian noise from acoustic origin

Mass density is proportional to acoustic pressure:

$$\delta\rho(\boldsymbol{r},t) = \frac{\rho_0}{\gamma P_0}\delta P(\boldsymbol{r},t) = \frac{\rho_0}{\gamma P_0}\sum a_n(t)\phi_n(\boldsymbol{r})$$

Modal expansion

=> Perturbations of the gravity potential

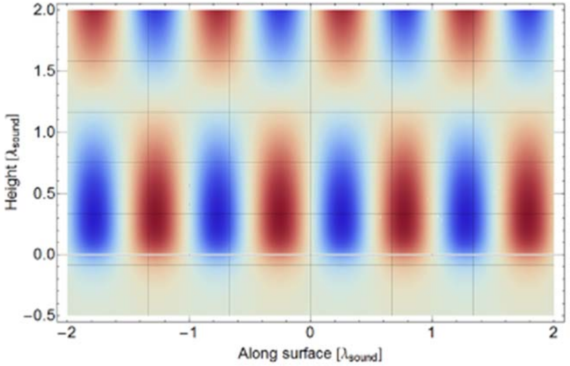
$$\delta\Phi(\boldsymbol{r}) = -G\int\frac{\delta\rho(\boldsymbol{r}')}{|\boldsymbol{r}-\boldsymbol{r}'|}\,\mathrm{d}V'$$

$$\delta\phi(\boldsymbol{r}) = \sum b_n(t)\psi_n(\boldsymbol{r})$$

Modal expansion

Gravity acceleration along a horizontal direction produced by a plane infrasound wave (oblique incidence 7π/6) reflecting on a rigid wall

J. Harms, Terrestrial gravity fluctuations,
DOI : 10.107/s41114-019-0022-2

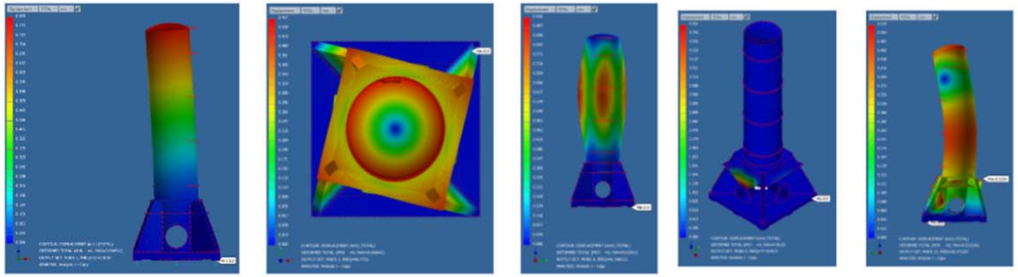


L. Maurin, M. Brun, D.Fiorucci, I. Fiori, M. Tringali, F. Paoletti, R. Passaquieti, S. Terrien, F. Gautier, M. Barsuglia, J. Harms, Modelling Newtonian noise of vibroacoustic origin in the Virgo gravitational wave detector, Internoise 2024, 25-29 August, Nantes, France (submitted)

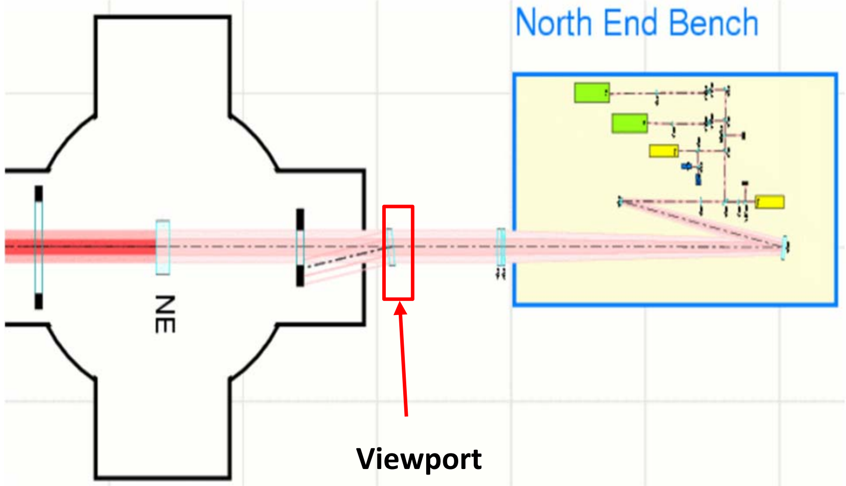
Application 2 : simulation of the tower vibration induced by the acoustic field

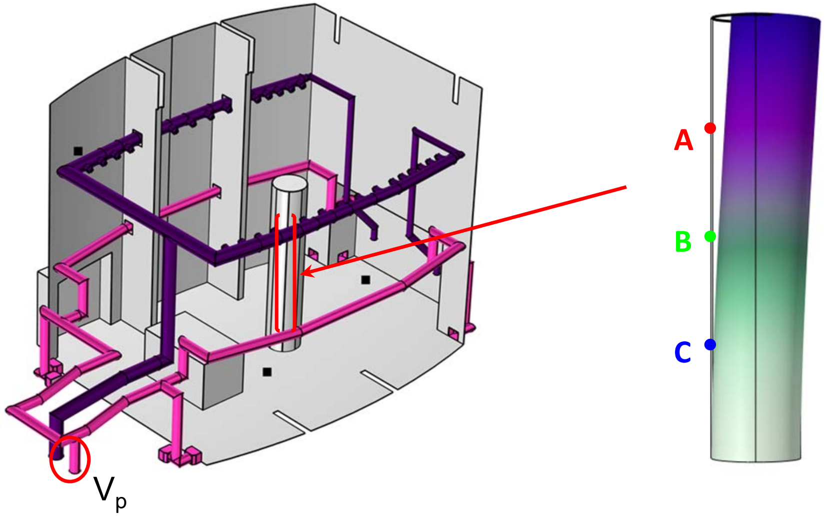
- FEM modal analysis => first bending mode 21 Hz
- => equivalent to a cylinder with equivalent mass and stiffness
- Damping ratio of 1%

Mode	Frequency (Hz)
1	20.9159
2	21.017
3	60.7733
4	61.6481
5	66.1167
6	77.4147
7	77.5606
8	77.7618
9	78.4267
10	85.4733

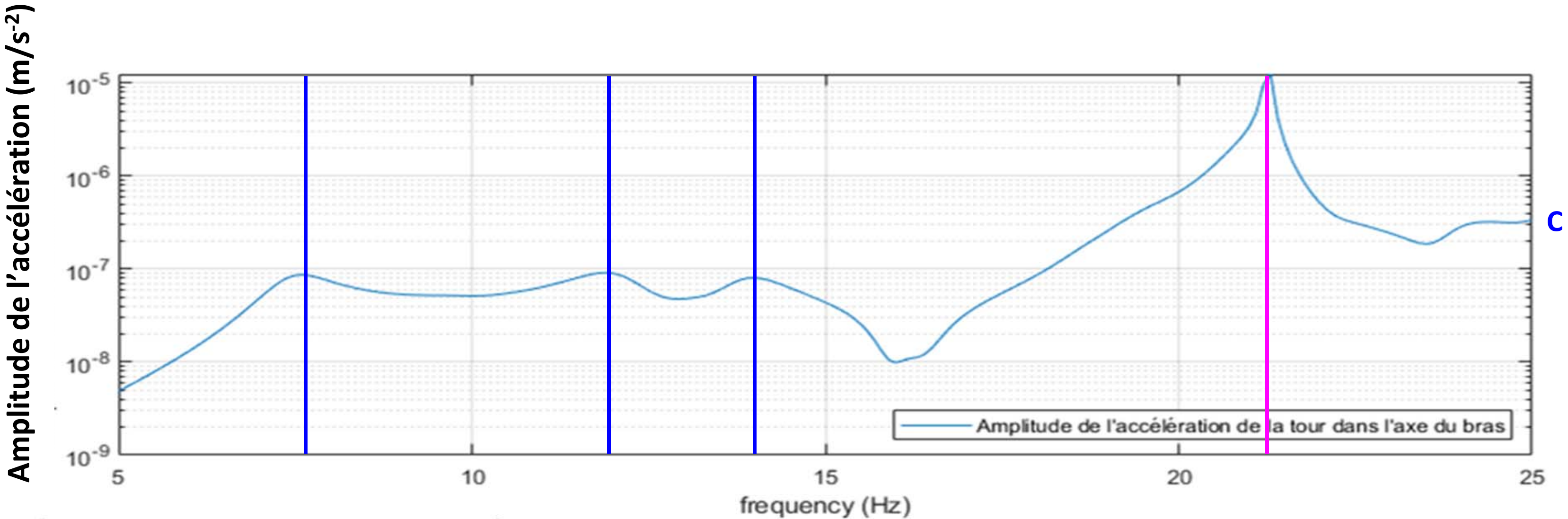


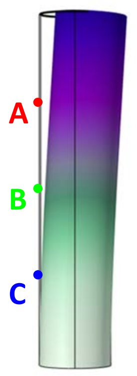
Numerical modal analysis by J.Gargiulo (2023)



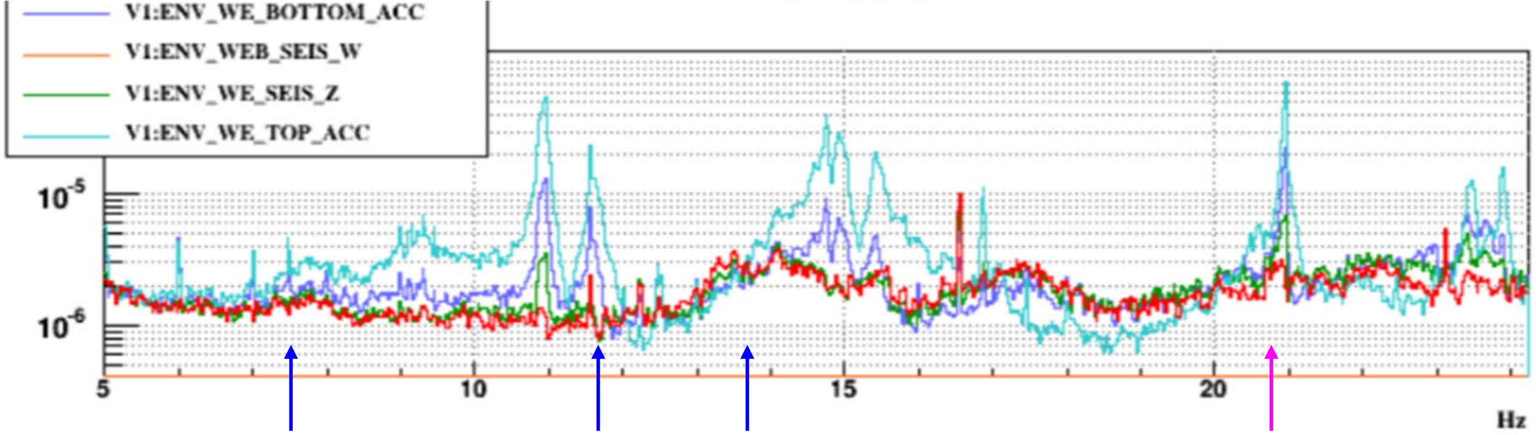


Order of magnitude of the amplitude of acceleration of the tower'bottom





$V_p = 3.10^{-3}$ m/s

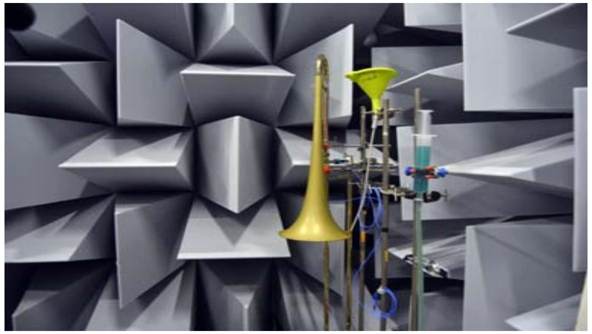


The measured level of accelation (deep blue curve) at the bottom of the tower is 10 times higher than the predicted level

=> structure borne excitation not taken into account

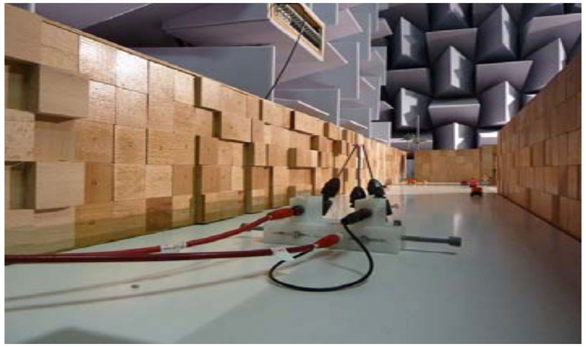
Chambre anéchoique

Rayonnement d’une source



Transmission à travers un réseau périodique

Propagation dans une maquette de rue



Grande salle Anéchoique du LNE

Longueur	9 m
Largeur	8 m
Hauteur	7 m
Hauteur / treillis	5,2 m
Surface	72 m^2
Volume	500 m^3

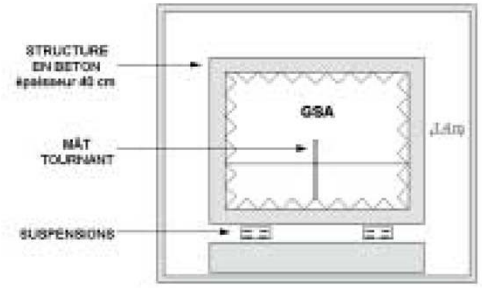
Anéchoïcité Fréquence de coupure de la salle [1] : 70 Hz

[1] fréquence à partir de laquelle le son décroît dans les conditions de champs libre.

Bruit de fond dB (réf 20µPa) ***Sans ventilation***	< 20 dB (Lin) (20Hz–20kHz)	< 0 dB (A)

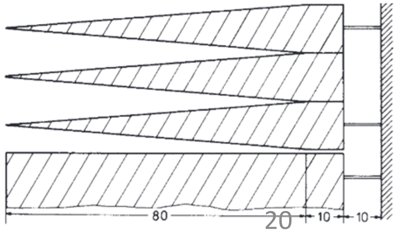
Structure de béton désolidarisée du bâtiment au moyen de **42** suspensions de type boîte à ressorts associées à 4 amortisseurs viscoélastiques.

Fréquence propre verticale des suspensions	2,1 Hz
Epaisseur des parois	40 cm
Densité du béton utilisé	2400 kg/m^3
Masse	721 Tonnes



Densité de la laine de roche	80 kg/m^3
Fréquence de coupure *	70 Hz
Nombre de dièdres posés	3200
Masse du revêtement	31 Tonnes

* Fréquence la plus basse, à partir de laquelle le coefficient de réflexion, mesuré au tube à ondes stationnaires, d’un échantillon de dièdres (testé dans la configuration de montage) est inférieur à 0,1.



Low frequency , broadband and thin acoustic metamaterial for acoustic insulation and absorption

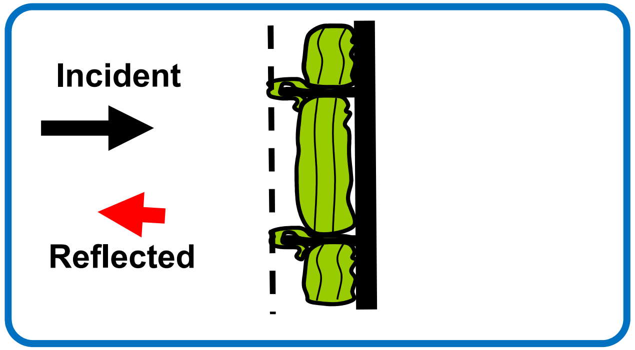
Very Low Freq. range | Low Freq. range | Audio range

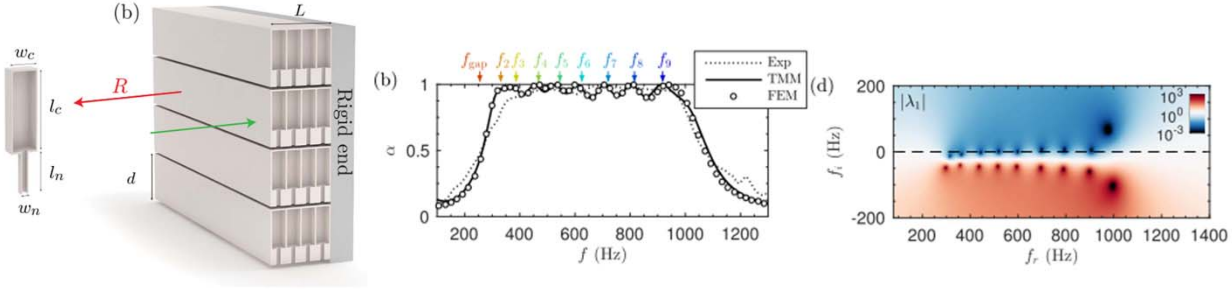
1Hz | 10Hz | 100Hz | 10000Hz

GW context- Virgo

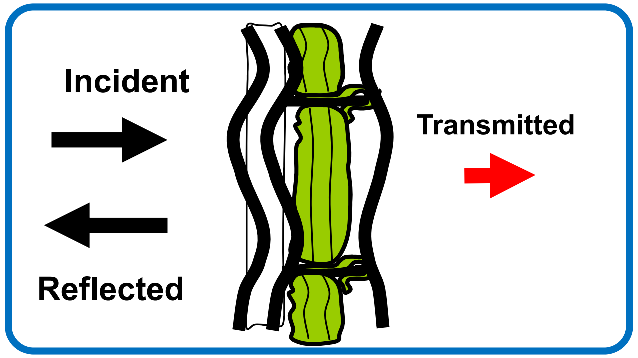
Building acoustics, transport industry

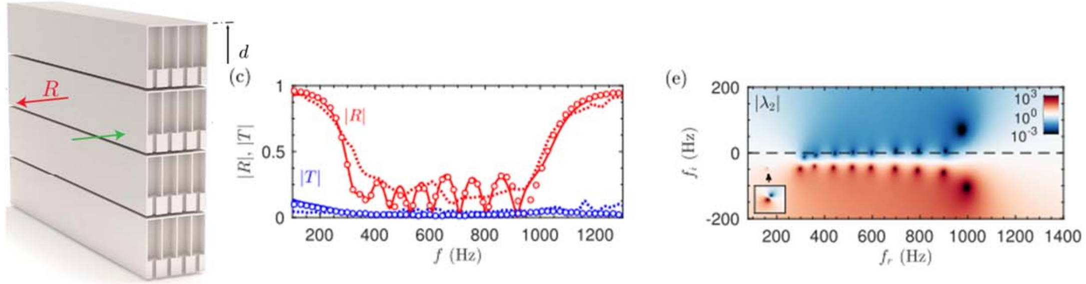
Absorption problem





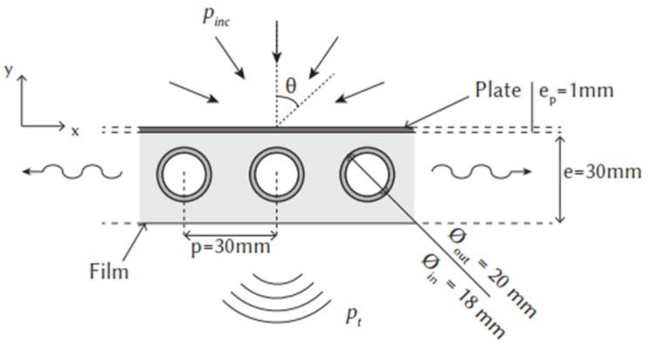
Insulation problem



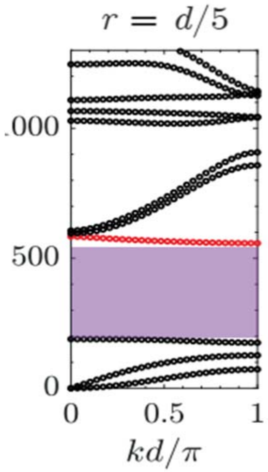


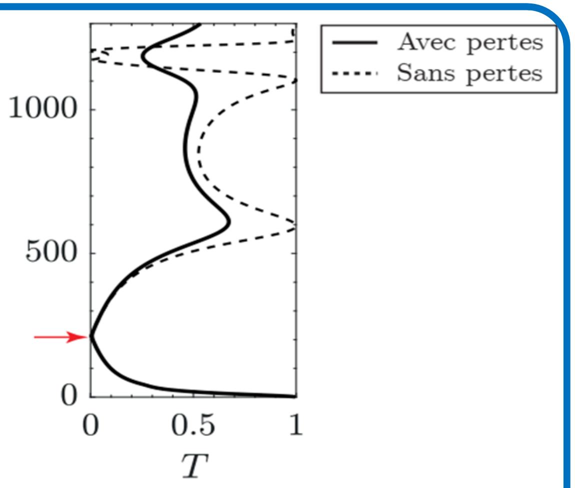
V. Romero-García et al., Design of acoustic metamaterials made of Helmholtz resonators for perfect absorption by using the complex frequency plane Comptes Rendus Physique, Volume 21, issue 7-8 (2020), p. 713-749. https://doi.org/10.5802/crphys.32

Metablocker



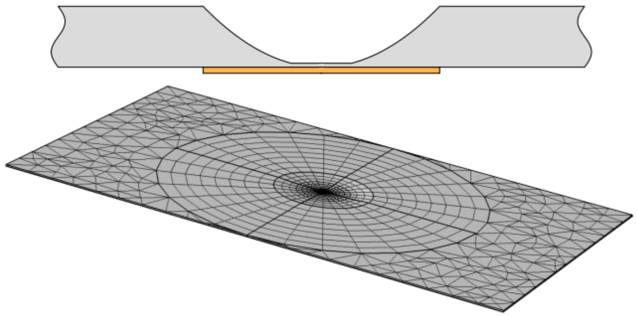
METACOUSTIC

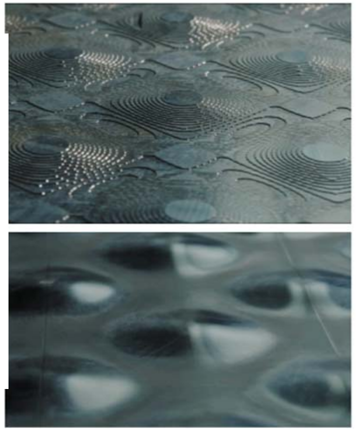


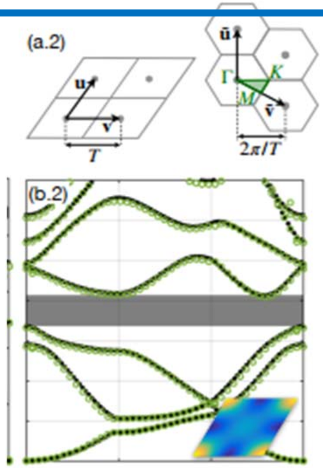


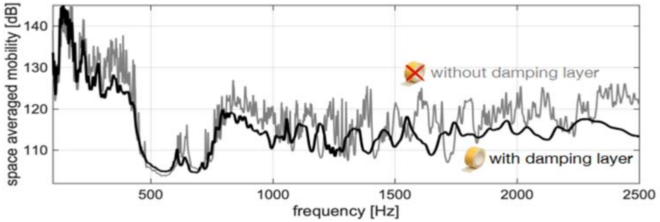
N. Aberkane-Gauthier, Soft solid subwavelength plates with periodic inclusions: Effects on acoustic Transmission Loss, Journal of Sound and Vibration Volume 571, 17 February 2024, 118005

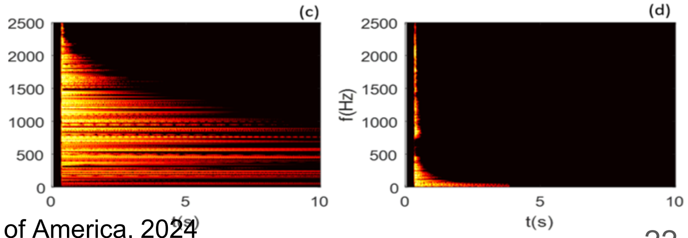
Acoustic Black Hole effect











F. Gautier, Broadband vibration mitigation using a 2D Acoustic Black Hole Phononic crystal, Journal of the Acoustical Society of America, 2024

Merging the metablocker and the ABH ‘s ideas and adapting the design to low frequencies

Acoustic Modeling : some concluding remarks

1 – Acoustic field in the NEB
- is dominated by HVAC noise
- is described by 25 modes below 30Hz
- The mean absorption coefficient **α** = 0.1
- Modal acoustic model of the NEB validated
- The leaks plays an important role in the very low frequency range (!)

2- HVAC acoustic source
- is represented by 2 equivalent pistons whose acoustic velocity is estimated from direct measurement
- is highly dependent on fan speed (power low).
- Inlets and outlets networks are equivalent to sets of acoustic monopoles

3- Recommandations
- Reduction of the fan speed !!!
- Thermal insulation needed to reduce the HVAC activity

4- Further works
- Acoustic modeling of (all) Virgo's experimental halls and ET's Caverns
  - Application 1 : estimation of the Newtonian noise (Master thesis M. Brun)
  - Application 2 : estimation of the viewport vibration => scattered light noise estimation
- Analysis of technical noises (PhD starting in Oct. 2024, Funding Le Mans University)
  - HVAC, Air Unit, water pumps, Cryostat...
  - Transfer Path analysis : Structure and Air borne sound, Monitoring
- Acoustic absorption / insulation
  - Specific design to be defined (PhD N. Ayyash, MSCA project Metavision, PhD 2024-2027)