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► **To cite this version:**

R. Sheng, L. Perret, F. Demouge, I. Calmet, S. Courtine, et al.. Wind Tunnel study of the flow around a wall-mounted square prism immersed in an atmospheric boundary-layer. International Workshop on Physical Modeling of Flow and Dispersion (PHYSMOD 2015), Sep 2015, Zurich, Switzerland. hal-01163963

HAL Id: hal-01163963

<https://hal.science/hal-01163963>

Submitted on 30 May 2023

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Wind Tunnel study of the flow around a wall-mounted square prism immersed in an atmospheric boundary-layer

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ABSTRACT: Predicting extreme values of wall-pressure on a tall building is a crucial step in the design process of the building but can prove to be very challenging. This paper describes wind tunnel study with a well-defined mean velocity gradient and turbulent characteristics. The experiments were performed in the NSA wind tunnel at CSTB, Nantes, France, at a 1:300 scale. The tower building was modeled by a wall-mounted prism of square cross-section (dimensions: 10 cm × 10 cm × 49 cm) equipped with 265 pressure taps used to measure the unsteady pressure distribution on the model walls. Comparisons between different measurement methods of the global wind load are presented. Differences between lateral and longitudinal loads are discussed in link with the physics of the flow.

1 INTRODUCTION

Wind load on the structures is one of the main wind effects which are very important for building construction. Most of the structures are bluff bodies hence the aerodynamics of bluff bodies is commonly studied in the wind engineering literature. Irwin (2008) has listed several examples of wind tunnel tests for bluff bodies and proved the importance of these tests can be to the safety and economics of large buildings and bridges. Evidently, full-scale measurements have no scale mismatch for all characteristics. However, they are costly and can be time-consuming. Additionally, the conditions of measurements can be hardly controlled. Every change of the environment can lead to the error of measurements. Hence, the well-controlled wind-tunnel tests were carried out for wind engineering. Niemann (1998) has compared the results of wind tunnel tests with those of full-scale measurements. Good agreement was found which ensure the quality of the wind tunnel measurements. Melbourne (1980) compared the results of wind tunnel tests from different laboratories for a same model and almost the same result was presented by those different laboratories. Hence we can conclude that conditions can be easily controlled for wind tunnel tests. Furthermore, wind tunnel experiment is a very important method for building construction.

The wind tunnel experiment with a tower building as a bluff body presented in the present paper is part of a broader research project, the target of which is to validate the ability of Large Eddy Simulation (LES) to predict extreme wall-pressure events against experimental measurements. In order to be able to prescribe the correct inlet condition, detailed wind

tunnel measurements were performed to measure the gradient of mean velocity and all the length scales of the turbulence. Different wind tunnel measurement techniques such as particle image velocimetry (PIV), high-frequency force measurement and unsteady wall-pressure measurements were also performed in this study. In the present paper, the focus is on the high-frequency force measurement and unsteady wall-pressure measurements to investigate spectral content of the wind load in lateral and longitudinal directions.

2 EXPERIMENTAL MODELS AND PROCEDURES

All the wind tunnel tests were performed in the NSA wind tunnel at CSTB, Nantes, France, which is a close-loop wind-tunnel with a test-section 20 m long, 2 m high and 4 m wide. These large dimensions can allow for the reproduction of natural wind at scales ranging between 1:100 and 1:400 for the usual local and global measures. The velocity of the flow in the wind tunnel is adjustable from 0 to 30 m/s. The floor of the wind tunnel is equipped with a turntable table to position models from 0 to $360^\circ \pm 1^\circ$. The simulation of the wind is made by placing different sets of roughness and vortex generators on the floor of the wind tunnel.

2.1 Model

The tower building was modeled with a wall-mounted prism of square cross-section (dimensions: $10\text{ cm} \times 10\text{ cm} \times 49\text{ cm}$) made of Plexiglas to allow for optical access. A second model equipped with 265 pressure taps was used to measure the unsteady pressure distribution on the model walls as shown in Figure 1.

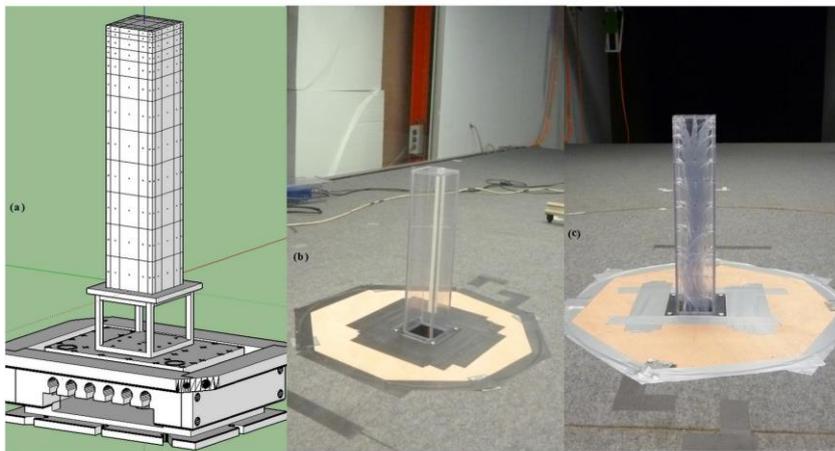


Figure 1: a) distribution of pressure taps, b) tower building for PIV measurements, c) tower building with pressure taps for pressure distribution measurements on the model walls

2.2 The wind flow characteristics

The wind tunnel tests were carried out in turbulent flow, simulating the vertical velocity and turbulence profile expected at the construction site using roughness elements which include a rough carpet and turbulence generators at the entrance of the section (cf. Figure 2a). The targeted code roughness is $z_0=0.02\text{ m}$ according to Eurocode 1 (2005). At the reference height $H_{\text{ref}} = 0.67H$ (where H is the building height), the reference mean wind speed $U_{\text{ref}}=10\text{ m/s}$. Figure 2b and Figure 2c show the profiles of mean velocity and the turbulent intensity of the generated boundary layer. Comparison between measurements and results from the literature shows a good agreement, which ensure the inlet condition simulated by the wind tunnel NSA.

In addition to the mean velocity and the turbulent intensity profiles, power spectra of the wind speed were also checked. Here we compare the power spectrum of the longitudinal wind speed u at the reference height with the result given by the Eurocode 1 (2005). Figure 3 shows again a very good agreement between the experimental data and the model profile from the literature. We can conclude that in the NSA wind tunnel we can simulate a turbulent wind which can reproduce the fluid characteristics as proposed in the literature.

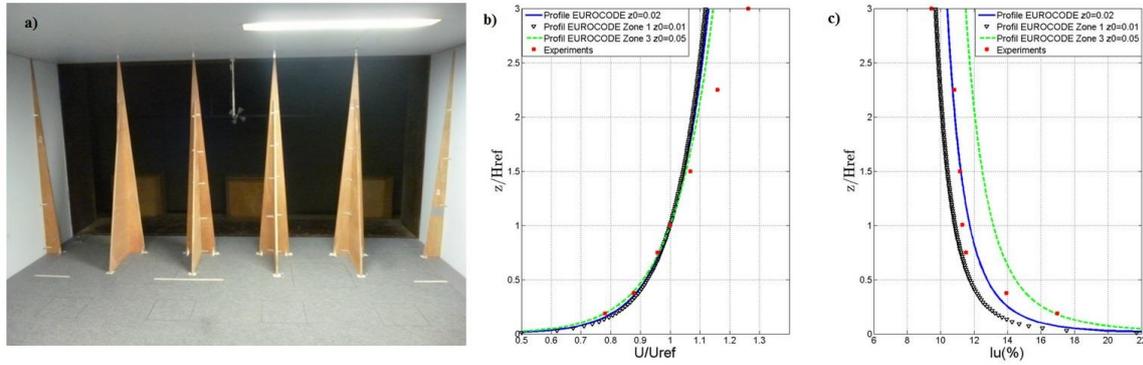


Figure 2: a) roughness elements to simulate the turbulent flow, b) mean velocity profile, c) turbulent intensity profile

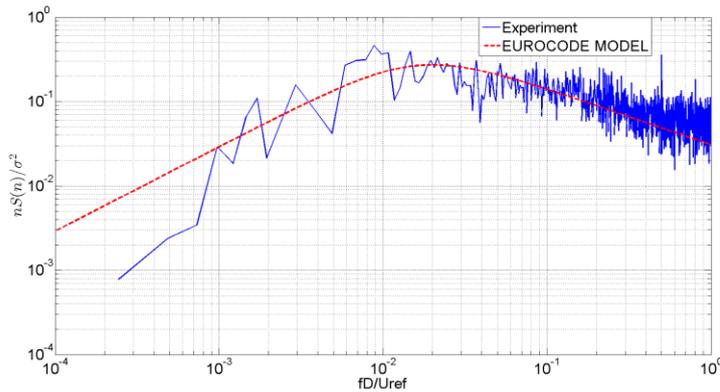


Figure 3: Power spectrum of the longitudinal wind speed u at the reference height

2.3 Experimental set-up

The tower building has been equipped with 265 pressure taps. Measurements were performed synchronously at a rate of 512 Hz for the pressure taps and 200 Hz for the force balance over 4 min. The pressure scanner designed by CSTB is the “1024 channels / 1024 Hz” capable pressure scanner. This accurate scanner is composed of high precision power supply over 32 channels. Each channel is connected to an ESP Pressure Scanners with 32 pressure ports multiplexed at 70 KHz. The tubing system was used to connect pressure tap and scanner port. The Helmholtz’s resonance effects due to the tube cavity were corrected by using traditional restrictors.

3 RESULTS AND DISCUSSIONS

In this section, a detailed analysis of the characteristics of wind load is presented, focusing on its dynamics. Indeed, thanks to the pressure tap measurements, all local information such as mean pressure, variance of the pressure signal and the power spectrum of the signal are available. Global force measurements are compared with the integration of the local wind loads obtained from the pressure measurements.

3.1 Global wind loads and force

With the pressure tap measurements, the instantaneous value of the local pressure can be obtained simultaneously at the 265 pressure taps. After integration over the building surface, the global force signal can be compared with the result of the force balance. The original power spectrum of the force is altered by the mechanic resonance of the equipment. To facilitate the analysis and comparison, a filter is applied to remove the resonance according to Caracoglia (2015). Figure 4 shows a good agreement found between the two types of measurements. A strong peak appears in the lateral force power spectrum which gives us a Strouhal number at about 0.11. The Strouhal number is defined as $St=fD/U_{ref}$ with D the tower width and U_{ref} the reference velocity. This value is very close to the one of 0.12 found in the literatures as Choi (2000) and Okajima (1990) for this type of structure. Difference exists because of the different definitions of U_{ref} , which is the reference velocity at $0.67H$ here and free-stream velocity in those papers.

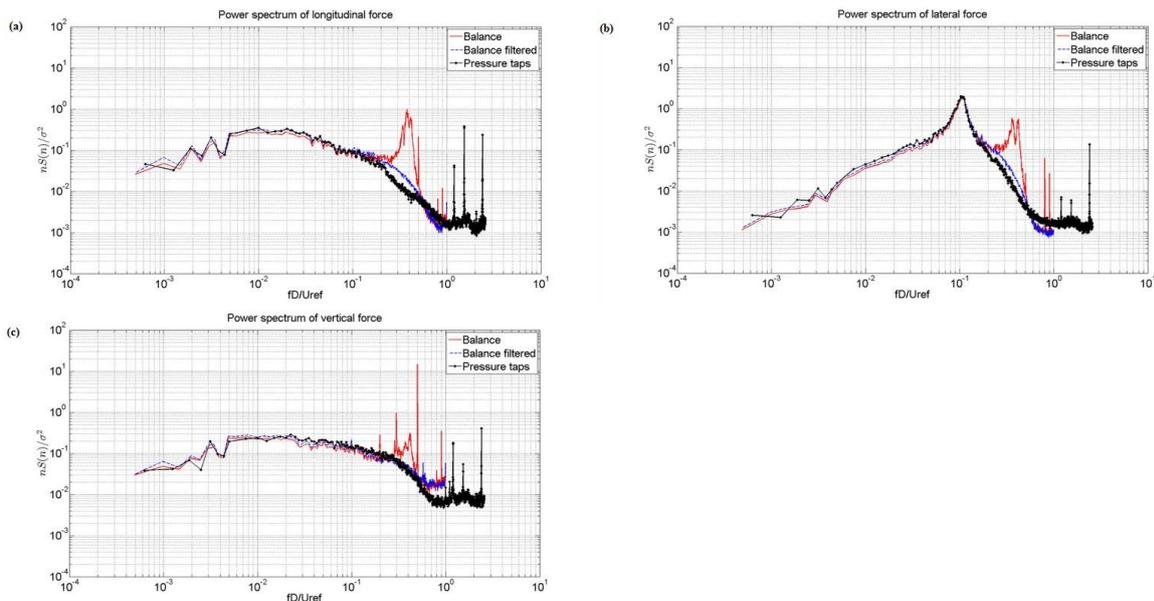


Figure 4: Power spectrum for three components of force: a) lateral direction, b) longitudinal direction and c) vertical direction

3.2 Local wind loads

A clear peak at $St = 0.11$ appeared only in the spectrum of the lateral force as shown in the Figure 4. We focus here on the local wind loads at the reference height to understand it clearly. We can number each pressure tap as shown in Figure 5b in which wind comes at the face of AB. Because of the symmetry of our tower building, identical results were found for sides BC and AD. Therefore, only the information at the three faces AB, BC and CD were needed.

Figure 5 shows the power spectrum for taps 1-15 around the tower at reference height. All the spectra on the BC side have a marked peak. This is expected as the lateral sides of the building are where shear layers at the origin of the vortex shedding cycle form and develop. The spectral peak corresponding to the Strouhal number of 0.11 also exists on the AB and CD sides for some pressure taps (tap 1, 5, 11, 12, 14 and 15 symmetrically). This was less expected, especially on the side AB facing the oncoming wind where the flow is upstream the separation points formed by the upstream building corners.

These tap locations are therefore under the influence of the vortex shedding. To better understand this phenomenon, the spectral coherence between different taps has been computed. At the frequency corresponding to the Strouhal number identified above, we found that there exists strong coherence (about 0.9) between two points on the same side of the face AB (tap 4 and 5) as shown in Figure 6a and also between taps located on the same side of the building (taps 5 and 6 to 10) (figure 6b), confirming that these tap locations are under the influence of the same shear layer. The coherence level drops to 0.65 for points at opposite corners of face AB (tap 1 and 5) as shown in Figure 6a. Even though vortex shedding from opposite sides of a bluff body is known to be well-synchronized (being roughly 180° out of phase), the marked loss of phase-coherence (also observed between two points from opposite sides) might be the result of the structure of the oncoming wind flow: the bluff body being immersed in a thick atmospheric boundary layer, the presence of strong turbulent structures might disturb the flow separation at the corners of the building side facing the wind near tap 1 and symmetrically tap 5. This loss of coherence of pressure signals measured on surfaces normal to the oncoming wind can therefore reduce or make disappear through the integration process the spectral peak in the global effort in the longitudinal direction.

Finally, we can notice the presence of the same noise in the power spectrum figures and in the coherency figures. It's attributed to acoustic noises that exist in the wind tunnel and depend only on the wind tunnel configuration.

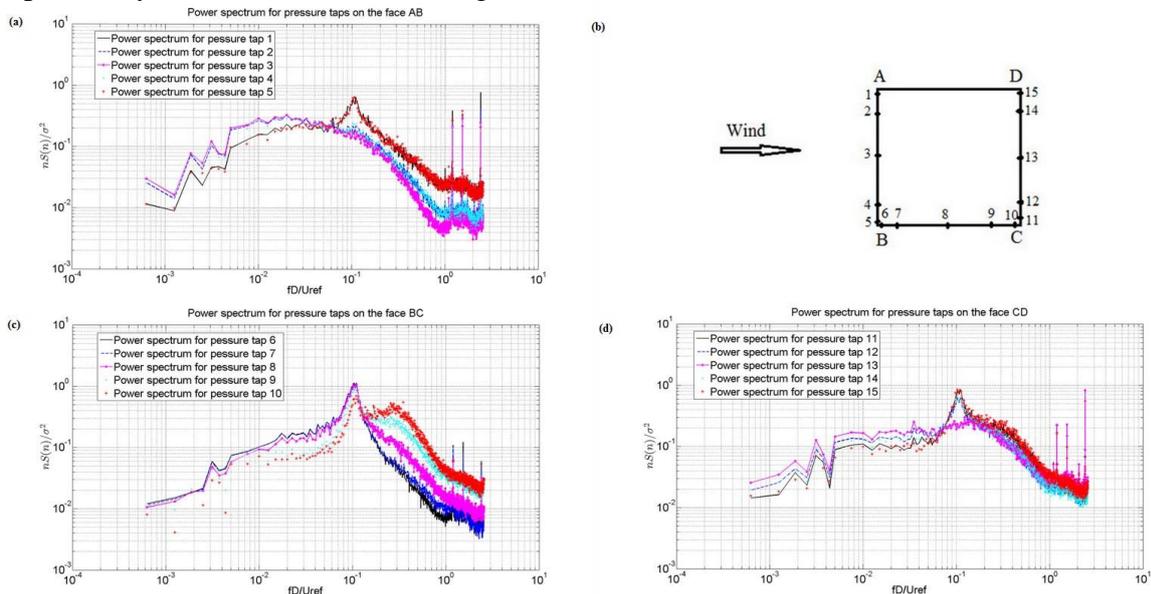


Figure 5: a) power spectrum of pressure on AB, b) Configuration of pressure taps for the present local spectral analysis, c) power spectrum of pressure on BC, d) power spectrum of pressure on CD

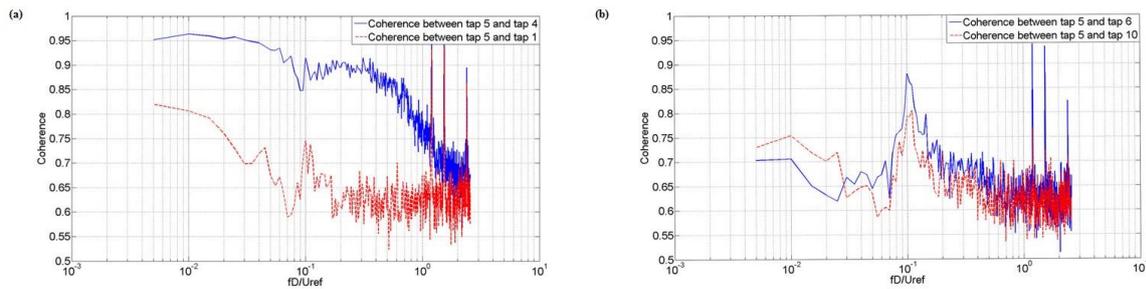


Figure 6: a) coherence between taps on AB side, b) coherence between taps on AB and BC sides

4 CONCLUSION

This paper presents different wind tunnel measurements performed to investigate the pressure load on a tall tower immersed in an atmospheric boundary layer. The characteristics of the oncoming inflow are well controlled regarding the mean velocity profile and the flow integral length scales at the reference height according to the literature.

Global and local wind loads were measured and compared. An analysis of the spectral characteristics of both measurements showed the presence of a marked peak at a Strouhal number of 0.11 only for the global lateral force whereas it was present in pressure measurements in building sides normal the oncoming wind. Based on the analysis of the spectral coherence between different pressure tap locations, the loss of this strong spectral signature for the global wind force in the longitudinal direction is attributed to the loss of phase coherence between pressure signals on these sides. The integration process used to obtain the global forces from the local pressure measurements using non-phase-locked signals smears out the spectral influence of the vortex shedding.

This point will be investigated further by analyzing the phase and coherence pressure signals at different locations. The fact that some locations of the side facing the oncoming wind are influenced by the vortex shedding even if theoretically located upstream the separation point will be investigated in future work using the PIV measurements to analysis the local structure of the flow.

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