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## A classification of aeroacoustic phenomena on building façades

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### ABSTRACT

*Wind-induced noise on building façades can be a source of domestic nuisances that is hard to investigate without recurring to costly methods like wind tunnel experiments or transient, compressible numerical simulations. Indeed, on a building façade, several different aeroacoustic phenomena can occur such as aeolian tones (e.g. from balustrades, gratings, etc), cavity noise (e.g. from openings) or wind-triggered acoustic resonances. Here, from a bibliography revision and a conceptual analysis, a list of aeroacoustic mechanisms on façades is given as a double-entry classification. On the one hand, it considers the way the noise is triggered (excitation), such as Von Kármán vortex shedding in the case of the aeolian tone. On the other hand, it considers how they could be amplified (amplifiers) by acoustic or structural resonators for instance. Some examples from existing buildings are also commented. The strategy of identification, prediction and control of wind-induced noise phenomena from façade elements shall depend on the location of the mechanism in the classification. A first example of methodology is elaborated.*

### 1. INTRODUCTION

Multiple aeroacoustic phenomena can occur on a building and can be a source of nuisance. This diversity does not allow a simple prior identification of potential risks, nor a single method for predicting the characteristics of the noise: spectral content and sound pressure levels (SPL). Indeed, many low-Mach number aeroacoustic phenomena such as aeolian tone, cavity noise or even aerodynamic noise can occur on a façade. These phenomena can be disturbing and create an unhealthy environment for the inhabitant of a building.

Nowadays, façades often recreate the perfect environment for these phenomena to settle. Elements such as double-skins, decorative structures or sun-shades can trigger aeroacoustic nuisance. From a conceptual analysis of the bibliography, it has been shown that each one of them is defined by two elements: the mechanisms responsible for exciting the noise and those that can amplify it. From this, a classification can be built as a first step to better understand and predict these phenomena. The

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classification is represented as a double-entry table considering these two characteristics in order to class every phenomenon that is archived in scientific literature.

In this paper, the possible excitations and amplifying mechanisms are first detailed, leading secondly to the classification. To illustrate how such a classification is used, an example is given as a case study with the purpose of predicting and preventing aeroacoustic nuisance to occur.

## 2. EXCITATION: FLOW AS A SOURCE OF SOUND

Deriving a D'Alembert equation from the non-linearised Navier-Stokes equations exhibits how the flow can act as a source of sound [1]:

$$\left(\frac{\partial^2}{\partial t^2} - c_0^2 \Delta\right) \rho = \frac{\partial^2 T_{ij}}{\partial x_i \partial x_j}, \quad (1)$$

with  $c_0$  the sound velocity and  $\rho$  the acoustic density. This equation is known as Lighthill's equation and is a wave equation with a source term including Lighthill's tensor  $T_{ij} \approx \rho_0 v_i v_j$  where  $\rho_0$  is the steady density of the fluid and  $v_\ell$  the  $\ell$ -th component of the velocity vector  $\vec{v}$ . As the source term includes parameters of the flow, it tells that it acts as a source of sound.

Then, Powell [2] and later Howe [3], in the attempt of showing how the vorticity within a flow is responsible for flow-induced noise, developed the Theory of Vortex Sound. In a similar manner as Lighthill's, they derived a D'Alembert equation but using the total enthalpy  $B$  as the propagating parameter, leading to a source term including the vorticity:

$$\left(\frac{\partial^2}{\partial t^2} - c_0^2 \Delta\right) B = \text{div}(\vec{\omega} \wedge \vec{v}), \quad (2)$$

where  $\vec{\omega}$  is the vorticity field and  $\vec{\omega} \wedge \vec{v}$  is called Lamb vector.

### 2.1. Unsteadiness in flows

The theory of vortex sound shows that aerodynamic sound is either produced or dissipated by either moving vortices, production of vortices or dissipation of vortices. However, these phenomena can occur in many different ways leading to tonal or broadband noise. In the frame of façades' whistling, some of the main different aeroacoustic phenomena are listed hereafter:

- Aeolian tone: is the noise produced by the periodic flapping of the shear layers in the wake of a bluff body (cylinder of whatever cross-section shape) immersed in a cross flow. The frequency of such a flapping is determined by the Strouhal number [4]:

$$\text{St} = \frac{fD}{U}, \quad (3)$$

where  $\text{St}$  is the Strouhal number (a non-dimensional number constant for a certain cross section's shape and flow regime),  $f$  is the frequency of the flapping,  $D$  the transverse dimension of the body and  $U$  the flow velocity. This periodic flapping is an instability known as the Von Kármán vortex street [5] as counter-rotative vortices are periodically shed from the obstacle.

- Turbulence noise: façade elements are obstacle that can cause turbulence: a chaotic movement of fluid particles triggered by shear in the flow leading to the production of vortices. These vortices then cascade into smaller and smaller vortices. Indeed, a shear flow can be unstable and produce vortices: this instability is known as the Kelvin-Helmholtz instability [6, 7]. This cascade of turbulence is responsible for broadband noise, as the eddies do not feature any periodic pattern.

- Cavity noise: a grazing flow past a cavity is often unstable. Indeed, the fluid inside the cavity has practically zero mean velocity, unlike the grazing flow, thus producing strong shear prone to Kelvin-Helmholtz instabilities. Vortices are then shed from the leading edge and the geometrical disposition of the cavity can set up a feedback loop or a resonance driving the frequency of the shedding of vortices (this will be further elaborated in Section 3). When such a feedback loop or resonance exists, the cavity noise is tonal.
- Edge tone: when a jet impinges on an edge, it becomes unstable as the jet can either pass below or above the edge. This instability leads to creation of vorticity downstream of the edge. Coupled with a resonator (further elaborated in Section 3), the frequency of the instability can be fixed, thus producing a tonal noise. For instance, it is the excitation mechanism for the tones produced by recorder flutes.

## 2.2. Façade elements as flow instabilities generators

What is shown here is that every aeroacoustic phenomenon occurring on a building façade comes from an instability in the flow: either a Von Kármán vortex street, a Kelvin-Helmholtz instability or a jet-edge instability. This is important to know in order to predict what aeroacoustic phenomenon could occur depending on the geometrical disposition of a façade. In order to elaborate on this statement, examples of façade's elements and flow instabilities caused by such dispositions are given, as reported in literature:

- No specific element: in that case, the roughness of the façade is enough to produce turbulence through Kelvin-Helmholtz instabilities. A broadband noise is emitted which SPL varies proportionally to  $U^8$  [1] where  $U$  is the mean flow velocity. If an obstacle is in the near-field of the source of noise, then the scattering of this sound by the obstacle makes the SPL vary following a  $U^6$  law [8].
- Obstacle immersed in a freestream: if the body's span is long, a Von Kármán type instability can be triggered producing an aeolian tone which SPL varies following a  $U^6$  law [8, 9] and which frequency can be determined by Equation 3. If the span is not long enough to trigger a vortex shedding, the turbulence in the wake of the body will produce a broadband noise following a  $U^6$  law [8]. Studies about aeroacoustic noise from this kind of obstacles on building façades were conducted for balusters [10, 11], blade-shaped façade elements like sun shades or louvres [12–14] or gratings [13, 15, 16].
- Cavities: small holes in the wall, open windows or junctions are cavities that are prone to cavity noise which is tonal and depends on the geometry of the cavity and the flow regime (see Section 3). A law for SPL determination is difficult to propose and the frequencies of the tone depend on the kind of the amplifying mechanisms involved. No studies tackling sound produced by cavities on building façades were reported but some were conducted for similar noise with open windows [17], grazing flow past gratings that acts like open-ended cavities [15] or arrays of blades with a grazing flow [16, 18].
- Ill-laid out plate: in that case, a jet-edge instability can take place leading to a tonal noise if the excitation is coupled with an amplifier (see Section 3). This is the rarest phenomenon that can happen on a building façade as no studies were reported.
- Perforated plates: flows through perforated plates result in unstable jets downstream of the plate (the shear between the jet and the resting fluid triggers a Kelvin-Helmholtz instability) that produce broadband noise if there is no feedback loop [19]. When the flow is grazing, a tonal noise can sometimes be heard as it is the case for the *Panoramik* tower in Rennes (France) which features such elements. A study on this kind of configuration [12] showed that

this phenomenon is complicated and depends on many parameters. The physical mechanisms behind this aeroacoustic phenomenon are not yet perfectly understood, thus it is not possible to find which exact instability excites such noise. However, it is intuitive to say that the holes might act as cavities, then a Kelvin-Helmholtz instability could trigger the noise and a coupling with the "array-effect" of the perforation could drive the instability to a preferred frequency.

### 3. AMPLIFIERS OF FLOW-GENERATED SOUND

The previous part educed the mechanisms that trigger aerodynamic noise on façades: Von Kármán wake instability, Kelvin-Helmholtz shear layers instability or jet-edge instabilities. However, for each excitation, many other phenomena are possible which cannot lead to an efficient classification of these. Indeed, as the sound is excited, it may interact with many different other systems and sometimes, a feedback loop is able to settle between the exciting mechanism and the system involved. The sound is thus amplified at a given frequency or not. These systems that interacts with flow-generated sound are here called "amplifiers".

On a building façade, the different systems with which an exciting mechanism can interact are either structural (vibrations), acoustic resonators or feedbacks between the fluid dynamics and the acoustics.

In order to give a clearer view of the interactions between these different systems, the block diagram proposed on Figure 1 is commented in the following subsections.

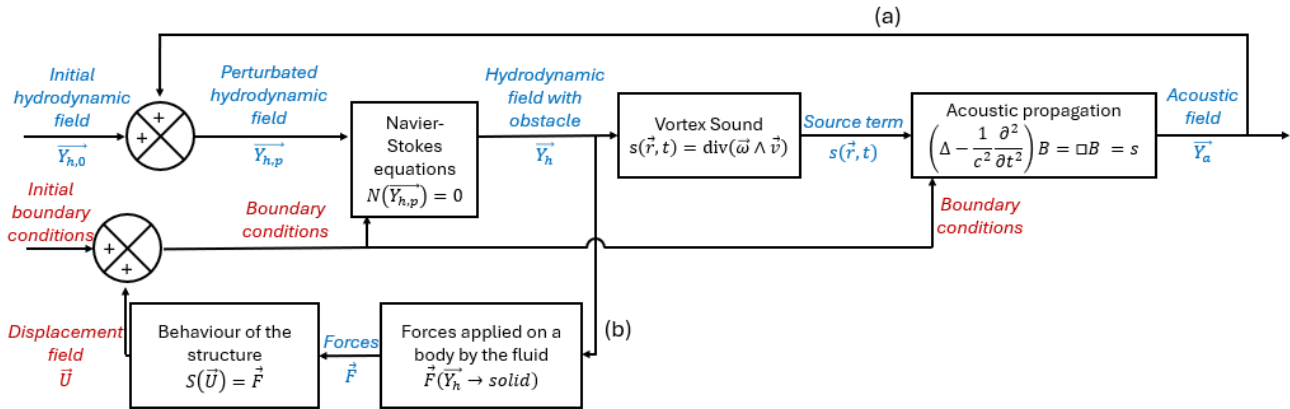


Figure 1: Diagram of the feedback loops between the acoustic and the hydrodynamic field that may occur in the frame of façade aerodynamic noise.

#### 3.1. Without amplification

In the case where it is not possible for the excitation to interact with any amplifying mechanism, the feedback loops represented by the branch (a) and (b) are inactive. The block diagram on Figure 1 works as follows:

1. An initial hydrodynamic field, containing the information of the mean flow, without any obstacle, is not perturbed by any feedback that could have come from branch (a). Along with boundary conditions, this field is necessary to solve the Navier-Stokes equations, giving a flow past a façade element.
2. Depending on the initial field and the boundary conditions, the flow is either steady or unsteady (either turbulent and/or unstable). The latter only allows the flow to produce noise. Using the theory of vortex sound from this hydrodynamic field, an acoustic source term is given that includes vorticity of the flow.

3. Finally, the D'Alembert equation derived from the theory of vortex sound gives the acoustic field. A sound is emitted.

But in the case of no possible amplification, the acoustic field is too weak to perturb the dynamics of the fluid through branch (a) as the flow is at low-Mach numbers. Therefore, since no structure vibrates the boundary conditions cannot be perturbed either through branch (b). In such a case, the only possible aeroacoustic phenomena are:

- The noise of turbulence, that does not need any obstacle to be generated, just a turbulent flow. In the case of no obstacle, Lighthill [1, 20] and Proudman [21] give a study of the expected noise from turbulence. And in the case where an obstacle is present near the acoustic source, Curle's analogy [8] predicts the resulting noise.
- An aeolian tone, when the flow passes around a cylinder or a long bluff body, the flow is unstable and oscillates at a periodic frequency given by the Strouhal number (see Equation 3) of the body and the flow regime. This emits a tone that exists without vibration of the cylinder [9].

For this case without amplification, the sound's frequency does not depend on the Mach number  $M = U/c_0$ , where  $U$  is the mean flow velocity and  $c_0$  the sound velocity. The SPL radiation does not depend on the Reynolds number  $Re = UD/\nu$ , where  $D$  is a characteristic length of the obstacle and  $\nu$  the kinematic viscosity, but scales with the Mach number [1, 9].

### 3.2. Resonance of the structure

If the flow applies forces on a flexible structure through pressure fluctuations and/or viscous stresses, the structure vibrates as a response. This is described by the equations of the structure dynamics noted  $S$  in Figure 1.

In the case where an unsteady load from the flow is applied to the obstacle, the branch (b) of Figure 1 is activated:

1. The unsteady flow given by the Navier-Stokes equations exert forces on the body. These forces are due to pressure gradients and viscous stresses.
2. These forces give boundary conditions to the structure dynamics equations and solving them returns the vibrating behaviour. Usually, these vibrations are too weak to perturb the fluid's boundary conditions in a way that would ostensibly perturb the fluid dynamics. But in the case where a natural mode of the structure is excited, a resonance can occur leading to strong amplitude vibrations [22].
3. These strong vibrations perturb the boundary conditions making them unsteady and drive the instability of the flow to a preferred frequency: the vibrating frequency of the structure.

The most obvious aeroacoustic phenomenon that features this kind of feedback is the aeolian tone coupled with resonant vibrations. When the frequency of the vortex shedding matches the natural frequency of the cylinder, the latter vibrates at considerable amplitudes. This vibration drives the shedding of vortices at the phase and the frequency of the vibration. The shedding is thus coherent along the span making the tone more intense [23]. Moreover, if the flow velocity is slightly changed, the vibration will have a greater effect on the shedding that carries on with the frequency of the vibration. The frequency is then locked, this phenomenon is known as the *lock-in*.

Although the lock-in phenomenon on vibrating cylinder has been thoroughly studied, until this day (May 2025) no work gives an explicit theory for the prediction of the radiated pressure levels from an aeolian tone with resonant vibration of the cylinder. As this amplifier is a resonance, the emitted frequencies are independent of the Reynolds and the Mach numbers. The SPL radiation is however, more complicated to predict.

### 3.3. Acoustic resonance

An other system with which the fluid's vibrations can resonate are the acoustics. Indeed, if a geometrical disposition has acoustic modes (natural modes of the acoustic propagation equation for a given set of boundary conditions and geometrical arrangement), an excitation at the same frequency than one of these modes may result in intense acoustic peaks. In the cas of flow-induced acoustic resonance, the flow must be unsteady and the unsteadiness must be able to excite such a resonance.

Different phenomena with different exciting mechanisms are possible with such an amplification and not all of them work with a feedback:

- Cavity noise: the exciting mechanism for a cavity noise is the Kelvin-Helmholtz instability that produces a broadband turbulence and thus, broadband noise. In the case of deep cavities, exciting frequencies matching depth modes make the two systems resonate and peaks are emitted [24]. In this case, no feedback loop is required. It is also the case for shallow cavities, but the exciting frequencies depends on the wind velocities with a Rossiter law [25] (see Subsection 3.4). An acoustic resonance for shallow cavities only happens at specific frequency while a deep cavity is always excited by a broadband noise that contains every frequency [26].
- Parker modes: on the one hand, an array of parallel plates immersed in a cross-flow sheds vortices with the Von Kármán instability; a light aeolian tone can be heard. On the other hand, the volume between two plates has acoustic modes and may be excited by the shedding: these are the Parker modes [27, 28]. However, these modes cannot propagate outside of the plates and thus cannot be heard, but the shedding starts immediately downstream of the plate and can be influenced by the mode. A feedback loop between the radiated sound and the flow, through branch (a), takes place and drives the phase of the shedding along the span making the aeolian tone coherent and thus more intense [29]. Parker modes may be the reason of the intense noise reported of the Beetham Tower in Manchester (United Kingdom) [30].

As for the resonance of the structure, acoustic resonances occur at Reynolds and Mach number independent frequencies.

### 3.4. Fluid-acoustics interactions

It is often said that in low-Mach numbers configurations, the acoustic field cannot perturb the hydrodynamic field. However, it is not always true. In an unstable flow, non-linear phenomena dominates and a small perturbation that may come from acoustics, as a butterfly effect, can produce great changes in the final sound heard.

Indeed, Blevins [31] showed how applying a tonal sound to a vortices-shedding cylinder is able to modify the frequency of the shedding when the tone's frequency is near the natural shedding's. Moreover, applied sound at the shedding frequency makes the shedding coherent in phase in the spanwise direction of the shedding cylinder: the resulting aeolian tone is thus more intense. In that case, the acoustic fields influences the dynamics of the fluid. Then, one may say that two identical side-by-side cylinders shedding vortices make more noise than two times one cylinder, as both of them interact with each other to enhance the coherence of their shedding.

For a Kelvin-Helmholtz excitation, in the case of a flow past a cavity, such an interaction also happens for Rossiter modes. Vortices shed at the upstream corner of the cavity via the flow instability travel to the downstream edge. As shown by the theory of vortex sound, an impinging vortex produces an acoustic wave that travels back upstream. When the wave impinges on the upstream edge, it perturbs the unstable flow: a stronger vortex is then shed at this moment. The vortex travels downstream and impinges on the edge, so on and so forth until the peak for the shedding of vortices is reached at a frequency which period is the sum between i) the time for a vortex to travel from the upstream to the downstream corner and ii) the time for an acoustic wave to propagate back to

the upstream corner. These possible frequencies are called Rossiter modes [25] and are given by the formula (for low-Mach numbers):

$$\frac{n}{f} = \frac{L}{U_c} + \frac{L}{c_0}, \quad (4)$$

where  $n$  is the number of the Rossiter mode,  $f$  is the frequency,  $L$  is the streamwise length of the cavity,  $U_c$  is the convective velocity of the vortices and  $c_0$  the sound velocity. Usually, a small delay is added that corresponds to the delay between the impingement of the vortex and the radiation of the acoustic wave.

For such an amplifier, the frequency is given by laws (either Strouhal or Rossiter) but the SPL radiation is hard to predict. It can be supposed that there is a dependence on the Reynolds and the Mach number in this case.

#### 4. CLASSIFICATION

It was previously shown that aeroacoustic phenomena occurring on a building façade can be defined by their exciting mechanisms and a potential way the exciting noise can be amplified. From this, a classification is built as a double-entry table considering the excitations and the amplifiers. It is proposed in Table 1

Table 1: Classification of aeroacoustic phenomena on building façades.

Excitation \ Amplifier	No amplification	Fluid-acoustic interactions	Structure resonance	Acoustic resonance
<b>Von Kármán</b> (wake instability from a bluff body)	Aeolian tone (with no vibration)	Aeolian tone amplified by sympathy (array effect)	Aeolian tone with vibrating resonance	Parker's modes (array of plates)
<b>Kelvin-Helmholtz</b> (shear flow)	Turbulence noise	Rossiter modes	Cavity with a flexible bottom	Cavity noise, array of plates with grazing flow (hypothetical)
<b>Jet-edge instability</b> (obstacle featuring an edge)	<i>no remarkable phenomena</i>	Hole tone	Vibration of an ill-laid out plate	Ill-laid out plate in presence of an acoustic resonator (similar to flutes)

This classification enhances the understanding of the mechanisms behind aeroacoustic phenomena that occur on building façades and could lead to prediction models as well. Indeed, a façade featuring cylinders is prone to a Von Kármán excitation which frequencies are known and then, the neighbouring disposition gives the possible amplifiers that make a configuration acoustically dangerous or not.

When it comes to predicting the intensity of the resulting noise, the task is more complicated. Indeed, apart from models for turbulence noise and aeolian tones with no vibration, few models exist.

## 5. CASE STUDY

Let an imaginary façade feature an array of cylinders of circular cross-section with the dimensions represented in Figure 2. This array of cylinders is a simpler model for balustrades or decorative elements. To know if this façade is prone to aeroacoustic nuisance, the classification can be used:

1. The first thing to acknowledge is the possibility of an aeroacoustic excitation. According to Table 1, the Von Kármán excitation is the most liable to occur as the façade features cylinders.
2. Then, a law giving the frequencies of the excitation as a function of the wind's characteristics is to be found. For a Von Kármán vortex shedding, the frequency of excitation can be found using Equation 3, where  $St \approx 0.2$  [32]. Thus,  $f \approx 0.2 \times U/D$  where  $D$  is the diameter (here  $D = 4\text{cm}$ ) and  $U$  is the mean flow velocity.
3. Now, possible amplifiers are to be determined. On the one hand, the cylinders are disposed in an array configuration, prone to the "array effect". The amplification is a fluid-acoustic feedback and can occur at any frequency of excitation. On the other hand, the cylinders may vibrate due to this excitation (Vortex Induced Vibration) and if resonance is reached, an intense sound shall be emitted. Let the natural frequency of vibration of the cylinder be 75 Hz, using the Strouhal law, it can be shown that a 15 m/s wind shall trigger a resonance. Here, Parker [27] showed that for such a disposition, no acoustic resonance can settle.

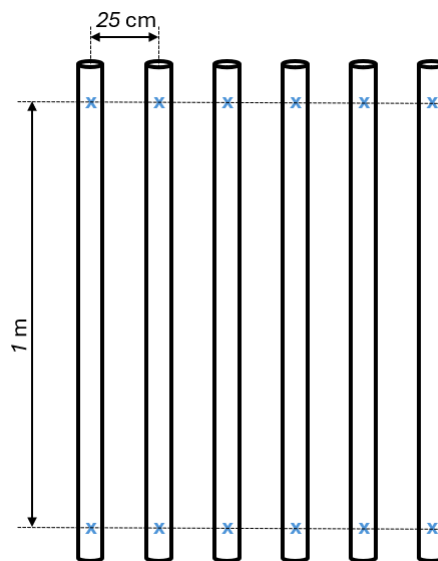


Figure 2: Array of cylinders of diameter 4 cm. The blue crosses represent the point where the cylinder is tethered to the wall. Here the fixations are simply supported.

So, there is a liability of aeroacoustic nuisance in this configuration:

- Aeolian tone with vibrating resonance can happen at 15m/s which is not excessive. To prevent this situation, it is possible to:
  - Change the material to make the natural frequency of vibration increase.
  - Get the fixation closer to reduce the side of the beam, thus increasing the natural frequencies of vibration.
  - Change the type of fixations as it will change the natural modes of vibration.

- Aeolian tone amplified by sympathy: this is the "array effect". To prevent this effect to happen, a solution could be to randomise the diameters so that the flow frequencies differs from one cylinder to another.

## 6. CONCLUSIONS

Aeroacoustic phenomena occurring on a building façade can be defined by how they are triggered and how they can be amplified. From this, a classification was built showing these phenomena in a double-entry table considering these two characteristics.

This classification clarifies the mechanisms behind aeroacoustic nuisances on a building façade and can also help to predict them beforehand. An example was given as a case study to demonstrate how such a classification could be used to predict and prevent aeroacoustic nuisances.

However, even if it clarifies the mechanisms behind aeroacoustic nuisances on building façades, the classification cannot always predict the characteristics of a sound. Some theory is lacking for the SPL prediction in some configurations, such as vibrating cylinders, Parker's resonances, array effects, cavity noise, etc.

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