

Hybrid Experimental - Numerical Method to Predict Far Field Noise of HVAC Unit.

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ABSTRACT

A hybrid method based on both experimental measurements and simulations to assess the sound pressure level emitted by an HVAC unit in far field is described

The measurement consists in the acquisition of sound pressure level in the near field all around the HVAC unit. Also, to validate and evaluate the accuracy of the method, some measurements are done in far field.

The simulation starts by the extraction of the pellicular modes and their radiation to retrieve the transfer function with each near field microphone. Thanks to the inverse method, the participation factor of each mode can then be calculated using a least mean square method. The excitation pattern of the pellicular surface can be generated and the solution can be reconstructed at the far field microphones location. A Thikhonov regularization is also investigated and applied to improve the accuracy of the prediction. Finally, sensitivity study on various parameters (like grid size, number of pellicular modes to consider, Thikhonov parameter value,..) is performed.

The conclusion is such hybrid method is adequate to predict sound pressure level of HVAC unit in far field using near field pressure measurement.

Keywords: HVAC Unit, Far Field, Simulation

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1. INTRODUCTION

The HVAC units are usually installed on roof of building or somewhere in the garden around the building. To manage the noise level in the neighbourhood, acoustic panels are placed around these units. As a unit manufacturer, it is a great benefit to provide guidelines regarding what would be the best positions, size,... of these panels with respect to a specific unit. To do so, the unit far field noise emission has to be characterized in terms of amplitude, directivity,...

As taking far field measurement around the unit is practically complicated, a hybrid method based on both sound pressure measurement in near field and simulations has been designed and set-up. The sound pressure level is evaluated at several microphone locations (near and far field) using an inverse method applied on the pellicular modes vibration pattern of the HVAC Unit. To validate the method and assess its accuracy, the extrapolated results in far field are compared with measurement as well.

A procedure completely based on simulation has not been explored. The various types of components (radiator, fan, compressor,...) and their complexity would have required a much bigger investment on the simulation side. Additionally, some of those parts are not directly manufactured by the HVAC unit producer. An important set of data would then be missing to feed a complete simulation process.

Outdoor Condensing Unit – ZXDE 030E-TFD-454 (single fan unit) is being used for this analysis.

2. BACKGROUND: Pellicular Modes Concept

The concept of pellicular modes is presented with reference to an acoustic radiation problem involving a mechanical structure (geometrical domain Ω_s) whose external boundary is denoted Γ_s [4].

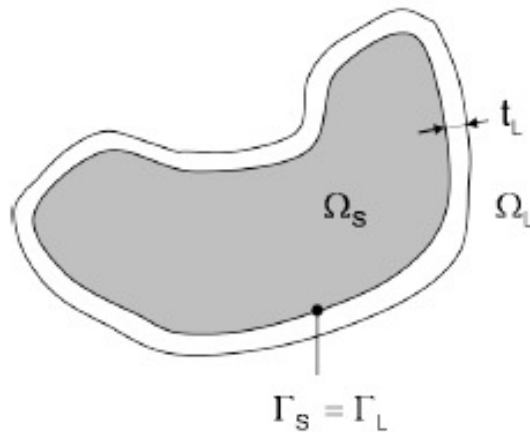


Figure 1 - Pellicular Mode Concept

This boundary supports the definition of a thin acoustic layer (geometrical domain Ω_L) whose inner boundary Γ_L coincides with Γ_s . Assuming the thickness of the acoustic layer is small w.r.t. the acoustic wavelength ($t_L \ll \lambda$), this layer can actually replace the physical domain.

The concept of pellicular modes can be exploited to assess the acoustic field radiated by a mechanical structure [3]:

- The starting point is the creation of radiation database which computes the transfer functions between the microphones and each of these pellicular modes
- It can then be used to solve an inverse acoustic problem (i.e. evaluation of the normal velocity profile leading to measured acoustic field pressure, reconstruction of the solution at other microphones, ...)

3. METHOD DESCRIPTION & ITS APPLICATION

The method consists in 4 different steps:

1. Measurement in near field (mandatory) & far field (for method validation only)
2. Measure signal phase shifting
3. Actran modelling & solving
 - a. Extraction of pellicular modes
 - b. Radiation of each pellicular mode individually
 - c. Inverse method applied used to retrieve the measured pressure field, at near microphone location, from excitation of pellicular surface and define the participation factors to be applied to each mode of this surface
4. Far field results Extraction & Analysis

3.1 Measurement set-up & Observation

As explained in section 2, near field sound pressure level measurements are required to retrieve participation factors of pellicular modes.

The near field measurement is performed on a box surrounding the unit. The dimensions of this “virtual box” is 1200x960x600mm and it is distant by 120mm of the actual HVAC unit. The distance between each microphone is defined at 60mm.

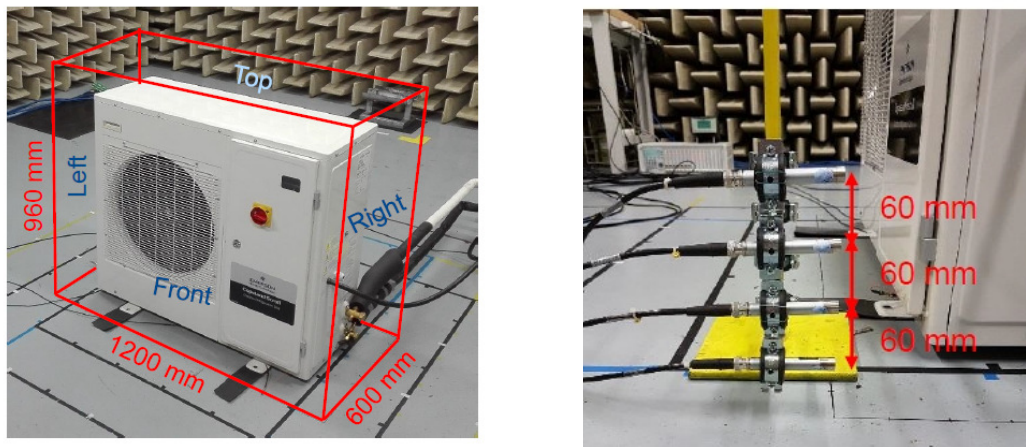


Figure 2 - Near Field measurement: *a. Virtual box around the unit b. Microphone Spacing*

This setup leads to 355 sets of 4 measurement points (total of 1420 measurement points) in near field. In addition, 76 sound pressure measurements are done in far field (respectively at 1m and 2m away from the unit). Finally, in order to be able to phase all 355 measurement sets to a common reference, 3 reference accelerometers are used.

Figure 3 presents standard measurements results. Same trend for all the microphones can be observed. Peaks due to the fan at Blade Pass Frequency and harmonics (in red) as well as peaks due to the compressor (in green) can be identified.

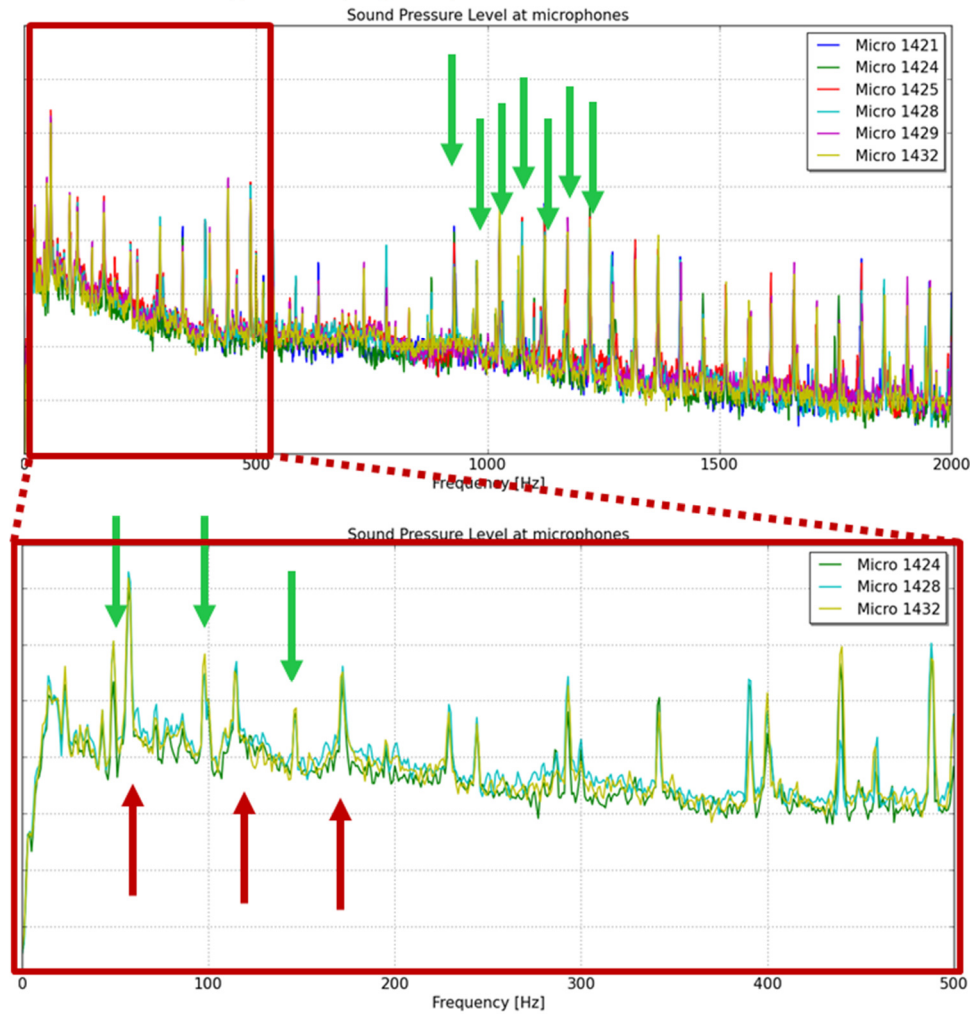


Figure 3 - Measurement Data

Thanks to a close look at the measurements, it was observed that measurements of microphones located in the area in front of the fan are polluted by the turbulent flow passing around the microphones themselves. These polluted microphone recordings are removed from the final data set.

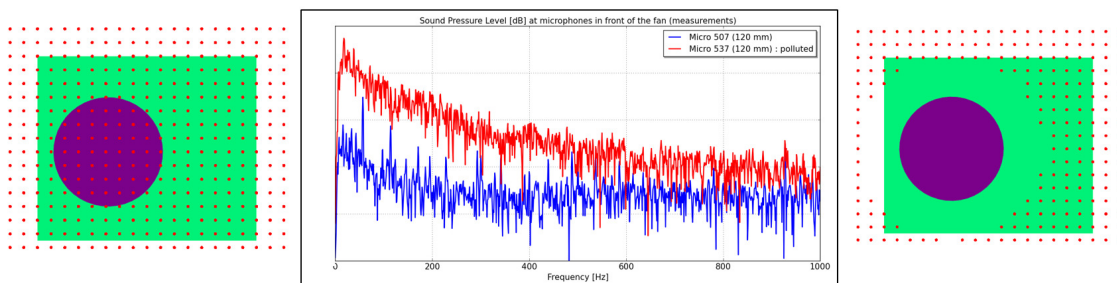


Figure 4- Polluted Measurement Data

3.2 Measure signal phase shifting

As described in section 3.1, one set of measurement records the pressure (amplitude and phase) for an array of 4 microphones. All measurements sets are therefore out-of-phase

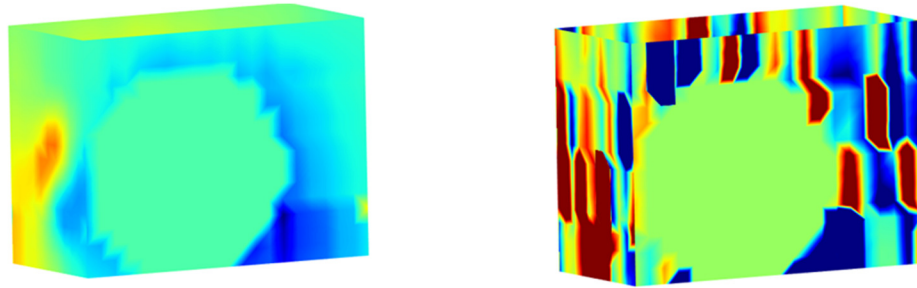
relative to each other's. In order to correct it, a phase shifting is done in the frequency domain for each microphone m_i as follows:

$$s_i(f) = \frac{m_i(f)}{r_i(f)} r_0(f)$$

Equation 1 - Phase Shifting

with: $m_i(f)$ the pressure measurement at microphone i
 $r_i(f)$ the reference signal associated to microphone i
 $s_i(f)$ the shifted measured signal

The real part of the pressure of the “shifted” signal can be visualized (Figure 5) to identify the spatial correlation between all the microphones. Between the peaks, pressure information is completely spatially de-correlated: the assessment of participation factors and therefore the reconstructed velocity field between the peaks should be considered carefully.



@Peak Freq: smooth spatial distribution Not @Peak Freq: no spatial correlation

Figure 5 - Spatial Correlation between Microphones

3.3 Simulation Model and Solution

The finite element model (*Figure 6*) consists of:

- 3D acoustic finite elements to propagate acoustic information (pressure) in near field around the HVAC unit
- An acoustic non-reflecting boundary condition based on infinite elements [2]. This boundary condition also allows to retrieve the sound pressure field in far field
- Pellicular mode excitation surface to simulate the HVAC unit box. This excitation surface is based on a velocity boundary condition in the acoustic finite element framework
- **Near Field microphones** referring to the measurements data
- **Far Field microphones** on which the Sound Pressure Level (SPL) is reconstructed

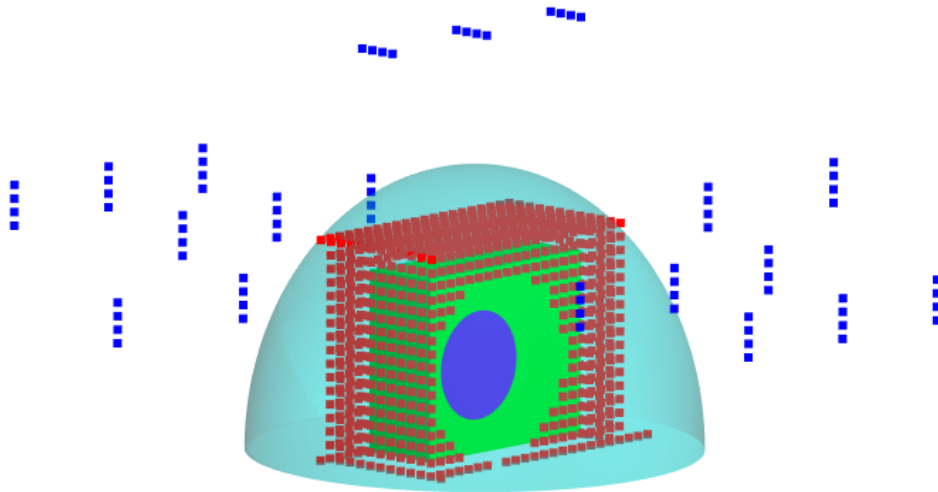


Figure 6 - Actran Model

The Actran computational procedure consists of three main steps:

1. **Extraction** of the pellicular modes: 95 Modes have been extracted
2. **Radiation** of each pellicular mode individually in order to assess the transfer function (T.F.) between each microphone and one pellicular mode
3. Based on the measurements and T.F. previously computed, compute the **participation factors** of each pellicular method using a **Least square method**.

The least square problem is solved by fitting the best the experimental results to compute the participation factors of each pellicular mode:

$$\|R\| = \|T \cdot F\|$$

Equation 2 - Least mean squared problem

with

- R (m x 1) = measured pressure re-scaled
- T (m x p) = T.F. between each micro and pellicular mode
- F (p x 1) = fitting matrix → contains **participation factors**
- m = total number of near field microphones
- p = number of pellicular modes

The usage of a least square solver is required as the system is overdetermined. Indeed the number of microphones is around 1200 while the number of participation factors to determine is 95.

Near field microphones are used to retrieve the excitation pattern while far field microphones define where SPL will be computed in later step to validate the model

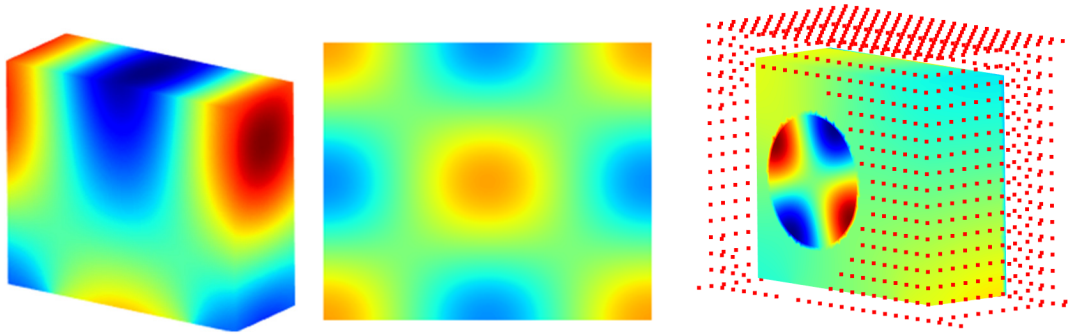


Figure 7 - Pellicular Modes Example

3.4 Simulation results

To validate the procedure, first reconstructed results at near field microphones are compared with experimental ones. Good matching is retrieved, both for tonal and broadband noise (global level). Shaky behavior between peaks is observed as expected (spatial decorrelation of measurements).

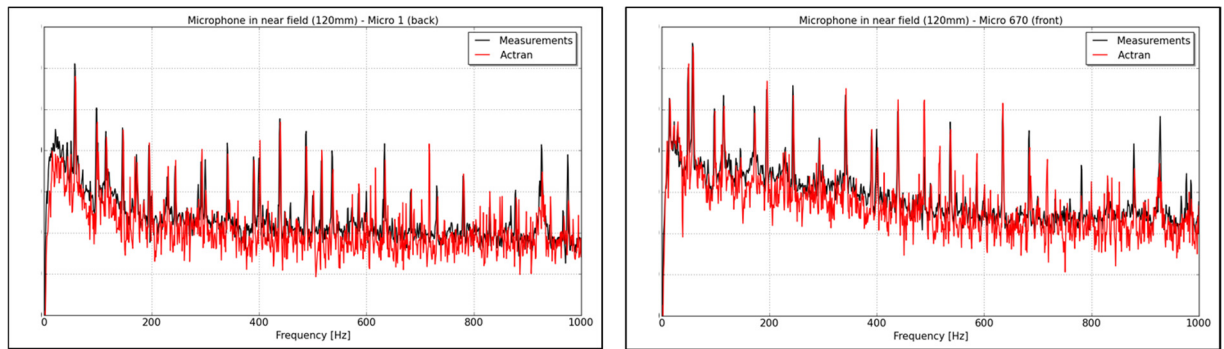


Figure 8 - Results Comparison in near field points

The method can successfully predict measured sound pressure level for near field point.

For far field microphones locations, good matching is also retrieved at back, left, top and right sides of the HVAC unit. Global trend of the curve is retrieved, and all the experimental peaks are identified. For left side narrow band, third octave band and OSPL errors equal respectively 4.69 dB, 1.48 dB and 0.04 dB. For front side these errors are 6.56 dB, 3.37 dB and 1.91 dB.

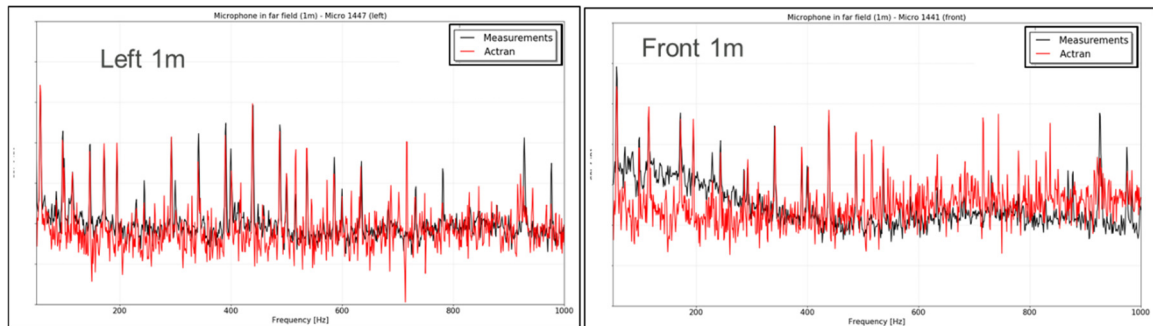


Figure 9 - Results Comparison in Far Field locations

Based on these observations, one can conclude that the numerical model can be used to investigate sound pressure level emission in the far field. To do so, directivity charts are built using pressure levels retrieved at virtual microphones polar arrays. Directivity at

different distances are then compared as well as evolution of the directivity at a fixed distance as function of the frequency (Figure 10).

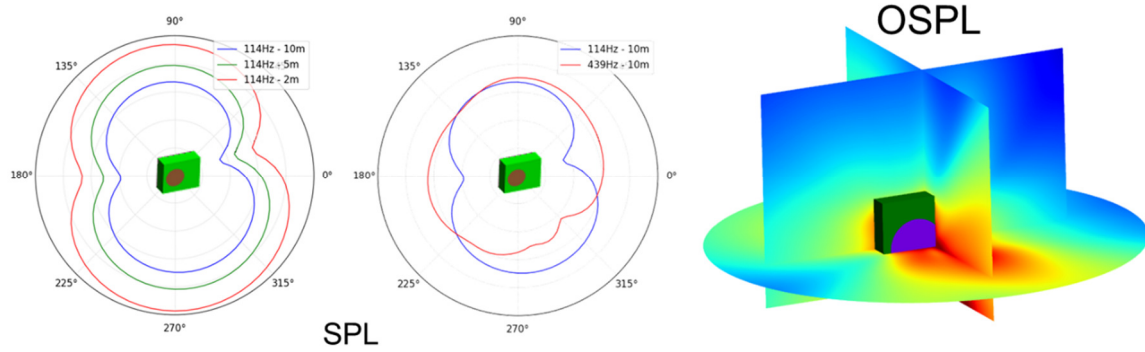


Figure 10 - Directivity Assessment

The radiation of the acoustic waves around the HVAC unit can be visualized for given frequency

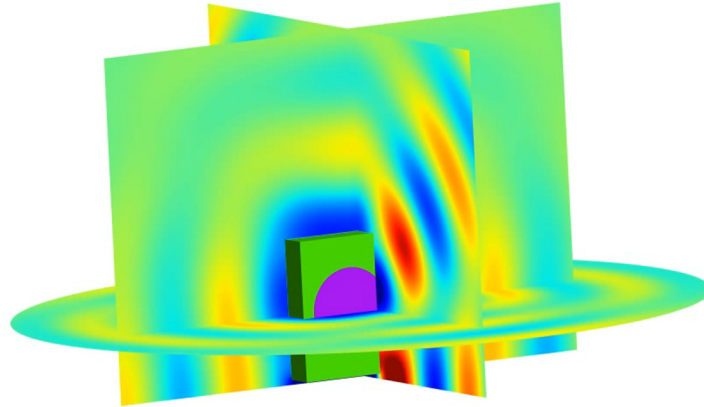


Figure 11 - Acoustic waves around the HVAC unit

4. SIMULATION PARAMETERS SENSITIVITY ANALYSIS

To assess the results sensitivity to the analysis parameters, four parametric studies were conducted. The purpose of each study and their conclusions are presented in the following sub-sections.

4.1 Tikhonov parameter (μ) for regularization

In order to avoid unrealistic high level of excitation, the idea is to minimize the error with respect to the target microphones while keeping the excitation level (normal velocity) fairly low. We would rather consider the following minimization problem:

$$\min \|\mathcal{T}_{ij} \cdot x_j - p_i\|^2 + \|\mu I \cdot x_j\|^2$$

Equation 3 - Minimization problem

The ponderation of one term with respect to the other is driven by the so-called Tikhonov parameter μ [1].

It was observed that:

- A too low value of Tikhonov parameter leads to an overestimated SPL. This means a too high participation factors and as a consequence a too high level of excitation
- A too high value of Tikhonov parameter leads to an underestimated SPL. This means minimization of the normal velocity is too important

4.2 Number of pellicular modes:

Analyses were performed with 3 sets of pellicular modes: 51 modes, 95 modes & 193 modes. It was observed that decreasing the number of pellicular modes prevent to obtain very high participation factors, especially for the later modes (the ones that are removed). This is very similar than converging to an optimized Tikhonov regularization factor. However, it must be stressed that reducing even more the number of modes will limit the complexity of the pressure field represented.

4.3 Number of (experimental) microphones

When decreasing the number of microphones, SPL in far field is less accurately represented for the higher frequency range (e.g. > 500Hz, microphone 1m back). This is due to a less detailed representation of the near field. The least square method generates higher participation factors for lower order modes which negatively impact the accuracy in far field. Using regularization allows to filter out those high participation factors and improve the final response..

4.4 Pellicular surface definition

Two discretization of the units are considered:

- Three Pellicular surfaces corresponding respectively to the fan front face area, the back grid area and the rest of the unit.
- One Pellicular surface: the unit is considered as a whole in a unique surface

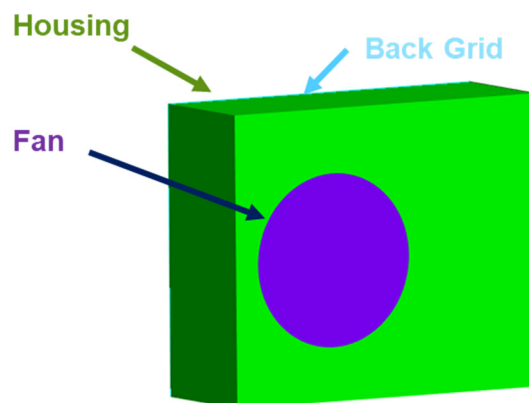


Figure 12 - Surface Discretization

When looking at the vibration pattern (normal velocity) reconstructed on the pellicular surface, there are almost identical (Figure 13, amplitudes are opposed)

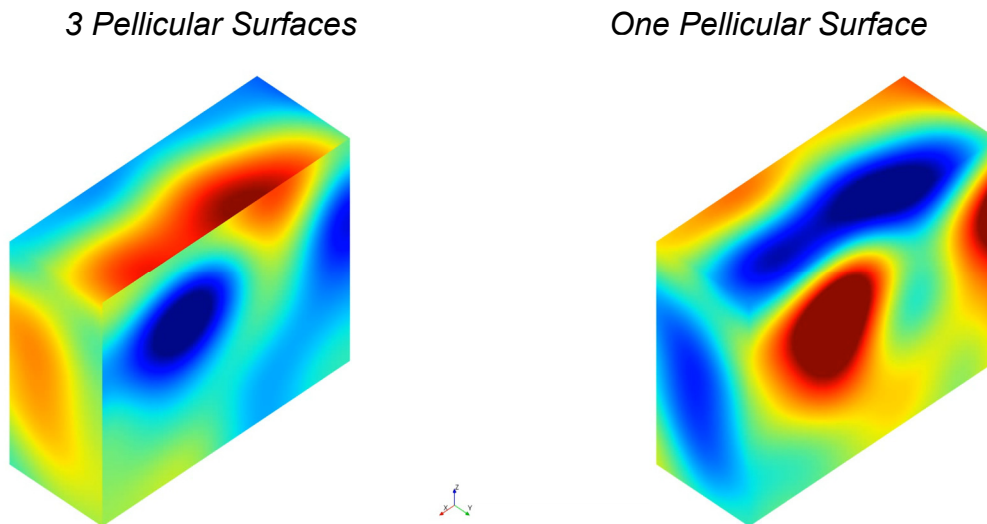


Figure 13 - Sensitivity on Pellicular Surfaces considered

5. COMPUTATIONAL RESOURCES

The computational resources of the three steps are described in the Table 1.

	Peak Memory	Time per frequency	Total time
Extraction	0.5 GB	/	28sec
Radiation*	77 GB	1min24	1day
Inverse	5.7 GB	<1sec	1hour

*20 threads, no parallelism

Table 1 - Computational Resources

The radiation step is the most expensive step. It consists in the computation of the transfer function between each pellicular mode and each microphone. The time per frequency as well as the memory consumption is directly related to the number of pellicular modes considered.

The computational time of the inverse method is driven by the access to the radiation database while the computation of the least square problem is instantaneous.

6. CONCLUSION & FURTHER WORK

The usage and accuracy of using the pellicular surface radiation technique to predict far field noise emission of HVAC unit has been demonstrated.

First the measurement setup and some observations has been presented. The finite element simulation model and the analysis procedure is then shared in detailed. Good match between far field measurements and model prediction as well as several possible results post processing charts are presented. From sensitivity studies, the usage of a

Tikhonov parameter for regularization approach help to achieve such an agreement between testing & simulation.

The following recommendations might be considered to improve the accuracy of the results and ease the near field sound pressure measurement step respectively:

- Microphone with bonnets could be used in front of the fan(s) to avoid flow noise pollution
- Bigger array of microphones (50,100) would allow to get rid of the phase shift between the different sets of measurements. This should ease the measurements procedure and improve globally the accuracy of the hybrid method

This methodology is a great benefit for EMERSON allowing the prediction of HVAC units sound emissions in far field, in all directions, without actually performing measurements. This reduces significantly the requirements for large scale testing facility.

Additionally, several noise control solutions such as absorbent wall or acoustic barrier can be tested virtually with very limited cost. Once the vibration pattern is retrieved, one can update the geometry of the surrounding environment without recalculating the transfer functions and participation factors (radiation step).

7. REFERENCES

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