Innovative design of façade elements to limit wind-induced noise in buildings

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Abstract - Wind-induced noise is often overlooked in building design. This noise can be generated by wind blowing across façade elements or through the various gaps inside buildings. Noise generated by wind-affected façade elements, particularly at higher wind speeds, has received increasing attention since the 2010s. In this paper a comprehensive literature review is carried out to draw general rules for limiting wind-induced noise in buildings. Next, an innovative design was proposed by Metravib Engineering for the Rabat Ibn Sina hospital designed by AIA Ingénierie. A dynamic analysis of these sunshades was then verified using the finite element method to ensure there was no vibro-acoustic coupling between wind excitation and the sunshade's structural modes. Finally, wind tunnel tests confirmed that the noise induced by these façade elements was under control and did not cause any particular annoyance.

1 INTRODUCTION

Figure 1: Beetham Tower, Manchester (England)

The slender structure of the skyscraper makes it one of the thinnest skyscrapers in the world. It was designed to stand out with this feature. A fin-like structure acts as an extension of the tower's south façade, accentuating its shape and serving as a lightning rod. Since its inauguration, the tower has been known to emit a very distinctive whistling / buzzing / humming sound (referred to as "hum" in English) at certain wind intensity ranges. This whistling has been reported to be audible up to at least 300 meters around the tower. Efforts to reduce or eradicate the noise started in 2007 with foam pads installed on the edges of the fins and other undisclosed and have been completed by February 2010. Permanent eradication attempts of the noise have been unsuccessful. The tower, particularly the design of the lightning rods, produces this impressive noise under specific wind conditions.

Ploemen et al. take two large buildings in La Hague, the Netherlands, as an example, which have become notorious for the noise generated at wind speeds of approximately 12 to 15 m/s [1]. They conclude that the steel grilles on their façades are the source of the noise. The addition of a metal mesh behind the steel grilles significantly reduced the noise without completely eliminating it. Tonal noises were still present but for higher wind conditions (> 25 m/s).

Another notable example is the noise generated by the pedestrian guardrails installed along the Eastlink Expressway in Melbourne, Australia. They are installed at six locations along the route [2]. Noise levels up to 40 dB above the background (or ambient) noise level were reported in neighbouring residential properties for particular wind conditions. Each guardrail fin is 2 m long, 125 mm wide and 6 mm thick. Typical tonal noises are reported at frequencies of 900 Hz and its harmonics of 1800 Hz and 2700 Hz. The sound event is most predominant for wind angles between 25º and 30º to the railings and for wind speeds of 6 to 7 m/s with gusts up to 10 m/s. According to Mitchell et al., the source of aerodynamic noise causing this acoustic response is associated with vortex detachment. The frequency of this noise is strongly determined by the Strouhal number, which is generally of the order of 0.2 for this type of structure. Various improvement solutions have been proposed and tested. They made it possible to reduce the tonal noise considerably. It is interesting to note that the authors conclude that the vortex detachment frequency is independent of the incident wind speed and that it is not this that predominates in the origin of the aeroacoustic phenomenon.

In his thesis, Gianoli Kovar presents another case study, that of the Hampton by Hilton hotel in Montevideo (Figure 2) [3]. This building has glass sunshades with separations varying between 7 and 25 cm, which under certain wind conditions cause acoustic disturbance (vibrations and aero-acoustic noise). In addition to the sunshades, the metal grilles on the raised access floor also cause tonal noise. It is also reported that some of the structure's tubes are unplugged and cause tonal noise (tube resonator effect).

Figure 2: Hampton by Hilton in Montevideo and technical floor (Uruguay)

Various studies and noise treatment operations were carried out. It was finally proposed to remove the sunshades and replace them with vortex-generating devices to control the flow over the façade element. Numerous acoustic measurements on one floor in particular were carried out following the installation of these mitigation solutions and confirmed that noise levels during windy periods (several wind directions studied) were significantly reduced. In the 2 years since this proposal was implemented, no criticisms have been reported.

In France, several examples of architecture also have poorly designed façade elements. The most obvious example is the Panoramik building in Rennes (Figure 3). Whistling with very high noise levels has been observed since its delivery in 2018. It is reported that the whistling is caused by the wind blowing under the perforated sheets. Depending on the direction and intensity of the wind, the noise differs in level but the perception is similar.

Work is underway to add plates to the back of the current perforated sheets, but at the time of writing this paper the improvements are still unknown.

Figure 3. Panoramik building in Rennes (France)

2 WIND-INDUCED NOISE IN BUILDINGS

2.1. Noise families and typology

According to Chanaud, one of the pioneers in discussions about aerodynamically generated noise, these noises can be divided into three classes based on the feedback mechanisms occurring as described in Figure 4 [4]. If the feedback mainly consists of aerodynamic oscillations, they are defined as Class I sounds or aerodynamic sounds. These sounds are rather broadband, akin to white noise. If the feedback from the instability region occurs directly through emitted waves, they are classified as Class II sounds and are called whistling sounds. These sounds tend to be more tonal in nature. Class III sounds are distinguished by feedback obtained from reflected sound waves, meaning they return to the instability region from one or more structures located on the periphery of the vortex creation region (aerodynamic oscillations). These sounds also exhibit pronounced tonal characteristics.

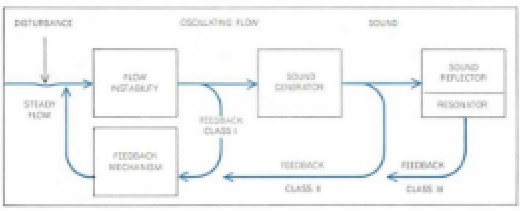

Figure 4: Aerodynamic noise classes [4]

Mitchell et al. [2] summarize in Figure 5 the feedback loop responsible for tonal noises when vortex noise is coupled with cavity resonances. This is the case, for example, with noises generated by pedestrian guardrails installed along the Eastlink Expressway in Melbourne. In this scenario, the cavity is open and corresponds to the depth of each fin/blade of the guardrail. The diagram proposed by Mitchell et al. is very similar to that proposed by Chanaud for Class III tonalities. The phenomenon of aerodynamically generated noises is expected only at low Reynolds numbers and under conditions where the flow of the boundary layer is coupled with the acoustic resonances of possible cavities. With an increase in flow velocity, Mitchell et al. assert that the flow becomes turbulent. The direct consequence is that the feedback is halted, and cavity resonances can be significantly reduced. This assertion is supported by measurements made by the authors.

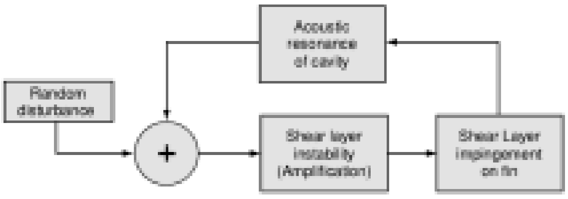

Figure 5: Diagram of the feedback mechanism for noise generation [2]

The aero-acoustic tonal noise, or vortex noise, originates from flows over structures creating alternate vortex shedding, which produces a characteristic tonal sound known as "Karman tone", typically associated with a whistling. These turbulences generate vortices downstream of the structures, resulting in harmonic disturbances in the pressure field and alternate lateral forces on them. The alternate lateral forces can further vibrate the structure, leading to a coupled effect between the fluid's acoustic response linked to the vortices and the mechanical response of the structure.

For a circular cylinder, this frequency can be obtained using the following Strouhal relation:

$$f_{Karman} = S_t \frac{u}{d} \tag{1}$$

where u is the velocity of the flow striking the cylinder in m/s and d is the diameter of the cylinder in meters. For Reynolds numbers (Re) ranging from 2.102to 2.105, the Strouhal number (St) remains relatively constant. For laminar flow, it can be approximated by the value of 0.2 [5]. The Strouhal number is a dimensionless number describing the mechanisms of oscillating circulation. This frequency can be directly associated with the periodicity of the oscillations. The Karman tone is not a pure tonal noise but a narrowband noise with a bandwidth of at least 1/3 octave. The bandwidth of the Karman tone increases with Reynolds number and approaching flow turbulence. By analysing the Strouhal relation, if there is an increase in the velocity of the incident flow, the frequency of vortex shedding increases. Therefore, this frequency may not coincide with the resonance frequency of the cavities present, which helps to avoid a coupling phenomenon of sorts.

In addition to the periodic shedding of vortices, the alternation of forces on obstacles (which can be likened to sound emission with a dipolar character) also amplifies when the flow is not completely laminar. Consequently, this results in small changes in flow resistance (force parallel to the flow direction) and buoyancy (force perpendicular to the flow direction). Finally, a quadrupolar sound excitation mechanism can be mentioned, which can be explained by the free turbulence occurring behind a façade. The air flow velocity, as well as the size and shape of the object, directly determine the frequency of oscillations. If the oscillation frequency matches the natural resonance frequency of a façade element, or if the wavelength of the vortex shedding frequency is in a similar proportion to the spacing of repetitive façade elements (e.g., sunshades), significant resonances can occur. These large resonances are the cause of high noise levels. It is therefore crucial to disrupt the periodic arrangement of these façade elements to avoid a cumulative phenomenon.

Fricke [6] asserts that the Australian Wind Code does not provide a clear method for determining wind speed on façade elements. Although velocity profiles on façades can be estimated using methods such as Eurocode 1 [7], these velocity profiles cannot always be correlated with the actual wind speed on each façade element.

However, determining these speeds is crucial for identifying potential aero acoustic tonal noises. Various tests and analyses have shown a significant increase in speeds for tall buildings, above the reference speed, due to flow distortion around the structure. Depending on the building, environment, and façade elements present, it may be overly conservative to assume high speeds in some cases. Speeds on a façade with numerous sunshades, balconies, or other elements may be relatively low due to the formation of a boundary layer generated by the elements themselves. One of the author's objectives was to study how the velocity field presents itself on a building façade, especially if it includes accessories such as sunshades. Unfortunately, no method is clearly proposed.

Moloney et al. provide a general discussion on testing and evaluating noise associated with wind building interaction [8]. The authors give a brief description of the types of noise generated by the wind. Based on the analysis of different phenomena, they propose a possible approach to these issues. According to them, most noise problems caused by wind-structure interaction are due to fluctuations in pressure or velocity fields. Such fluctuations can produce audible resonance in structural components or generate audible waves.

Based on these elements, it is possible to group certain noise generation mechanisms into families:

• **Aero-acoustic tonal noise (Karman tone):** This noise occurs when a vortex is generated, such as when airflow passes through a cable or an aerodynamic profile. It is generally high frequency and characterized by peaks in the spectral decomposition of the signal, with well defined and distinct frequencies. This type of noise is particularly bothersome for humans.

• **Resonator-type effects noise (tube or Helmholtz):** Generated when the volume of air in a cavity periodically increases or decreases. This is the case, for example, with an open tube where resulting pressure fluctuations give rise to audible sound, similar to musical instruments like the pan flute.

• **Structural vibration-related noise:** Originates from movement and friction between different components of a structure generated by wind passage.

• **Shear layer-related noise:** Generated by friction between air flow boundaries and/or increasing velocity. This occurs when wind passes through narrow spaces or gaps, which can produce sounds very similar to whistling, like aero-acoustic tonal noise.

• **Broadband aerodynamic noise:** This type of noise is always present during wind-structure interaction. It is generally generated by fluid flow over the structure without distinct vortex generation. Its broadband nature, with a very wide frequency content, means that discomfort associated with it is less than with tonal noise as long as the levels are not too high compared to background noise levels in the absence of wind.

2.2. Guidelines for the design of façade elements

Currently, no comprehensive study methodology has been fully developed to address these phenomena, and the limited existing knowledge is not always applied in practice. However, in recent years, some authors have sparked interest in attempting to explain the phenomenon and to define at least some general guidelines regarding the effects of wind on structures.

Moloney et al. propose various approaches for identifying and addressing the problem depending on the cases studied [8]. They recommend paying attention to possible sources of noise in a building, such as narrow spaces between façade elements and the building, panels with holes, and panels with sharp profiles, among others. The authors suggest studying façade elements using two or more testing methods to ensure critical noise phenomena are not overlooked. Once these methods are applied, the noise generation mechanism can be identified. The use of a multi-physics model combining CFD simulations with an acoustic model could help predict sound intensity inside and outside buildings. However, these methods should be implemented at a minimum after applying simple design rules.

The work of Coppa and Paduano [9] has resulted in establishing various charts based on different laboratory tests for façade elements such as fins (rectangular sunshades). For the most common wind speeds and Reynolds numbers ($10^3$to 10^5), these results indicate that the transverse dimensions of the elements should be greater than 100 mm. It is interesting to note that for transverse dimensions greater than 100 mm, the frequency range corresponds to frequencies lower than 50 Hz for wind speeds up to 25 m/s. This frequency range causes less discomfort to humans because the human ear is less sensitive to these frequencies.

For perforated plates, the experimental measurements conducted by Blinet et al. [10] along with numerical simulations carried out by Vanoostveen [11] allow for drawing general conclusions.

There are general guidelines that can be followed to minimize the risk of vortex shedding problems in the design of new buildings. In order to assess the likelihood of wind-generated noise, the guidelines in the following Table 1 can be used, although these values are not fully confirmed and validated by the entire community of building acousticians. It is primarily a summary of the results of research, laboratory tests, and feedback from previous projects found in the literature.

2.3. Perforated panels guidelines

From previous work, it can be concluded that regardless of geometric dimensions, vortex noise will always be present for specific ranges of wind angles of incidence and velocities. Furthermore, it is often reported that as wind speed increases, the tonal height also increases (resulting in an increase in the frequency of the heard sound). These parameters (wind speed and direction) are elements that cannot be controlled and are often erratic on a building, especially if it is composed of numerous façade elements. However, it is observed that the geometric parameters of plates or panels can be carefully selected to avoid wind-induced noise problems:

- The hole diameter can be selected based on the range of wind speeds to which the panels are expected to be exposed. One approach is to select a rather small hole diameter so that the maximum expected wind speed is not high enough to produce marked tones. However, such panels will necessarily produce broadband noise and may produce tonal noise for low wind speeds and specific angles of incidence. A second approach is to select a larger hole diameter so that tones are produced at low wind speeds, but the amplitude of these tones is sufficiently low not to be bothersome. The second approach should be prioritized in the majority of cases.
- The angle of incidence is important for the tonal or broadband character of the noise. However, it cannot be controlled.
- Small diameter perforations tend to increase tonal noise levels. The frequency decreases as the diameter of the perforations increases.
- Holes with a diameter less than 50 mm should be avoided if possible.
- Phenomena evolve towards high frequencies as the plate thickness decreases and as wind speed increases.
- The larger the ratio D/t between hole diameter D and panel thickness t, the more tonal noises occur at smaller angles of incidence and over a narrower range of angles. On a building, this will result in whistles occurring less frequently.
- The amplitude of tonal noises increases as the panel interacts with the wind. If the wind flow can be interrupted at a particular point along the length of the panel, it may be possible to limit the amplitude of this noise.
- Regularity in panel perforations should be avoided. Different hole diameters in the same panel should be prioritized, especially if it is installed periodically on the façade. · The influence of perforation rate is

not a predominant parameter. The relationship between hole spacing, diameter, and panel thickness is more important.

- Specific work on hole finishing at the outlet of the flow can significantly reduce tonal noise. · Sequencing for hole diameters following a pseudo-random sequence could be used to break up the periodicity in the structure. This technique is also used to create sound diffusion on diffuser panels in the field of room acoustics.

Table 1: Guidelines to limit noise associated with façade elements

Element / opening	Recommended dimensions	Typical Rules
Slots, openings, and exposed unsealed elements in the façade.	> 100 mm	For exposed elements, the implementation of anti-vibration treatments is necessary. For cavities and openings, it is recommended to close all openings and entrances to avoid the creation of resonating cavities. The frequencies of resonating cavities can be easily calculated.
Wires, circular cables, square or round tubular elements, hollow profiles.	> 50 mm	If a dimension larger than 50 mm cannot be accommodated, a special treatment (such as adding a deflector, damping material, flexible fabric or latex elements) needs to be provided at the trailing edge to prevent the creation of vortices. If possible, modify the design to have an airfoil-type profile or a thick laminar profile, or introduce a non-planar surface (e.g., golf ball dimples).
Periodic elements (arrays)	> 100 mm	In the case of a regular array of elements, it is important to avoid smaller dimensions for the openings. If not possible, special treatment should be provided (such as adding a deflector, for example) or minimize periodicity by varying the distances and/or characteristic sizes between the periodically installed elements as much as possible.
Grilles or perforated plates	Depends on the ratio of hole diameter *D* to panel thickness *t*.	Ideally, it is best to avoid such perforated panels and to block the holes as much as possible, for example, with acrylic sheet panels. Minimize the *D/t* ratio. Prioritize holes with diameters larger than 50 mm. On the same panel, use multiple hole diameters to limit periodicity in the structure. Pseudo-random sequencing should be considered. Introduce deflectors to break up the vortices. Limit flat surfaces and provide texture to the panel.
Any type of construction element	> 100 mm	Irregular constructions should be prioritized to disrupt vortex formations.

Experimental work conducted by Feng [12] demonstrates the possibility of converging towards a semi-empirical formulation derived from the Strouhal relationship, which relates the frequency of tonal noise to the diameter of perforations and the thickness of a panel. This formulation has been experimentally verified in the studies by Blinet et al. [10] and is given by:

$$f_{Karman\_PerforatedPannel} = 0.01 * S_t \frac{u}{\text{Ø}t} \quad (2)$$

where *u* is the velocity of the airflow striking the cylinder in m/s, Ø is the diameter of the perforations, and *t* is the thickness of the panel.

3 INNOVATIVE DESIGN TO LIMIT WIND-INDUCED NOISE

The future Rabat Ibn Sina hospital in Marroco will have a height exceeding 150 meters and will be located near a seaside (Figure 6). For this project, it has been chosen to use sunshades to limit the energy consumption.

Figure 6: Rabat Ibn Sina hospital project (Marroco) – Visual: AWM Architectes Urbanistes © All rights reserved

The wind study conducted for this project by AIA Ingéniérie considers a reference wind speed of 27 m/s, but with velocities that can vary. At the maximum height of the building, this speed may reach over 45 m/s. The installation of sunshade elements will always have an impact on noise levels due to the interaction between the wind and this structure. It is difficult to assess this impact, but it is possible to minimize this effect by applying the sizing rules from Table 1. Previous studies suggest that regardless of geometric dimensions, vortex noise will always be present for specific ranges of incidence angles and wind speeds. This is especially true for perforated panels. With a judicious choice of the structure's geometry, it is possible to minimize its effect so that it is barely audible or non-audible.

For this project, it has been decided not to carry out a comprehensive CFD numerical study, but to validate the design through structural numerical analysis (to avoid fluid-structure coupling phenomena) and then to validate the design with wind tunnel tests.

Experience in room acoustics has shown that pseudo-random sequencing provides a good compromise between sound diffusion and absorption. This type of sequencing prevents a favored frequency range in sound diffusion and avoids periodicity in the behavior of acoustic waves in rooms. Although we are dealing with an aero-acoustic effect here (tonal noise from vortices), the same logic can be applied, and a pseudo-random sequence using a Schroeder-like sequence could be employed [13]. A sequence with 7 different sizes has been chosen. This type of sequence would help prevent the emergence of a predominant frequency (and its harmonics). Additionally, a deflector element could be installed on the air outlet side to disrupt vortex formation. These deflectors would also provide the necessary rounding on the outlet edge of the panel.

From equation (2) and taking a Strouhal number of 0.2 (sufficiently representative), it is possible to calculate the frequencies of aero-acoustic tonal noise based on the panel thickness and the diameter of the perforations (Figure 7). For the sunshades of the Rabat Hospital, the chosen aluminum panel has a thickness of 4 mm. Although it is below the frequency band that would be preferable to avoid (200 to 10,000 Hz considering the sensitivity of the human ear), we can choose a minimal diameter for the perforations of 50 mm to limit the aero-acoustic tonal noises. With these perforations, the frequencies vary between 50 and 250 Hz within the range of wind speeds to which the panels will be exposed. For the larger diameter, a diameter of 150 mm can be chosen to have frequencies of tonal noise higher than 50 Hz, and to limit the risk of mechanical coupling between the dynamic response of the panels and the excitation due to wind/structure interaction for wind speed higher than 15 m/s. Aerodynamic oscillations (vortex) can occur for low wind speeds and frequencies ranging between 20 and 50 Hz.

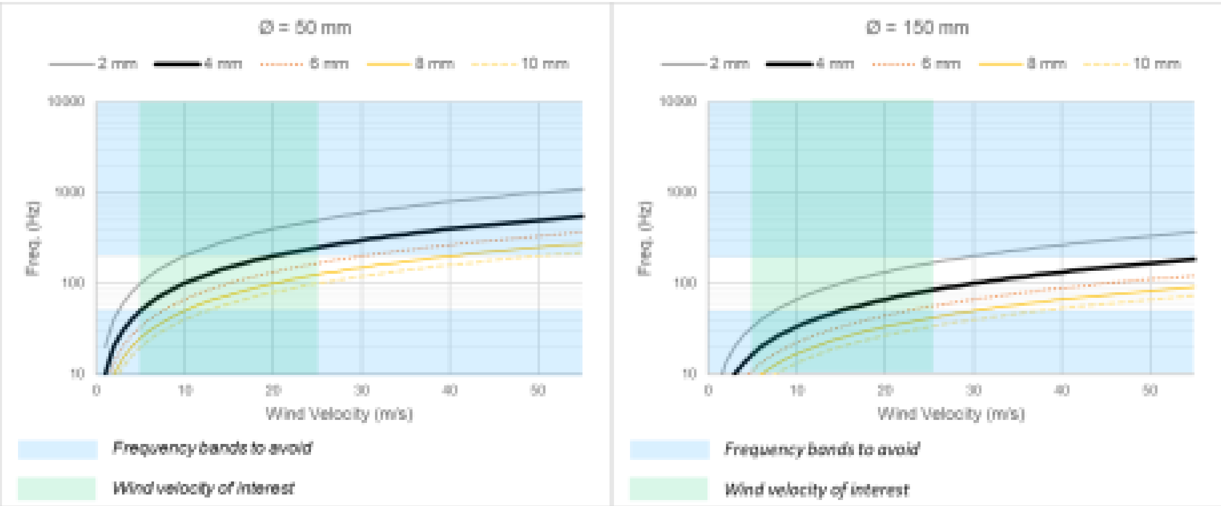

Figure 7: Frequencies of aero-acoustic tonal noise according to the wind speed and panel thickness for the largest and the smallest diameter of the sequence

The following Figure 8 show the final design for the sunshades according to the previous recommendations and a detail of the mesh for its numerical validation using the finite element method.

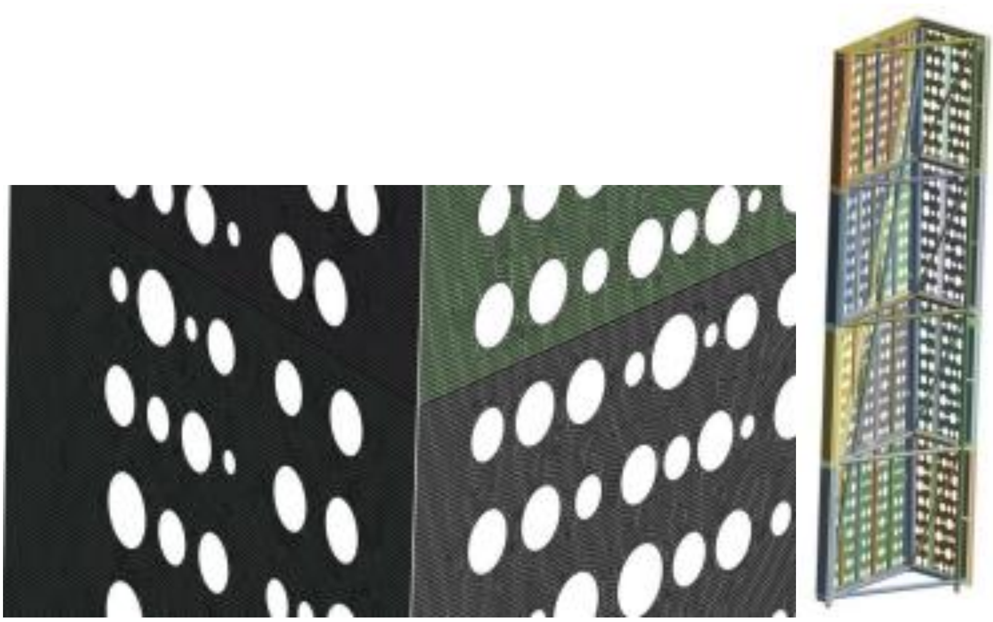

Figure 8: Sunshades design and detail on mesh for numerical validation

Different pseudo-random sequences have been studied and analyzed. Given the size of a panel (1.7 x 2 m) and the acceptable diameters of the holes, only a sequence of 7 sizes of perforations appears feasible considering the width of the panel. This allows for a panel perforation rate of 34%, which complies with the brightness constraints imposed by the project.

4 DESIGN VALIDATION OF THE SUNSHADES FOR THE RABAT HOSPITAL

For the numerical model, a damping ratio of 0.1% have been considered for the panel in aluminum. A unit normal force was applied to the surface of the largest perforated plates. The first modal frequencies of the panels are higher than 15 Hz and the mode density is high enough for frequencies higher than 50 Hz (> 10 modes for each 5 Hz step above 50 Hz). This allow a validation of the design to limit the risk of mechanical coupling between the dynamic response of the panels and the excitation due to wind/structure interaction. Furthermore, the absence of modes below 15 Hz is a favorable condition. Few vibrational levels could be transmitted to the hospital and coupled with dynamic responses of the building.

Following this validation, wind tunnel tests are being conducted on a scale prototype of the panels (Figure 9).

Figure 9: Scale prototype panel in wind tunnel (Cnam, Institut Aérotechnique)

4 different wind directions are tested from 0 to 25 m/s. Sounds and vibrations are recorded at different positions as presented in Figure 10.

Figure 10: Wind direction for the tests and sensors positions

The scale prototype are still under evaluation and the data are being analysis. They are showing promising results of the design.

CONCLUSIONS

As part of this work, a literature review was conducted to define design rules to limit the noise generated by the interaction between wind and the structures of façade elements. These rules were implemented in an innovative design utilizing a Schroeder-like sequence for the hole diameters of a perforated panel utilized as a sunshade for the Rabat Ibn Sina hospital in Morocco.

Before the panels are finally installed, various validations are still being evaluated, ranging from a scale prototype to a comprehensive Computational Fluid Dynamics (CFD) model including all the sunshades. The initial findings of the proposed design are promising, although the acoustic performance of the entire structure is yet to be confirmed

ACKNOWLEDGEMENTS

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