

Design process to evaluate potential of wind noise at façade elements

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Summary
Wind noise generation from a solar shading façade is a design concern of engineers. A shading façade consists typically of a series of fins which repeat sequentially and that is mounted at a certain distance from the building surface, forming with it the sides of a duct where the wind can pass through. The flow instability created by the vortex detachment from the fins can excite the acoustic mode of the duct and instigate a phenomenon of aero-acoustic resonance which manifests with the generation of tonal noise. No design tools are currently available to assess the likelihood of tonal noise to occur in similar façade. Existing guidance notes have been used by Arup Acoustics for the last 20 years and have never been fully tested in the built environment to confirm their validity. A numerical methodology is presented here which aims to predict, through the CFD modelling of the aero-acoustic resonant system, if the coupling of ducted flow and vortex shedding around the fins element of a façade could lead to tonal noise generation.

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1. Introduction

Some level of flow-induced noise is likely to develop around any structure/building or part of it exposed to the wind. The characteristics of that noise and the conditions under which it occurs will influence whether or not noise from a particular structure is likely to cause annoyance. Under certain conditions, wind flow across structures and gaps within the building facade can adopt tonal characteristics, which, if sufficiently loud and frequent, can cause disturbance. This is due to the fact that this noise can sound as a ‘whistling noise’ propagating through the façade structure and may disturb the activities within and outside the building. Tonal noise from a building facade can be the indicator of a physical phenomenon known as “aero-acoustic resonance” which typically occurs when a ducted flow is interested by a periodic vortex shedding which exhibits frequencies which are close enough to one of the acoustic mode of the duct itself. In order to assess the likelihood of the wind generated noise to

occur, existing guidance notes have been used by Arup Acoustics for the last 20 years and had never been fully tested or studied extensively in the built environment to confirm their necessity, and/or further optimisation. For years they have been more of a “catch-all” approach that is too often deemed impractical and unreasonable from an aesthetic and façade engineering standpoint (see Table I below).

Elements-aperture	Dimension	Comments
Unsealed slots, apertures and exposed elements within façade cladding	>100mm	For exposed elements introduction of vibration damping treatments needed. For cavities and apertures it is recommended to close all openings and apertures to avoid the creation of resonant cavities.
Wires, circular cables, tubular elements or hollow sections	>50mm	If a bigger dimension than 50mm is not possible to be included then provide special damping treatment.
Array elements	>100mm	In case of regular array of elements, smaller dimension of apertures should be avoided or provide special damping.
Constructions	>100mm	Irregular constructions should be used to break-up vortex street formations.

Table I: Existing guidance notes [1,2].

Recently, in light of the higher demand and use of solar shading, there has been the need for the existing guidance to be reviewed and further studied. A list of Arup Acoustics projects have been selected falling within two categories:

1. Projects analysed only through a desktop study and/or a CFD modelling study of vortex shedding at fins elements (without any on-site measurements or wind tunnel tests) – the façade elements are studied with the likelihood of disturbance generated by the elements in terms of ‘low, medium, high level’. The desktop study has been based on the evaluation of the Reynolds Number using as reference length the fins one(see figure 1 and figure 2).
2. Projects analysed with on-site measurements or wind tunnel tests – in this case, the likelihood of disturbance generated by the façade elements is also provided and confirmed in terms of tonal noise frequency.

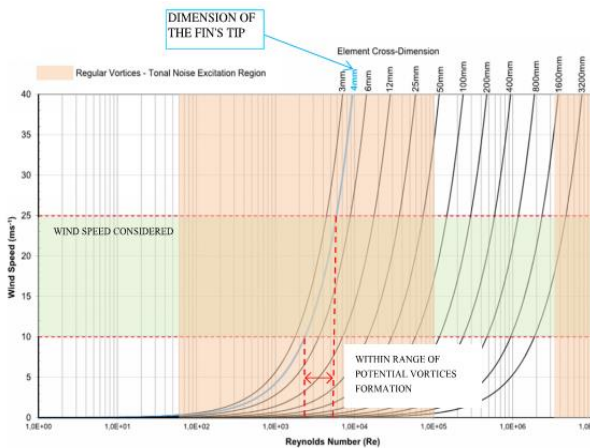


Figure 1: Relationship between wind speed and Reynolds Number with varying cross-dimension of the façade fin [1].

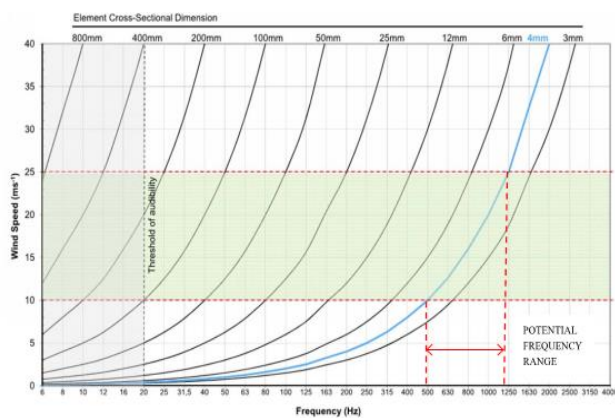


Figure 2: Relationship between wind speed and Reynolds Number with varying cross-dimension of the façade fin [1].

In light of the limitations offered and discovered by the existing acoustic guidance (see Table II), a design process has been implemented for evaluating, using analytical methods, the shape and layout of façade element in order to avoid the instigation of aero-acoustic resonance.

Assessed Projects	Exhibits Noise or predicted > Low Risk (i.e. Med or High)	How it contradicts the Guidelines
<i>Project 1) Desktop study undertaken</i>	✓	Unsealed slots, apertures and exposed elements within façade cladding should be > 100mm
<i>Project 2) Site measurements undertaken</i>	✓	Unsealed slots, apertures and exposed elements within façade cladding should be > 100mm – louvre blades are 150mm but tonal noise was measured. However a regular construction with array of elements was installed.
<i>Project 3) Desktop study undertaken + wind tunnel tests</i>	✓	When arrays of elements are presented in the façade it is recommended the spacing to be >100mm - The spacing between façade tube elements is designed to be 10mm but no tonal noise was found in the wind tunnel tests.
<i>Project 4) CFD + wind tunnel tests</i>	✓	Unsealed slots, apertures and exposed elements within façade cladding should be > 100mm - The perforation dimension (rectangular) is 20mm width and 90-305mm height but no tonal noise was measured in the wind tunnel facility.

Table II: Analysis of Arup projects with existing guidance notes [1].

2. Aero-acoustic behavior of a shading facade

Aeroacoustic resonance is experienced when a ducted flow is interested by a periodic vortex shedding. The frequency of vortex shedding approaches the acoustic frequency of the duct a flow is interested by a periodic vortex shedding and exhibits frequencies coincidence or close enough to the transverse acoustic mode of the duct itself[3].

As the flow passes the body, vortices are shed periodically at a frequency that increases linearly with the flow velocity. This relationship is characterised by a constant Strouhal number. During aero-acoustic resonance, the acoustic field modifies the hydrodynamic field so that the vortex shedding frequency coincidences with the acoustic resonant frequency not at a single flow velocity, but over a range of flow velocities. This is called *lock-in* [3,4]. During lock-in the shedding

frequencies remain constant as flow velocity is increased until resonance subsides and the vortex shedding process reverts to the frequency indicated by the Strouhal number. This behaviour is shown schematically in figure 3.

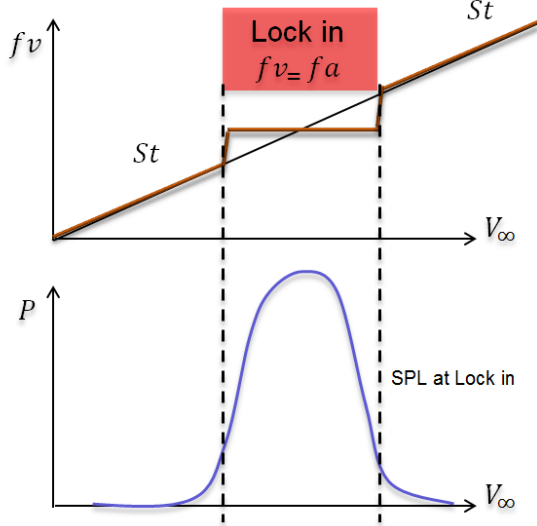


Figure 3: Scheme of frequency synchronisation and related sound pressure level (SPL) during lock-in condition [3]

In a shading façade this can occur when the flow instability created by the vortex detachment from the fins can generate unsteadiness in the flow passing through the duct formed between the shading façade and the building surface. This can excite the acoustic mode of the duct and instigate aero-acoustic resonance that manifests with tonal noise.

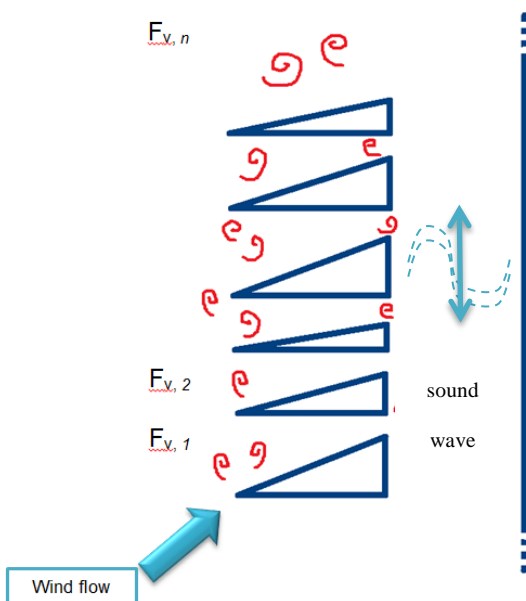


Figure 4: Vortex shedding and propagation of first transverse acoustic mode.

3. Proposed methodology

The proposed methodology aims to investigate the potential of a shading façade to generate tonal noise as a consequence of *lock-in* being instigated between the fins of the façade and the ducted flow configuration which they form with the building surface behind them. This involves evaluating if the following conditions are occurring when a typical section of the façade is exposed to wind flows:

- The fins are generating a vortex shedding phenomena at considered wind flows conditions and,
- The flow within the duct behind assumes an oscillatory nature due to vortex shedding such to excite the acoustic mode of the duct and,
- The acoustic mode of the duct trigger in *lock-in* range the vortex shedding frequencies of the fins.

In case that the above conditions are verified and therefore aero-acoustic resonance is likely to occur for the façade, then the methodology could guide the engineers toward the selection of more appropriate combination of fins – ducted flow which follow within the *off-resonance* range.

3.1 Use of an hydrodynamic analogy to simulate aero-acoustic resonance

The frequency of the transverse acoustic mode of a rectangular section duct can be calculated using the following formula [3]:

$$f_a = \frac{nc}{2w} \quad (1)$$

Where c is the sound speed (340 m/s), w the width of the duct and n the number of transverse acoustic modes in the duct. The primary flow induced acoustic mode in a rectangular section duct consists of a transverse standing wave (i.e. normal to flow direction). Tan *et al.*[4] proposed an hydrodynamic analogy in which the acoustic field is represented as an oscillating cross flow velocity boundary condition applied to an incompressible flow. A sinusoidal velocity of the form $A \sin(2\pi f_a t)$ is applied perpendicularly to the flow direction as shown in figure 5; A represents the acoustic particles velocity amplitude. The analogy is well known in literature as it has been applied successfully for the

modelling of aero-acoustic resonance of bluff bodies ducted flows [4].

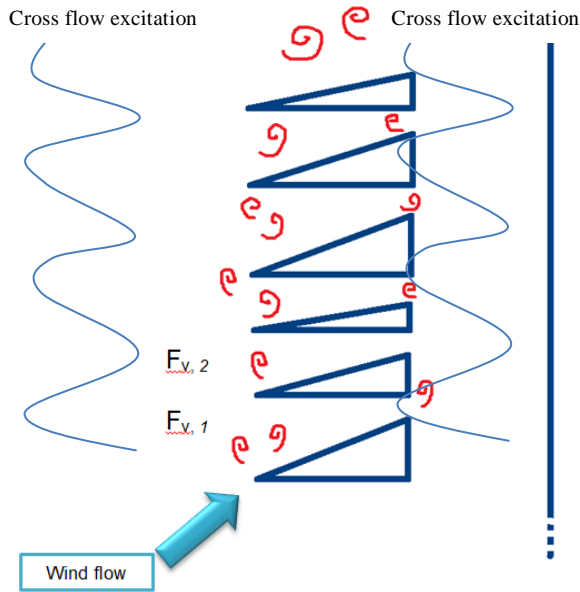


Figure 5: Scheme of cross flow oscillating velocity condition to model the acoustic excitation.

4. Methodology application to a shading façade layout

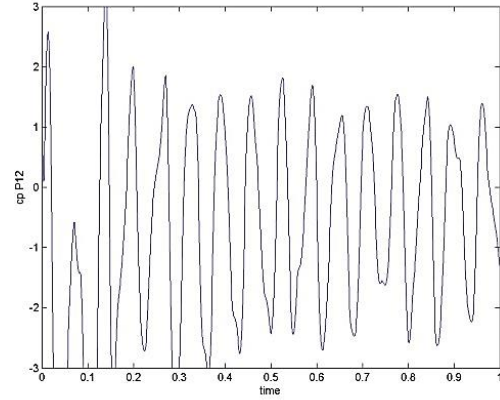
A series of CFD simulations are performed to solve the flow around a typical sequence of fin elements of a shading façade and the spacing behind it, this at a range of wind conditions. In order to verify the risk of tonal noise being generated by the analysed configuration, the following steps are implemented:

A. Evaluation of vortex shedding at the façade fins

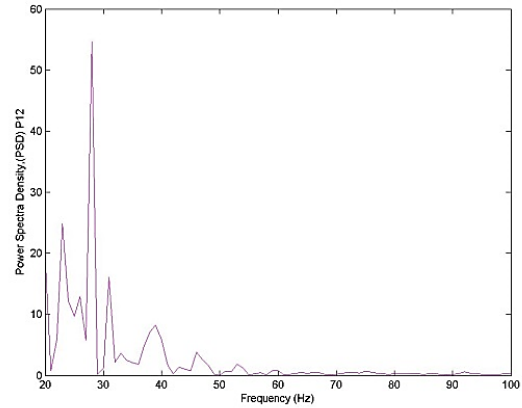
The objective of this phase of the methodology is to verify if a periodic vortex shedding may form, under the considered wind flow conditions, from the fins. A 2D model of a typical section of the façade is prepared. The façade is exposed to 4 different cross flows at 10 m/s, 15 m/s, 20 m/s, 25 m/s and also 4 incidence angles for each flow magnitude (0° , 22° , 45° , 67°).

The presence of possible vortex shedding structures is at first investigated by observing the contour plots of the vorticity fields obtained for each of the cases simulated. During these analysis the time trace of the coefficient of pressure (c_p) is collected for each of the fins and a probe is inserted at the center of the spacing formed by the shading façade and the building surface to record time variations of the velocity magnitude of the

flow passing through it. A FFT (Fast Fourier Transformation) of the time signal of the above quantities (c_p and V_{duct}) is produced in order to investigate their spectra frequencies content. In case of periodic vortex shedding, a clear spike at a single frequency is visible in correspondence of the natural vortex shedding frequency [4].



(a)



(b)

Figure 6 (a) Time trace of the c_p collected at the downstream fin. (b) FFT of the oscillating c_p .

B. Verification of risk of aero-acoustic resonance due to frequencies coincidence ($f_v = f_a$)

The first transverse acoustic mode (f_a) of the duct is calculated using the empirical formula applicable to ducted flow. At first comparison is considered to verify if the frequency of vortex shedding obtained around the fins is similar to the acoustic frequency which could be instigated within the spacing behind. For the façade configuration analysed the acoustic frequency has been found to be $f_a = 212$ Hz.

This correspond to a frequency ratio $f_a / f_v \sim 4$. However, the lack of coincidence between the frequencies above does not ensure the lack of

tonal noise being emitted from the façade. The lock-in phenomena in fact can trigger resonance in a large range of frequency ratio and therefore this possibility must be considered by the study.

C. Verification of risk of aero-acoustic resonance due to lock-in phenomena

During this step the method focuses on investigating the possible extents of the lock-in range. In particular it is evaluated if the frequencies of vortex shedding, obtained at the previous steps could be driven in a lock-in mechanism by the excited acoustic frequency and which is the amplitude of acoustic necessary for this to occur. Acoustic excitation is therefore introduced in the model as a flow boundary condition. This is in the form of an oscillating velocity representing the flow oscillation that the acoustic wave causes once instigated. The oscillating velocity is a sinusoidal wave of frequency (excitation frequency f_{exc}) equal to a ratio of f_a , in the range of 0.5 to 1.5 and, with an amplitude A equal to 10% and 5% of the incoming wind flow. The c_p is collected from the simulations run with excitation and the frequency spectras plotted. In the case of lock-in, the frequency spectra shows a shifting of the vortex shedding frequency in correspondence of the frequency of acoustic (see figure 7) otherwise, if the system remain in *off-resonance* conditions then the two frequencies (vortex shedding and acoustic) are both appearing in the spectra, this indicating that the two periodic phenomena are co-existing but the acoustic wave is not able to enhance itself and self-sustain by triggering vortex shedding into a resonance phenomenon.

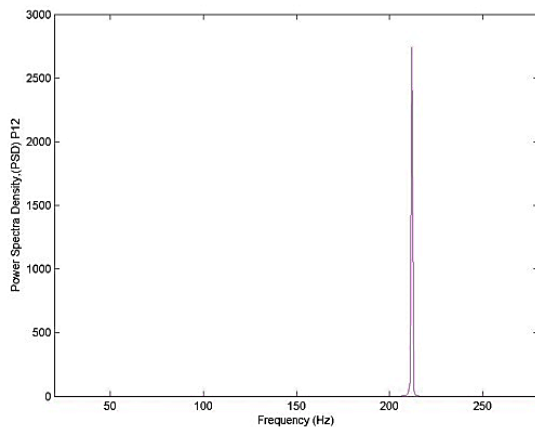


Figure 7: Scheme of frequency synchronisation and related sound pressure level (SPL) during lock-in condition (ref).

5. CFD Model description and simulation assumptions

In the 2D model built to represent a typical section of the façade the fins have a reference length (L) of 300 mm and a pitch ratio measured at the fins edge (L/d) going from 2 to 5.

The width (w) of the spacing behind the fins is of 800 mm. The computational domain consists of an upstream and downstream of 5 times the total length of a fin. The side boundary of the domain are kept at a distance of 6 times the width w .

The flow is assumed to be incompressible standard air with $\rho=1.225 \text{ Kg/m}^3$ and $\mu=1.78 \times 10^{-5} \text{ kg/m} \cdot \text{s}$. The lower inlet boundary has a constant velocity. The upper and outlet boundary is defined with a constant static reference pressure (0 Pa). The right and left side boundaries are maintained as no slip walls for the simulations where no acoustic excitation is provided.

When the acoustic excitation is imposed, these boundaries are velocity inlets/outlet with an instantaneous spatially invariant velocity which is temporally periodic and with a zero mean.

The flow is solved using URANS. All modelling steps are prepared using the commercial CFD code ANSYS Fluent 14.5[6].

6. Simulation results

6.1 Natural vortex shedding frequency of the fins

The first set of simulations is executed with no acoustic excitation to reproduce the vortex shedding phenomena for each wind flow considered.

The contours of vorticity showed a clear and strong vortex street for each simulations. The frequency of vortex shedding is obtained from the FFT of the pressure coefficient collected at each of the fins. Almost all pressure coefficients of the fins demonstrated a periodic behaviour for each of the wind speed and incidence angle considered. For the flow velocities simulated the frequency of vortex shedding were in the range of 40-30Hz.

In addition, the oscillation of velocities were collected within the ducted flow, this displayed the same flow periodicity that was achieved by the flow around the fins.

Figure 8(a) that follows, shows the vorticity plot obtained when the wind flow applied is 25 m/s and the wind incidence angle 67° .

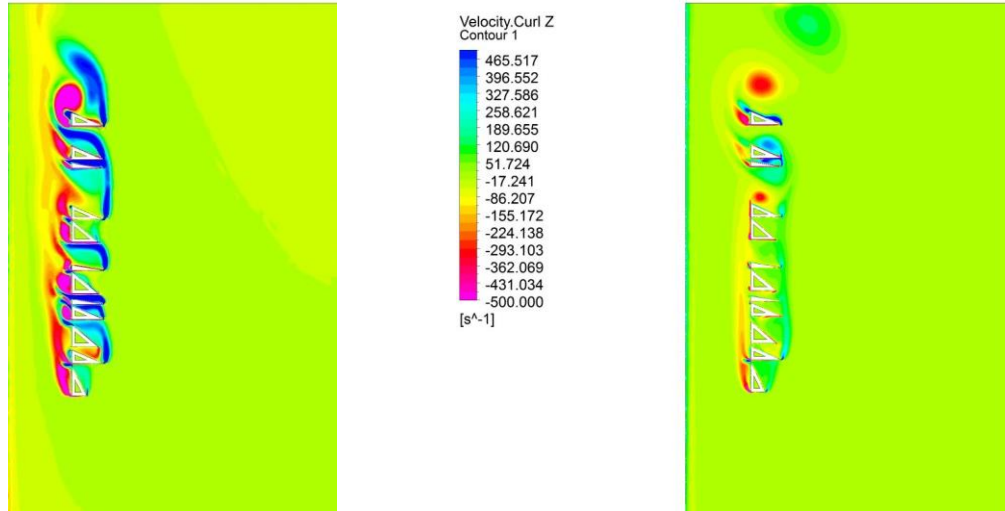


Figure 8: (a)Vorticity field at 25 m/s and $\theta=67^\circ$ without excitation. (b)Vorticity field at 25 m/s and $\theta=67^\circ$ with excitation of $A=10\% V_{wind}$ (i.e. 2.5 m/s) and $f_{exc}= 212\text{Hz}$.

6.2 Excited vortex shedding frequency of the fins

The second set of simulations is executed with acoustic excitation, this for each wind flow considered. The contours of vorticity, in the case that have seen lock-in, have showed a reduction of the vorticity content. Figure 8(b) shows the vorticity plot obtained for the wind flow applied of 25 m/s and for an incidence angle of 67° and with the applied excitation frequency of 212Hz and $A=10\% V_{wind}$.

	25 m/s - $\theta=67^\circ$ NO excitation		With excitation $A=10\% V_{wind}$ - $f_a=212\text{ Hz}$	
	C_p	$f_v(\text{Hz})$	C_p	$f_v(\text{Hz})$
Fin1	No periodic	—	No periodic	—
Fin2	Periodic	~ 25	Periodic	Lock in
Fin3	Periodic	~ 35	Periodic	Lock in
Fin4	Periodic	~ 42	Periodic	Lock in
Fin5	Periodic	~35	Periodic	Lock in
Fin6	Periodic	~ 39	Periodic	Lock in
Fin7	Periodic	~ 40	Periodic	Lock in
Fin8	Periodic	~ 23	Periodic	Lock in
Fin9	Periodic	~ 25	Periodic	Lock in
Fin10	Periodic	~ 55	Periodic	Lock in
Fin11	Periodic	~ 25	Periodic	Lock in
Fin12	Periodic	~ 25	Periodic	Lock in

Table III: Summary of spectra analysis results.

7. Conclusions

The simulation have shown that at all the wind flow velocities above the 20m/s the vortex shedding from the fins can be triggered into *lock-in* by the excited acoustic frequency as can be seen in table III which report the response of vortex shedding of each fins for the analysis carried out with wind flow speed of 25 m/s and incidence angle of 67° . The methodology illustrated in this paper can be used to verify if a combination of fins of a solar shading façade and the spacing formed by the façade and the building surface could lead to tonal noise, this as consequence of aero-acoustic resonance being instigated. The methodology could be further validated to verify which façade features lead to an *off-resonance* condition.

References

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