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Vortex induced vibrations of rectangular cylinders arranged on a grid

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ABSTRACT

A grid arrangement of hundred rectangular cylinders fixed to the facade of a house generates strong and disturbing mono-harmonic noise. The cross-flow vibration of the rectangular cylinders is identified as the origin of the noise. The present article proposes a complete investigation of the Vortex Induced Vibration (VIV) combined with a grid effect. It is based on *in situ* measurements, numerical (finite elements and Computational Fluid Dynamics (CFD)) and extensive wind tunnel modelling. A comparison between unsteady pressure tap measurements and CFD results allow to understand the vortex shedding process and synchronization type depending on the wind incidence and spacing of the cylinders. On the basis of this multi-approaches parametric investigation, a deep understanding of the VIV-grid phenomenon enables to propose two mitigation techniques. These techniques are tested and their effectiveness is reported in terms of vibration amplitude and acoustic intensity.

1. Introduction

A vertical louver structure installed on the facade of a house is composed of aluminium rectangular cylinders with a constant horizontal spacing (Fig. 1). This architectural structure is dedicated to isolate the occupants installed on the outdoor terrace from the neighbourhood. The grid was designed based on aesthetic and static loading constraints: it is clamped at four extreme points into the piers of the facade.

An intense acoustic emission was reported under specific wind conditions (fall and spring). This undesirable phenomenon creates a characteristic single frequency noise between 50 Hz and 100 Hz. Due to the large number of rectangular cylinders (100 in total), the phenomenon taking place is similar to a mono-frequency wind instrument creating a strong and unacceptable noise. In addition, vibrations of the louver are transmitted to the structure of the building. On top of this comfort problem, the issue of the safety due to a potential accelerated fatigue degradation of the structure must be considered.

In this paper, a complete analysis of the behaviour of the grid under wind is performed. The objective is first to understand and characterize the aeroelastic instability and then to solve it using an adequate mitigation technique. The starting point is the study of the grid in its initial configuration, then some parameters will be explored, to understand their effects and how they can be changed to solve the problem. The results of the study can be extended to similar structures where the aesthetic objective leading to light and flexible designs must be consistent with external excitations such as atmospheric wind.

For that purpose, *in situ* measurements are performed, to make the link between the vibration of cylinders and the wind conditions (amplitude and direction). Afterwards, a wind tunnel model is developed, based on the real grid, to reproduce real conditions and study other configurations through a parametric analysis. The controlled conditions in laboratory enable to investigate the interaction between wind conditions, vibration and acoustic levels. Finally, numerical methods are used to compare and validate results, by studying structural (modal) properties of the grid on one side (using FEM) and fluid dynamics around the grid on the other (using CFD, with OpenFoam).

From the initial observations of the structure installed on the house (single frequency, wind direction and amplitude dependencies), the aeroelastic effect responsible of these vibration is the vortex shedding process in the wake of each rectangular cylinder. Hence it consists of a Vortex Induced Vibration (VIV) phenomenon, which results from the interaction between fluid and structural forces, at a given frequency (Techet, 2005; Blevins, 1990). Indeed, observations show a phenomenon which is self-limited, directional and occurs for a certain velocity range (5 m/s to 8 m/s). It is shown that galloping is not taking place in this range of wind speeds. This instability taking place on a grid arrangement, is characterized by the following quantities:

$$\left[\frac{A}{D},\frac{f_s}{f_s^0},\frac{f_{vs}}{f_s^0}\right]=f(U_r,Re,m_r,\zeta) \qquad (1)$$

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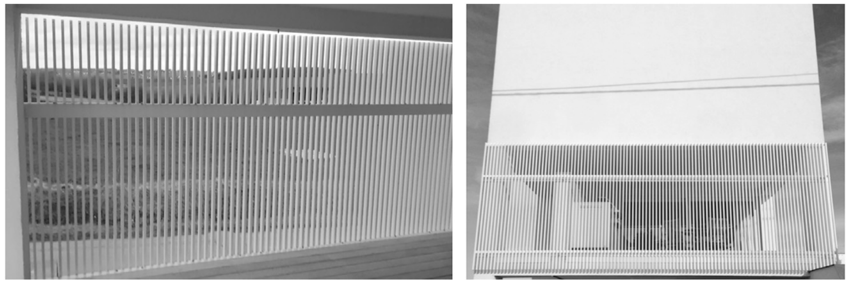

Fig. 1. Real grid on site, from inside (left) and outside (right).

where, f_s is the free motion structural frequency of the structure under wind, f_s^0 is the free motion frequency at wind-off conditions, A is the amplitude of the free motion, D is the depth, f_{vs} the frequency of the vortex shedding process (with motion), m_r is the ratio of the structural mass m_S to the fluid mass m_F, ζ is the structural damping. The following non-dimensional numbers are used to characterize this fluid-structure phenomenon: the Scruton number $Sc = \frac{4\pi m_S \zeta}{\rho BDL}$, the Skop-Griffin number $SG = 4\pi^2 St^2 Sc$ and finally the reduced velocity $U_r = \frac{U}{f_s^0 D}$. B is the chord and L is the spanwise dimension. The flow behind a bluff body is separated, the shear layer instability (flow speed outside wake is much higher than inside) makes the vorticity clustering in the upper and lower layers. The Strouhal number quantifies the vortex shedding process $St = \frac{f_s^0 D}{U}$. This number is a characteristic of a given geometry and depends on the Reynolds number, $Re = \frac{DU}{\nu}$.

In the present study, the Reynolds number is ranging between 2,000 and 40,000 and no geometric scaling is performed. In this range, Sumer (2006) showed that the Strouhal number is independent of the Reynolds number, hence Re can be omitted from the right hand side of equation (1).

The VIV instability occurs when fluid and structure are 'frequency matched', $f_{vs}(U_r^{crit}) = f_s^0$ leading to $U_r^{crit} = 1/St$. The lock-in is the velocity interval of U_r where VIV instability occurs. It depends on the structural mass and damping, represented by the Skop-Griffin number SG: the higher SG, the lower the lock-in range. Zdravkovich (1985) studied two adjacent interfering circular cylinders and deduced their critical reduced speed U_r (and so St) depending of spacing between them (non--dimensionalised with T/D): the lower the spacing T/D, the lower U_r^{crit} and the higher St.

In the scope of a grid arrangement, the VIV-grid phenomenon is characterized by the amplitude of oscillation A_{max} and the lock-in range according to

$$(A_{max}/D, \text{Lock}-\text{in}(U_r)) = f(SG, \alpha, T/D) \tag{2}$$

where α is the angle of attack. This relation establishes the parameter space to investigate in order to characterize the VIV phenomenon taking place on a grid. It provides a starting point to study all the aspects of the present aeroelastic problem up to its mitigation.

Table 1
Modal parameters of the grid, comparison between experimental modal analysis, analytical and numerical approaches.

	f_1 Hz	f_2 Hz
Experimental	59	176
Euler-Bernoulli	66	158
FEM	64	172

2. Approaches

Three complementary approaches are carried out to understand the phenomenon and mitigate the problem: *in situ* measurements, wind tunnel parametric study on a 1:1 scale model and comparison with numerical models (FE and CFD).

2.1. In situ measurement

Experimental measurements are performed on the grid during half a week in windy conditions leading to vibrations of the structure. Anticipating the mitigation technique, two rectangular cylinders were filled with sand. The instrumentation is shown in Fig. 2. It consists in:

1. Three mono-axis accelerometers (PCB-Piezotronics 3713B112G) are placed at mid-height of 3 central cylinders of the grid. The two cylinders filled with sand are instrumented, plus another one empty. These three cylinders are next to each other.
2. An anemometer to measure the wind speed U and direction α. The wind components (u, v) are measured in the system of reference of the grid.
3. An acquisition system (computer and internet connection) to remotely acquire data at 640 Hz.

The modal properties of the grid are identified experimentally and

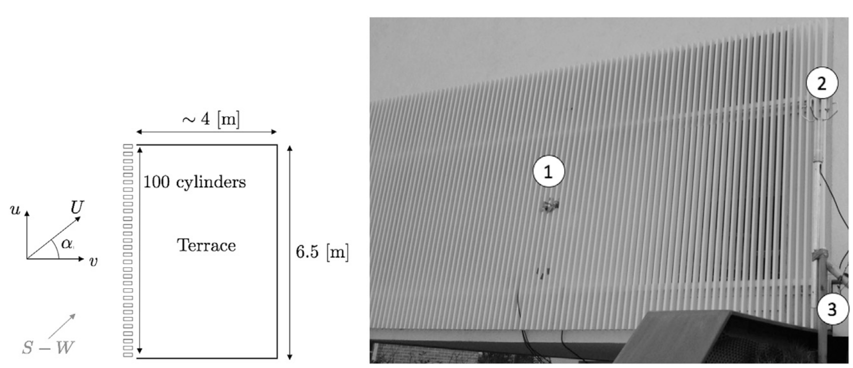

Fig. 2. Grid and terrace geometry, wind components (left) and *in situ* instrumentation: accelerometers (1), anemometer (2), data logger (3) (right).