Workshop GdR développement des détecteurs

Modelling Newtonian noise of acoustic origin in the Virgo gravitational wave detector

Maël Brun

Master thesis (05/02 – 12/07)

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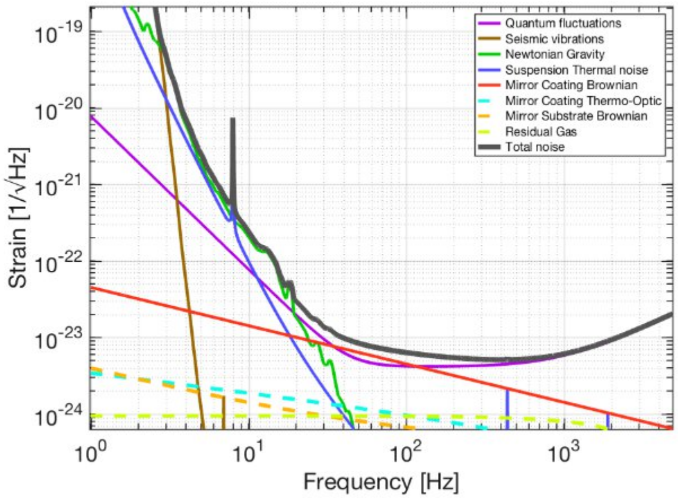
- M. Barsuglia (APC)

17/06/2024

Modelling Newtonian noise of acoustic origin in the Virgo gravitational wave detector

Context of the study

- The acoustic pressure field implies spatial fluctuations of the air mass density, depending on the frequency.
- Frequency range: 3 Hz – 20 Hz.



Noise budget for Advanced Virgo (AdV) design sensitivity.

Reference: Eleonora Capocasa. Optical and noise studies for Advanced Virgo and filter cavities for quantum noise reduction in gravitational-wave interferometric detectors. Instrumentation and Methods for Astrophysic. Unversité Paris VII (Denis Diderot), 2017.

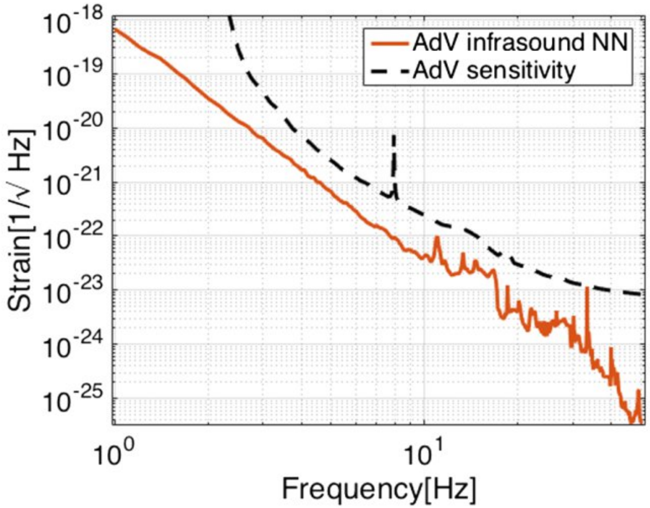
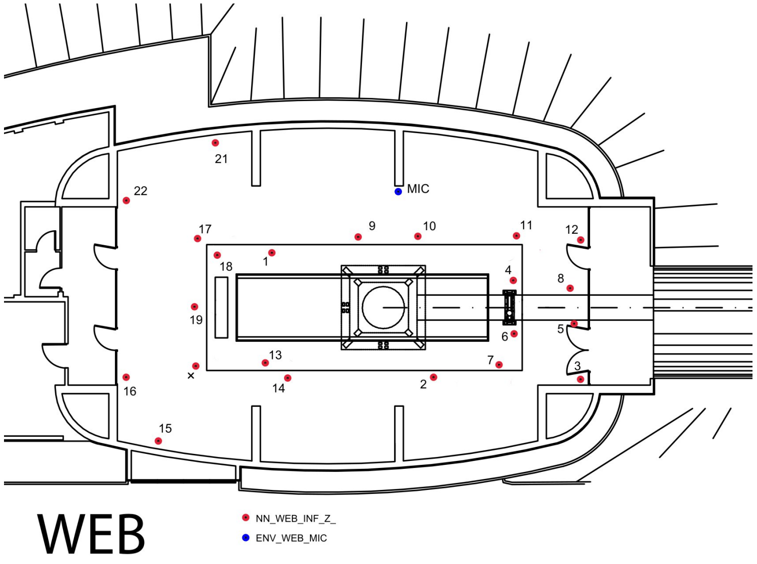


FIG. 10. Estimate of the AdV infrasound NN, by using sound spectra recorded at AdV site, see Fig. 4.

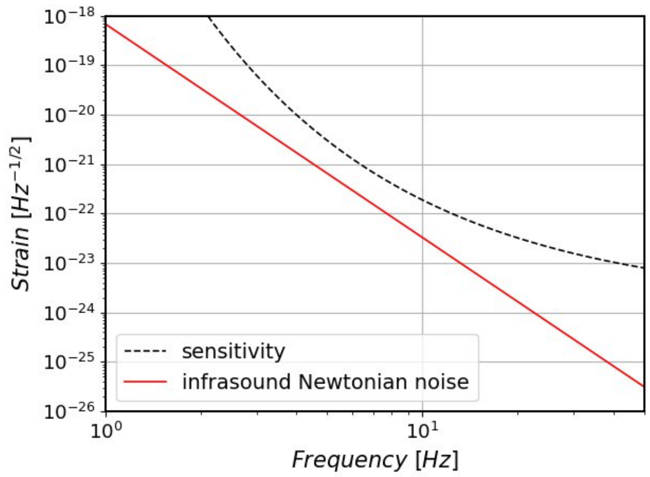
Reference : D. Fiorucci, J. Harms, M. Barsuglia, I. Fiori, and F. Paoletti. Impact of infrasound atmospheric noise on gravity detectors used for astrophysical and geophysical applications. Phys. Rev. D, 97, 2018.

Context of the study

- **Goal: quantify the impact of the acoustic pressure fluctuations on the Newtonian noise in the end building.**
- The West End Building (WEB) experimental hall has an infrasound microphone array set up by AstroCeNT researchers.



WEB map with all the microphones' locations specified (blue one: 4m from the ground, red: 1m from the ground)

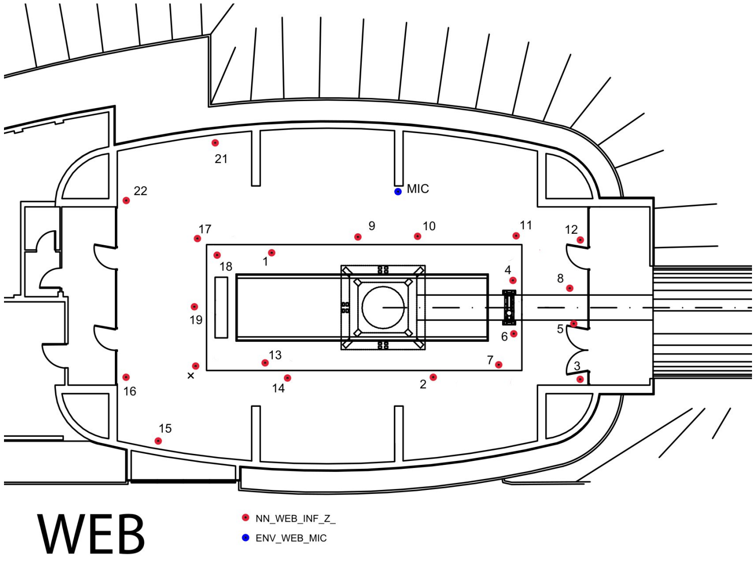


Advance Virgo (AdV) sensitivity and estimated infrasound Newtonian noise comparison.

Reference : D. Fiorucci, J. Harms, M. Barsuglia, I. Fiori, and F. Paoletti. Impact of infrasound atmospheric noise on gravity detectors used for astrophysical and geophysical applications. Phys. Rev. D, 97, 2018.

Context of the study

- **Goal: quantify the impact of the acoustic pressure fluctuations on the Newtonian noise in the end building.**
- The West End Building (WEB) experimental hall has an infrasound microphone array set up by AstroCeNT researchers.



WEB map with all the microphones' locations specified
(blue one: 4m from the ground, red: 1m from the ground)

- Study:

  → Building an acoustic model of the hall.

  → Checking the microphone array data.

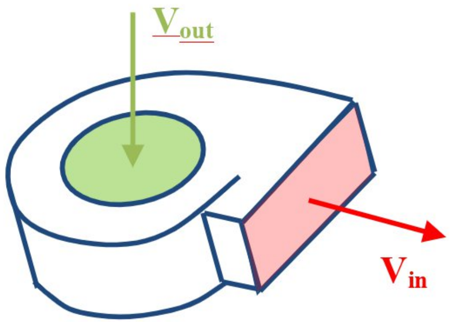
  → Estimating the Newtonian noise from the acoustic pressure field modelled at the test mass location.

  → Proposals to limit the Newtonian noise.

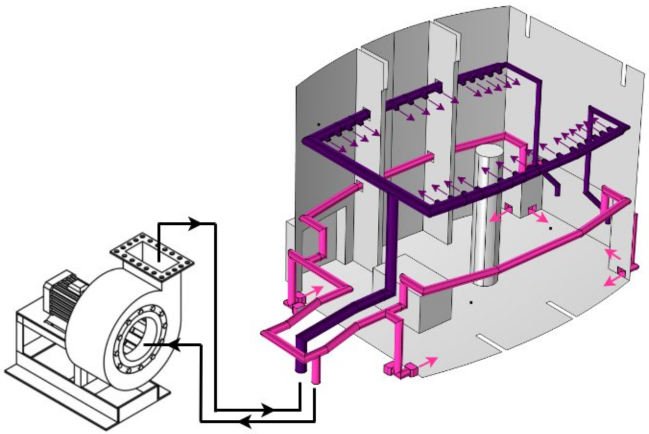
Building a realistic acoustic finite element model

Complete model

- **COMSOL Multiphysics**: finite element simulation software.
- **Noise source**: mainly the Heating, Ventilation and Air Conditioning (HVAC) system.
- **Model**: two equivalent acoustic rigid pistons at the beginning of the duct network.



The HVAC system is modelled as a piston both for the suction and the injection circuits.

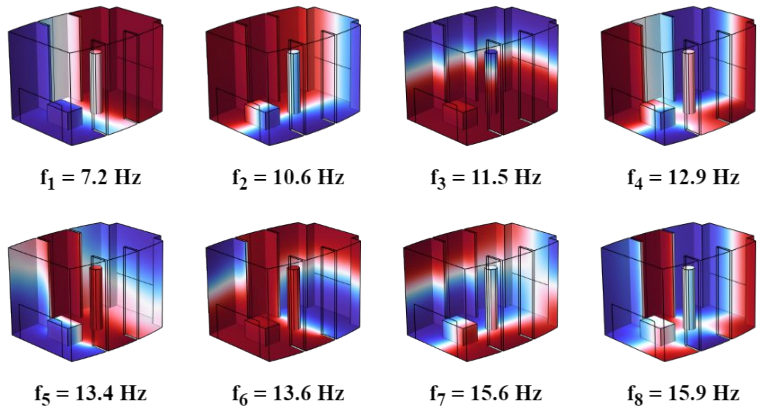


Model of the WEB experimental hall built in COMSOL. The HVAC system ensures air circulation through the suction (magenta) and injection (purple) circuits.

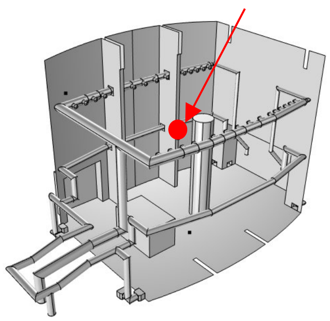
- $V_p = V_{out} = V_{in} = 1$ m/s, piston speed equivalent to the fan rotating.

Validation with measurements

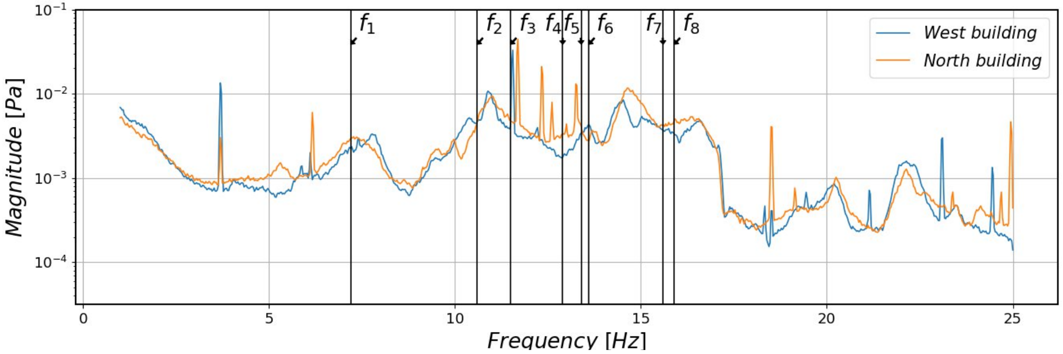
Complete model

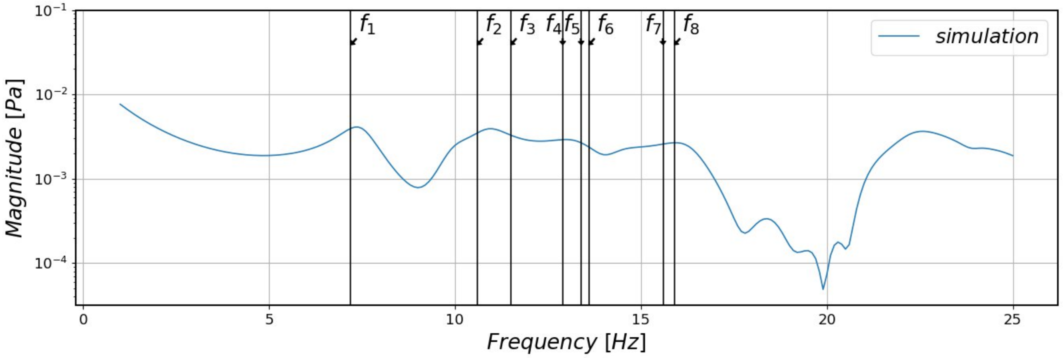


Modal analysis of the experimental hall.



- Absorption coefficient of the room and ducts (~10%):
  → Smooth response due to the modal overlap.



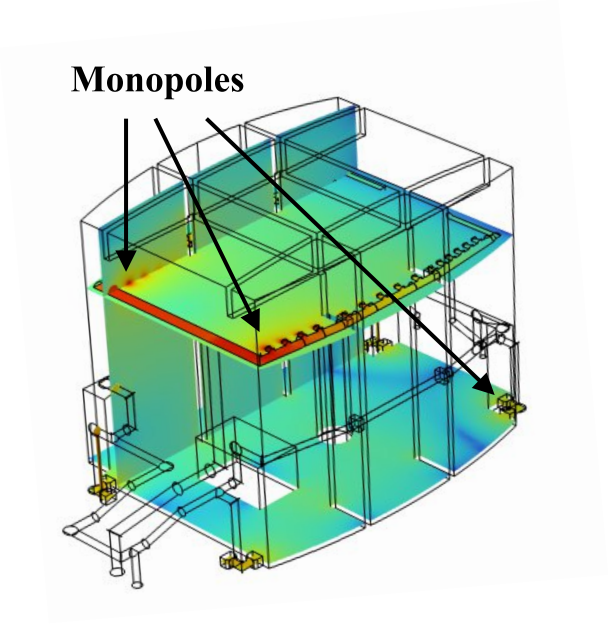


- Tuning: $\tilde{V}_p = 3.10^{-3}$ m/s.

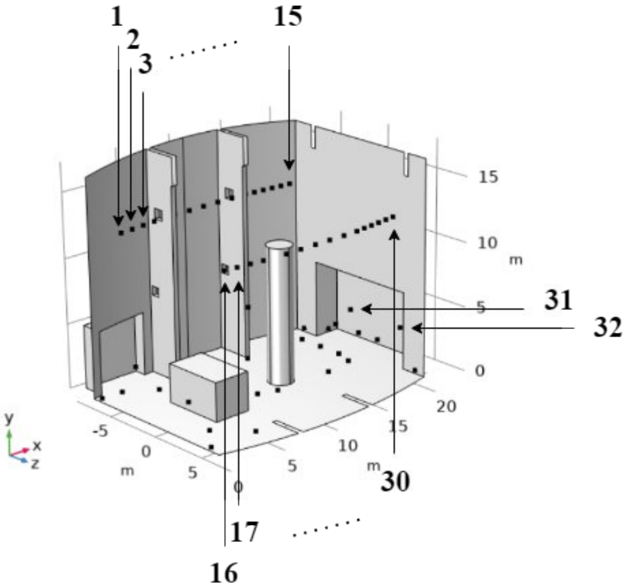
Noise source equivalent to the HVAC

Simplified model

- HVAC = collection of acoustic monopoles.



Inlets duct network.

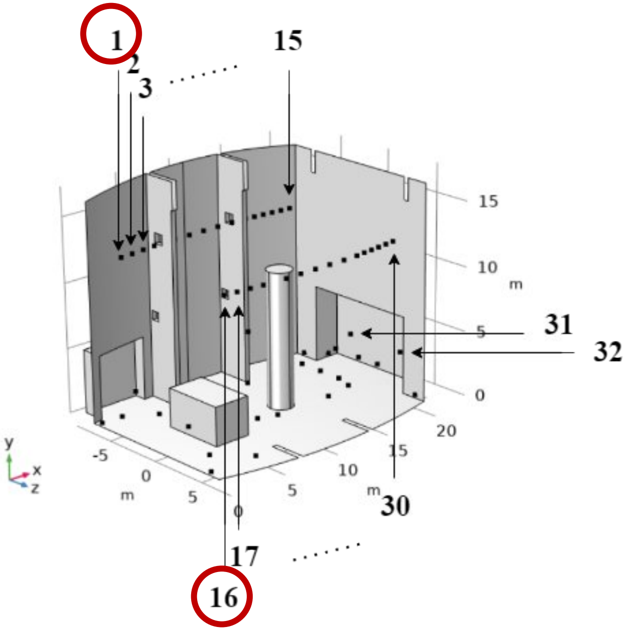


Model of the WEB without the ducts.

Noise source equivalent to the HVAC

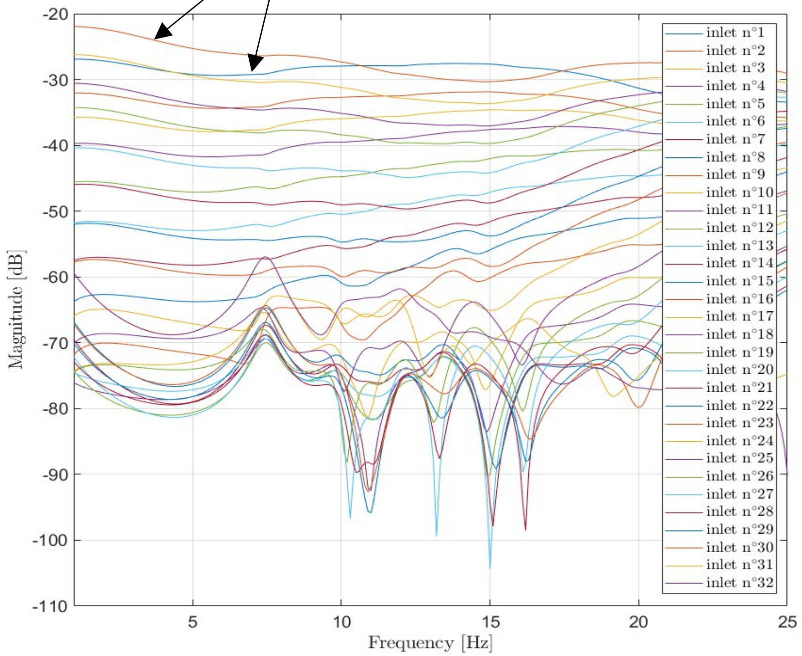
Simplified model

- HVAC = collection of acoustic monopoles.



Model of the WEB without the ducts.

Inlets 1 and 16: dominant acoustic monopoles.

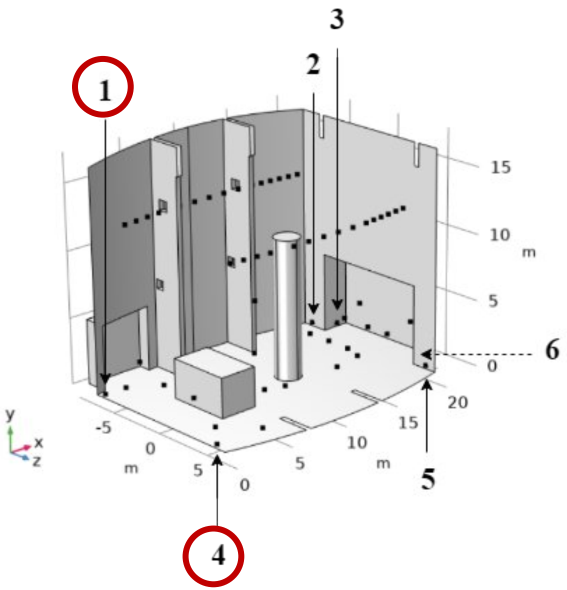


Normal inlet air flow rate amplitude computed from the complete model.

Noise source equivalent to the HVAC

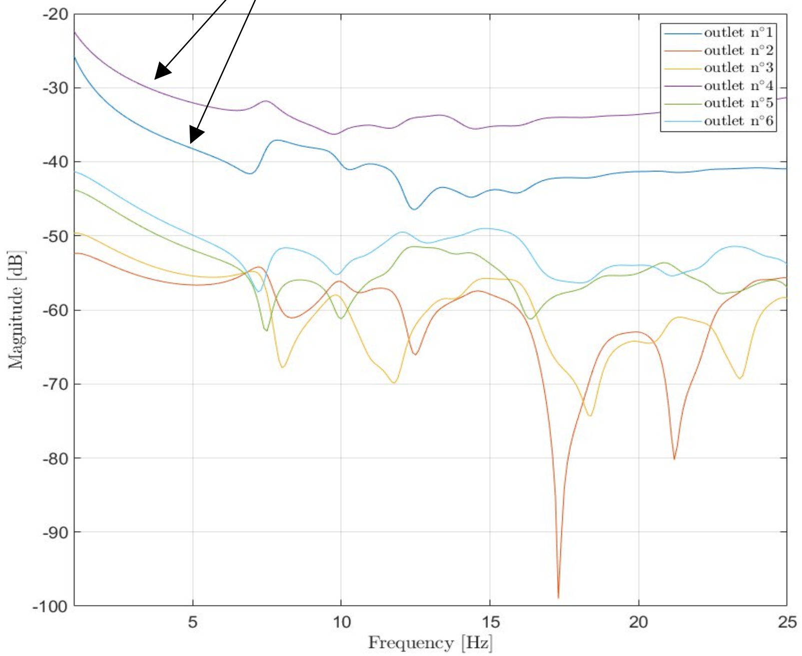
Simplified model

- HVAC = collection of acoustic monopoles.



Model of the WEB without the ducts.

Outlets 1 and 4: dominant acoustic monopoles.

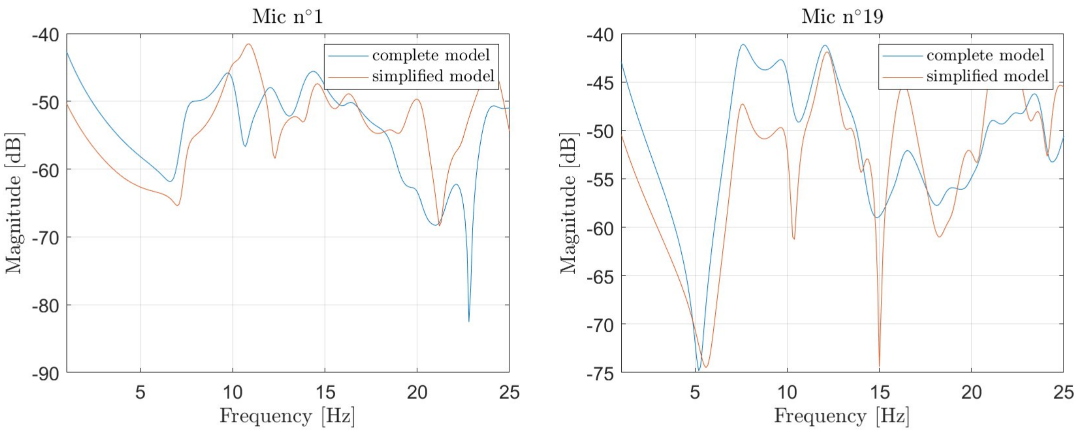


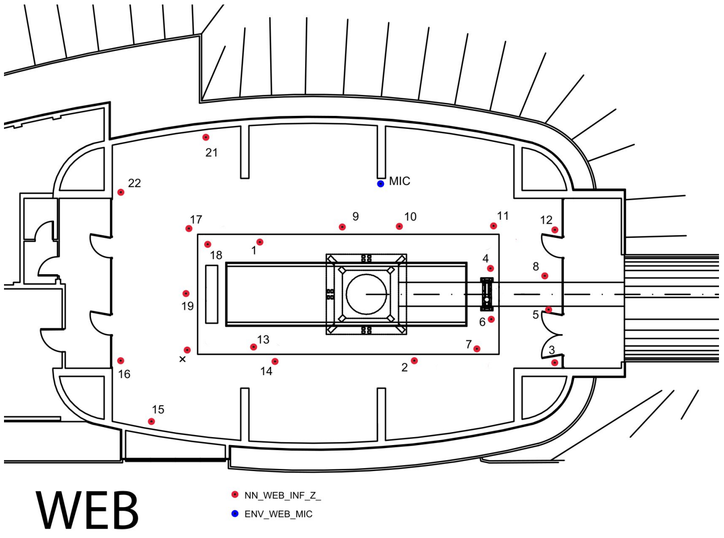
Normal outlet air flow rate amplitudes computed from the complete model.

Validation with the complete model

Simplified model

- The pressure field is now computed with the simple model.





Examples of spectra comparison at different locations of the microphone array.

- Parameters of this simplified model:

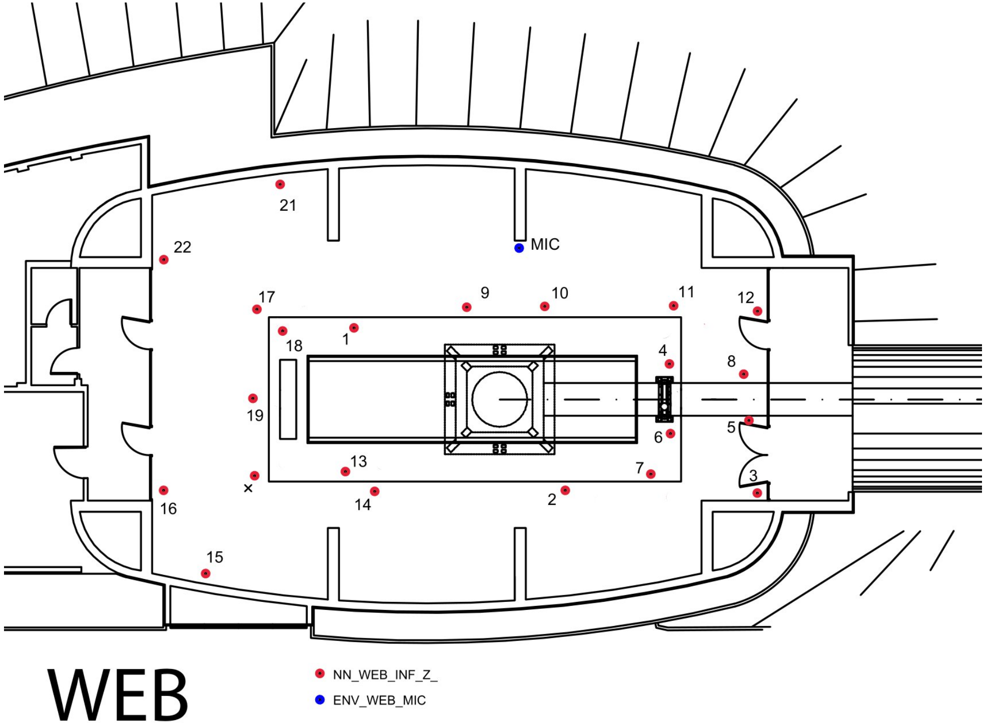
  → The rotation speed of the fan

  → The number of inlet sources

  → The absorption on the room walls

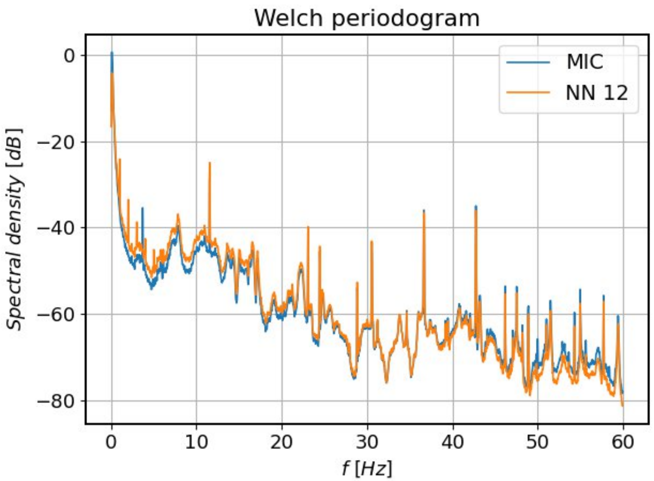
Relative calibration of the Newtonian noise (NN) microphone

- The microphone array is checked thanks to a reference infrasound microphone (Frequency range: 0.07 Hz – 20 kHz).
- Data displayed:
  - time series → **1.01s delay**
  - spectra

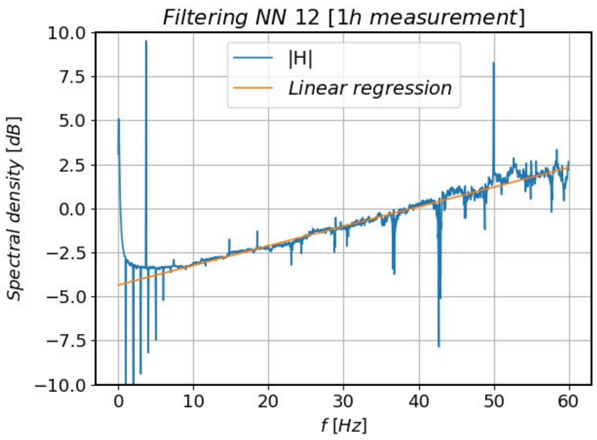


Relative calibration of the Newtonian noise (NN) microphone

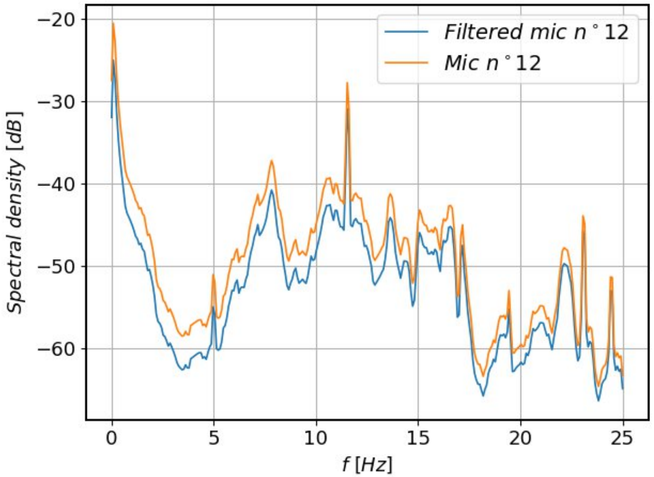
- The 1.01s delay is taken into account before processing any signal.
- Frequency range: 0.03 Hz – 60 Hz.



- A factor is computed between the two signals to obtain the best overlap.



$$H = \frac{P_{ref}}{P_{array}}$$



- The filtered microphone:
  → is calibrated ;
  → electronic issues are removed.

- **The corrected microphone array data can be used to build the acoustic model.**

Modal analysis

Acoustic

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

Gravity field

- Potential: $\delta\Phi(\vec{r},\omega) = \sum_n B_n(\omega)\psi_n(\vec{r})$
- Gravity field: $\vec{g}(\vec{r},t) = -\vec{\nabla}\Phi(\vec{r},t)$

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

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

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

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

Modal analysis

Acoustic

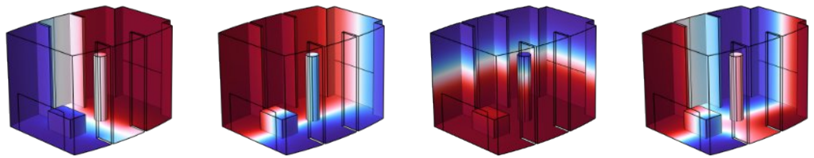
$$\delta p(\vec{r},\omega) = \sum_n A_n(\omega)\phi_n(\vec{r})$$

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

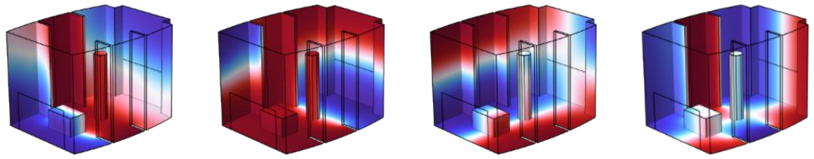
$$\psi_n(\vec{r}) = \int_V \frac{\phi_n(\vec{r'})}{|\vec{r'}-\vec{r}|} dV(\vec{r'})$$

Gravity field

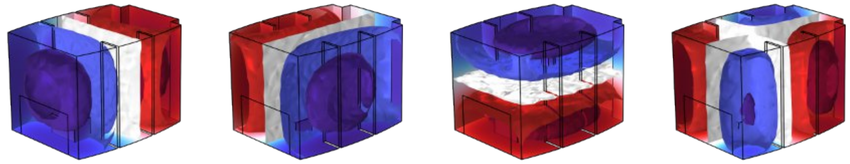
$$\delta\vec{g}(\vec{r},\omega) = -\sum_n B_n(\omega)\vec{\nabla}\psi_n(\vec{r})$$



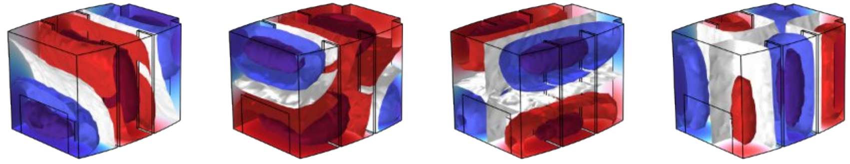
f_1 = 7.2 Hz f_2 = 10.6 Hz f_3 = 11.5 Hz f_4 = 12.9 Hz



f_5 = 13.4 Hz f_6 = 13.6 Hz f_7 = 15.6 Hz f_8 = 15.9 Hz



f_1 = 7.2 Hz f_2 = 10.6 Hz f_3 = 11.5 Hz f_4 = 12.9 Hz

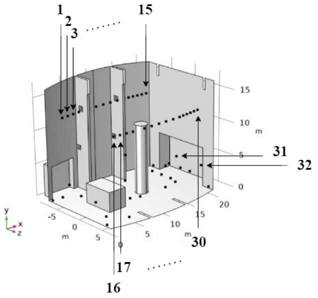


f_5 = 13.4 Hz f_6 = 13.6 Hz f_7 = 15.6 Hz f_8 = 15.9 Hz

Modal analysis

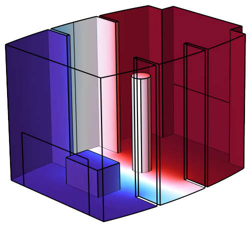
Acoustic

- A_n depends on the source location and the amplitude of its flow rate Q.



flow rate of the source number i

mode n at the location of the source i

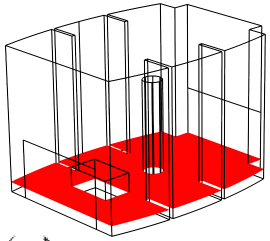


$$A_n = \frac{\sum_i Q_i \phi_n(\vec{r_i})}{\Lambda_n (k_n^2 - k^2)}$$

normalisation

frequency dependance

$$\frac{2\pi f_n}{c_0}$$



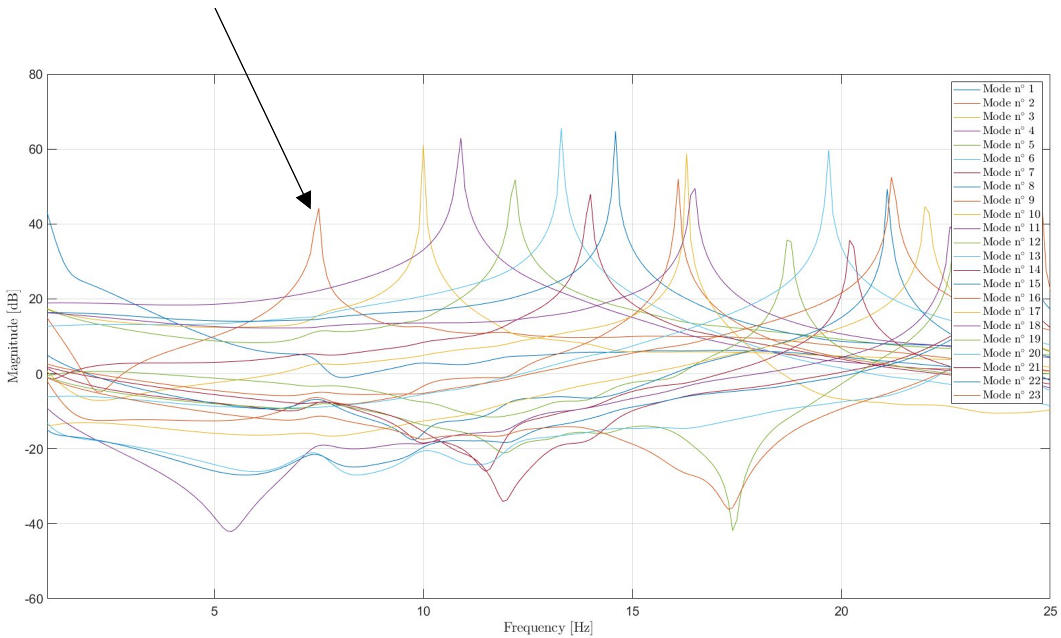
- Damping ξ_n: $f_n = f_{n0}\left(\sqrt{1-\xi_n^2} + j\xi_n\right)$
- Pessure: $\delta p(\vec{r},\omega) = \sum_n A_n(\omega)\phi_n(\vec{r})$

Modal analysis

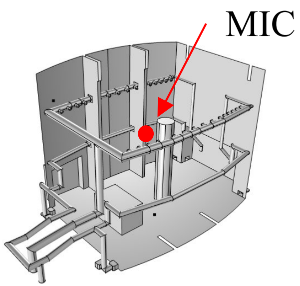
Acoustic

- The pressure field is now well-known in the room.

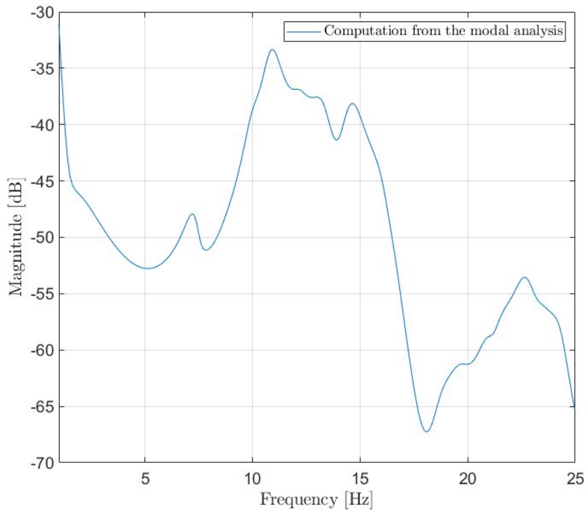
$$A_n = \frac{\sum_i Q_i \phi_n(\vec{r_i})}{\Lambda_n (k_n^2 - k^2)}$$



Modal amplitudes associated to the acoustic pressure field.



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

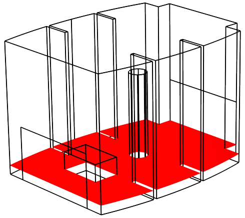


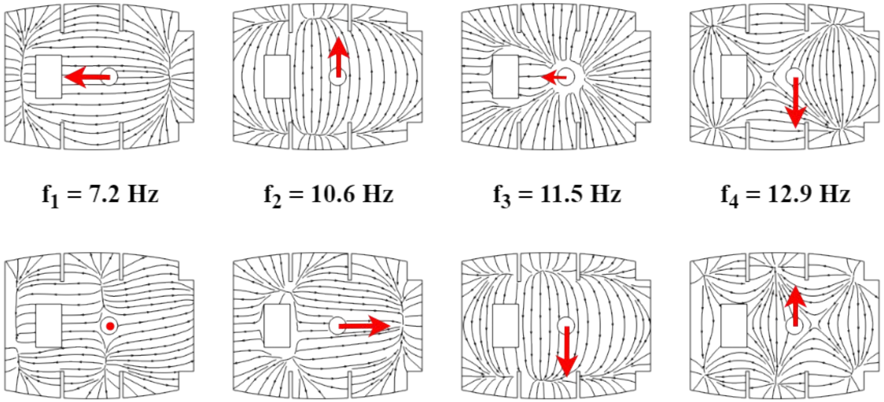
Pressure computed with the modal expansion.

Estimating the Newtonian noise from the simplified acoustic model

Gravity field

- What is the impact of the Newtonian noise on the suspended test mass?





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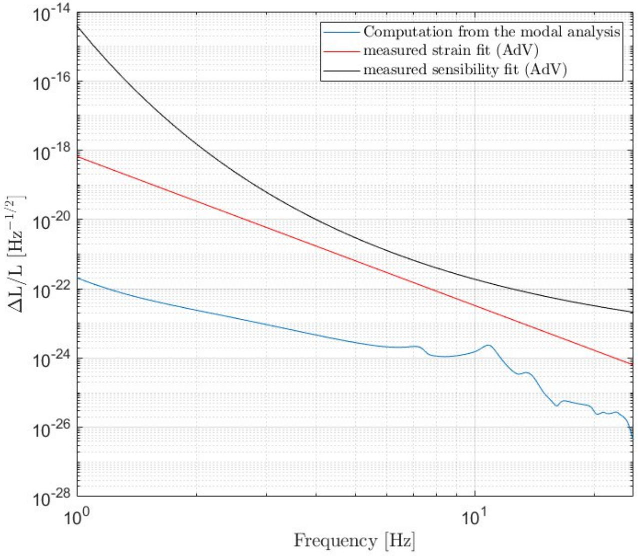
f_5 = 13.4 Hz f_6 = 13.6 Hz f_7 = 15.6 Hz f_8 = 15.9 Hz

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

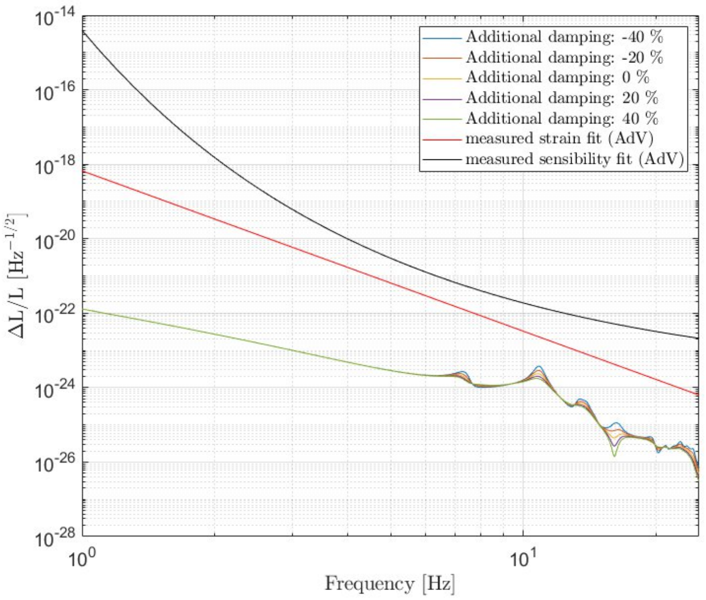


Strain computed at the location of the test mass from the simplified acoustic model.

How to limit the Newtonian noise: two proposals

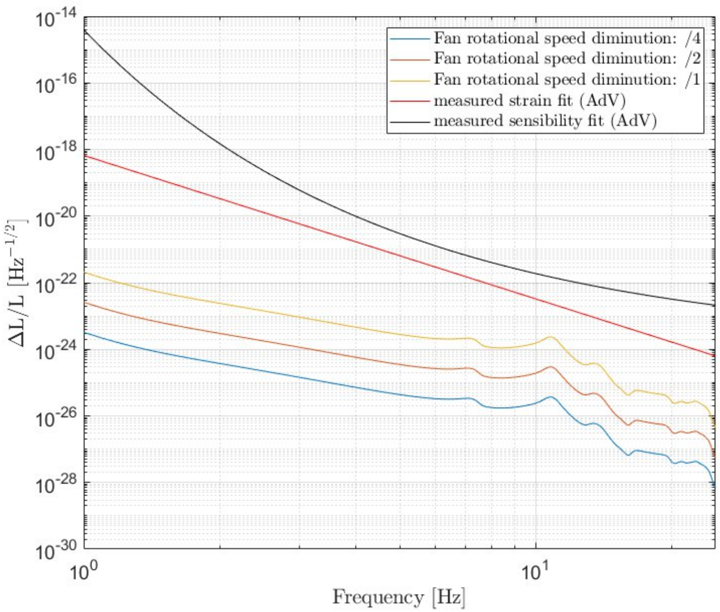
Gravity field

- Absorption of the experiment hall walls.



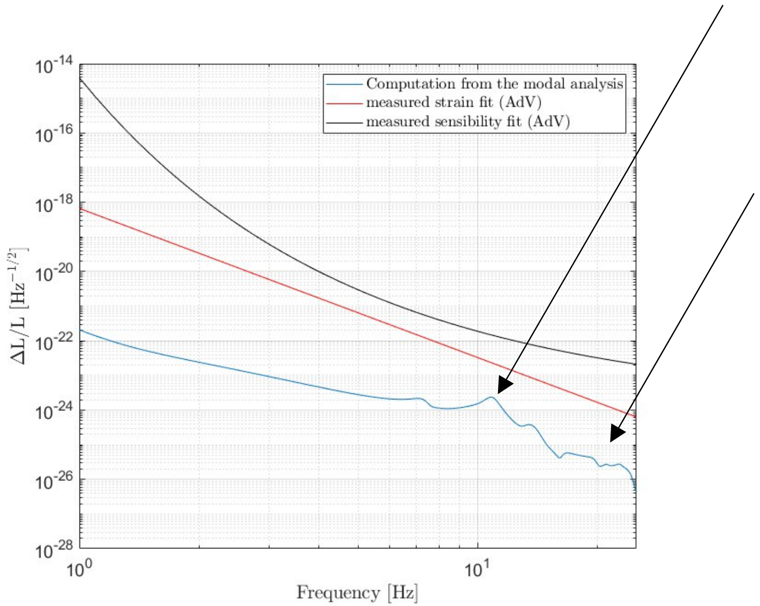
Simulating different absoprtion coefficients throught the damping ξ_n.

- Rotational speed of the fan from the HVAC.

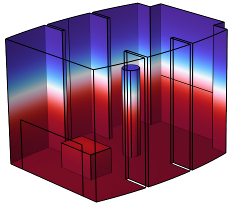


The fan rotational speed to the power 3 and acoustic pressure are proportional.

Modelling Newtonian noise of acoustic origin in the Virgo gravitational wave detector



- Room mode 3 (~10.8 Hz).
- Level controlled by the absorption.

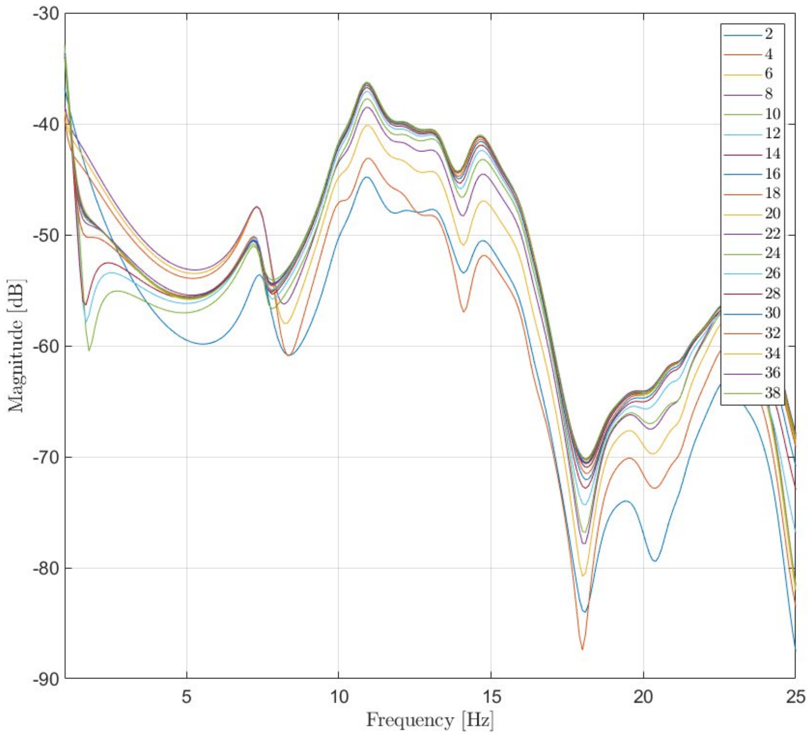


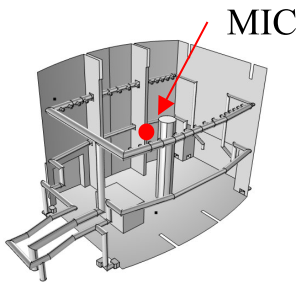
- Mean level characterised by the HVAC system.

- Investigating the impact of different locations for the point sources and/or a different location of the tower on the Newtonian noise.
- Designing experimental halls for E.T.

Extra slides

Simplified model





Effect of the number of point sources on the spectrum at MIC location.