EACWE2022

8th European-African Conference on Wind Engineering

20-23 September 2022 | Bucharest, Romania

The appearance of constant-frequency time cells during vortex-shedding from a square cylinder in accelerating flows

Stefano Brusco 1*), Guido Buresti2), Yuan-Lung Lo3), Giuseppe Piccardo4)

1) Postdoctoral researcher, University of Genoa, Italy, stefano.brusco@edu.unige.it
2) Consultant Scientist, University of Genoa, Italy, guidoburesti@gmail.com
3) Associate Professor, National Taipei University of Technology, Taiwan, yllo@mail.ntut.edu.tw
4) Full Professor, University of Genoa, Italy, giuseppe.piccardo@unige.it

ABSTRACT: A wind tunnel test campaign is conducted to trace the temporal variation of the shedding frequency of a square cylinder tested under the action of accelerating flows. These are characterized by flow accelerations which are consistent with those typical of thunderstorm outflows. Time intervals in which the shedding frequency is constant are found. The presence of these constant-frequency time cells reflects a local violation of the Strouhal law, and it seems to be connected with the flow acceleration. Furthermore, the ensemble mean of the Strouhal number is seen to decrease for higher levels of acceleration.

Keywords: Thunderstorm outflows, transient aerodynamics, constant-frequency time cells

1. INTRODUCTION

Bluff-body aerodynamics has been extensively studied in the course of the second part of the last century, in particular thanks to the use of wind tunnels, appositely built to design slender structures capable of withstanding wind-induced actions. Amongst the tested shapes, the square one stands out. In fact, during the Seventies, many architects and engineers designed their skyscraper avoiding any sort of modification of the regular cross-section with height, but relying on robust systems of structural elements and foundations to withstand the wind-induced actions. With time, the sectional model of a square cylinder has become a benchmark replicated by many laboratories and research centres to validate their measurements, proposing investigations that enlightened the effects associated with the sharpness of the edges, the presence of free-stream turbulence and the occurring of Reynolds effects. As a matter of fact, the contribution of wind tunnel test campaigns to the design of slender structures has been striking. Indeed, sets of adequate pressure and force coefficients were evaluated for many design configurations. They were then treated as constant quantities and combined with the knowledge of the kinetic pressure to derive the full scale aerodynamic loading, by invoking the applicability of the strip and quasi-steady theory (Kawai, 1983). This procedure is well-consolidated when studying effects on structures induced by synoptic winds, which have indeed steady characteristics in both wind speed and direction (Solari, 2014). On the other hand, the transient nature of thunderstorm outflows might subvert its validity. Thunderstorm outflows are non-stationary phenomena occurring at the mesoscale, whose duration may be limited while their flow direction may exhibit remarkable irregularities (e.g., Choi, 2000). A transient conditions is expected to affect the vortex-shedding phenomenon and its development, as well as the non-dimensional coefficients, since these may depend on the regularity and configuration of the shedding of the vortices (Buresti, 2012). The topic of transient aerodynamics constitutes one of the most uncovered aspects related to thunderstorm outflows (Solari, 2020). In fact, the literature on transient aerodynamics is often not

---

*) *Corresponding author*

relevant to thunderstorm outflows, being usually associated with tests carried out for accelerations which are too high to be considered representative of this type of flows (e.g., Sarpkaya and Kline, 1982).

The present work – collocated within the framework of the ERC Project THUNDERR – is based on a wind tunnel test campaign carried out at the multiple-fan wind tunnel of the Tamkang University (TKU-MFWT), in Taipei. Multiple-fan wind tunnels were conceived in Japan in the Nineties, and they allow the reproduction of rapid changes in velocity thanks to the reduced inertia of their fans. A sectional model of a sharp-edged square cylinder, equipped with 94 pressure taps, has been installed in the test chamber, and subjected to the action of different accelerating flows. These are calibrated to be consistent with full-scale thunderstorm outflows, in particular in terms of flow acceleration (Brusco et al., 2022). Attention is particularly given to the non-dimensional cross-flow coefficient linked with vortex-shedding, aiming at detecting the temporal variation of the shedding frequency. In doing this, tailored time-frequency analyses (based on the continuous wavelet and Hilbert transforms) are proposed.

2. THE EXPERIMENTAL FACILITY AND THE WIND TUNNEL MODEL

The Tamkang University multiple-fan wind tunnel is an actively controlled wind tunnel endowed with 72 individually controlled fans to drive the flow, arranged in a 12 x 6 matrix. The test cross-section is 1.32 x 1.32 m. No roughness elements are used to develop the velocity profile and all the internal surfaces are smooth. The contraction rate is 1:2, acting on the vertical dimension only, and the total length of the facility is 10.43 m. The nominal mean wind velocity in the tunnel ranges from 2 to 16 $\frac{m}{s}$, with an average turbulence intensity of approximately 2.5 %.

The wind tunnel model is a sectional model with a side of 6 cm, which spans the entire width of the test section. As shown in Fig. 1, it is studied for zero incidence only and 94 pressure taps are installed along its extension, 46 of which are placed in correspondence to its mid-span section.

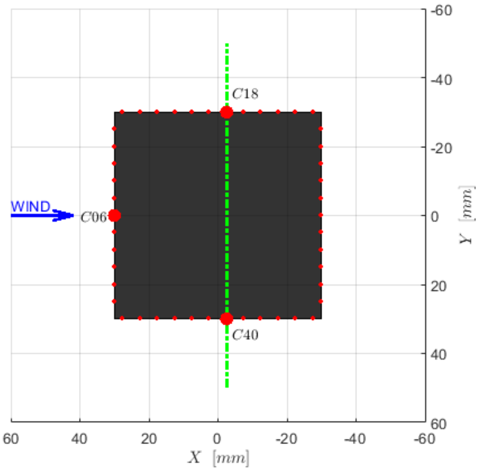

Figure 1. Tapping scheme of the mid-span section of the sectional model.

In particular, the signal difference of the couple of taps *C18*/*C40* is made non-dimensional by normalizing it with the reference dynamic pressure, thus obtaining a non-dimensional cross-flow coefficient, $c_{\Delta P_L}$, which is linked to vortex-shedding. To enhance the two-dimensionality, an adequate containment of the flow is obtained by installing two circular end-plates 60 cm apart; the resulting effective slender ratio of the model is then equal to 10.

The instrumentation installed in the wind tunnel has the scope of capturing the pressure and the wind fields generated around the model. Two 64-channels ZOC 33 pressure transducers (Scanivalve Corporation) have been employed, each one incorporating a high speed multiplexer (45 kHz). The sampling frequency is set at 300 Hz, which is a rate that assures a significant level of accuracy for a frequency range that well encloses the one expected for the vortex-shedding from the studied configuration.

Steady and unsteady flows have been reproduced in the facility, and for each condition multiple repeats have been carried out. As for the unsteady flows, a total of 13 different conditions have been simulated, each one characterized by a number of repeats equal to or higher than 30. The accelerations estimated by such cases are consistent with those evaluated by analysing full-scale data gathered by the Giovanni Solari Wind Engineering and Structural Dynamics Research Group through an extensive monitoring network in the High Tyrrhenian Sea.

The baseline test UF_1 (UF = unsteady flow) has been set to feature the maximum absolute values of the acceleration, connecting the upper and lower bounds of the wind velocity range tested under steady flow conditions in the shortest amount of time allowed by the TKU-MFWT servomotors. A total of 90 repeats have been conducted for this case. Data relevant to one of them are now selected and presented in the next section, where the methodology of the analysis is also briefly described.

3. PRELIMINARY RESULTS AND CONCLUSIONS

While the study of the data gathered in steady flows is straightforward, the corresponding quantities evaluated in accelerating conditions require the design of tailored analyses. A selected repeat of $c_{\Delta P_L}$ (from UF_1) is shown in Fig. 2, whose temporal axis refers to the ramp-up of the wind velocity. Even from a visual inspection, it is evident that the variation of the shedding frequency is not always regular. In fact, the final condition is achieved either through phases in which the frequency increases continuously, or through other time intervals in which the frequency remains almost constant. These different phases are separated by abrupt changes.

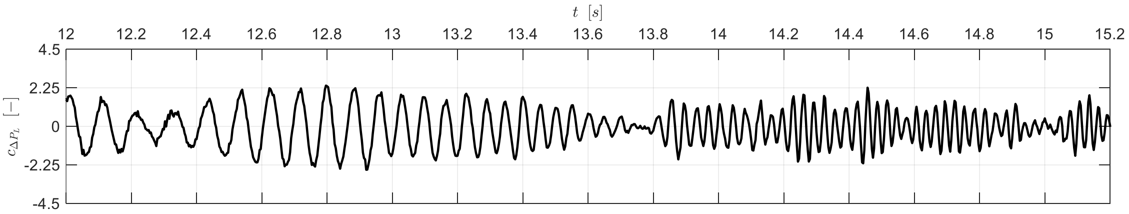

Figure 2. Selected time-history of $c_{\Delta P_L}$, focusing on the ramp-up.

To study the temporal variation of the shedding frequency, time-frequency analyses represent an extremely suitable tool. The ones here proposed are based on the continuous wavelet and Hilbert transforms, and are used to analyse the sensitivity of the results to the relevant parameters.

As regards the continuous wavelet transform, the complex Morlet wavelet is employed, which provides an excellent compromise between time and frequency resolution. The Morlet wavelet is characterized by the central frequency ω_0, whose reduction produces an enhancement of the temporal resolution, whilst its increase translates into an improvement of the frequency resolution. In light of these remarks, the cases relevant to ω_0 equal to 2π, 4π and 6π are investigated. From the corresponding energy maps on the aforementioned coefficient $c_{\Delta P_L}$, the relevant ridges are extracted, in order to trace the time-variation of the instantaneous dominating frequency of the signal. For the chosen repeat of $c_{\Delta P_L}$, Figures 3a and 3b report selected results obtained from the aforesaid time-frequency analyses. Fig. 3a shows the wavelet energy map, obtained using a value of ω_0 equal to 6π. The discontinuous light line represents the corresponding extracted ridge. The same line is reported (in black) in Fig. 3b, which also shows the time-histories of the ridges evaluated with lower levels of the central frequency ω_0 (with lighter scales of grey). Moreover, this graph is also enriched with a dash-dotted line, which provides the theoretical variation of the frequency following the Strouhal frequency-velocity law. Finally, the black dots represent the estimates of the instantaneous frequency evaluated from the temporal spacing between the maxima. All in all, the entire set of techniques shows a good level of similarity with the theoretical curve when the flow acceleration is low, whilst for higher levels of flow acceleration the frequency seems to remain constant during intervals that may be considered as constant-frequency time cells. Discontinuities are found during the passage from one cell to another, and these may become even more evident by studying the time-varying Strouhal number, which permits to observe a local the violation of the Strouhal law.

From the analysis of these results, it is then possible to appreciate that in presence of an accelerating flow the vortex-shedding frequency does not always follow linearly the variation of the wind speed. Furthermore, from a detailed scrutiny of all the repeats and conditions considered in the present test campaign, the number of constant-frequency cells, as well as the timing of their occurrence, are seen to be not always regular. Finally, considering the behaviour of the mean variation of the shedding frequency at given instantaneous velocities, it appears to be similar to or definitely lower than its steady counterpart.

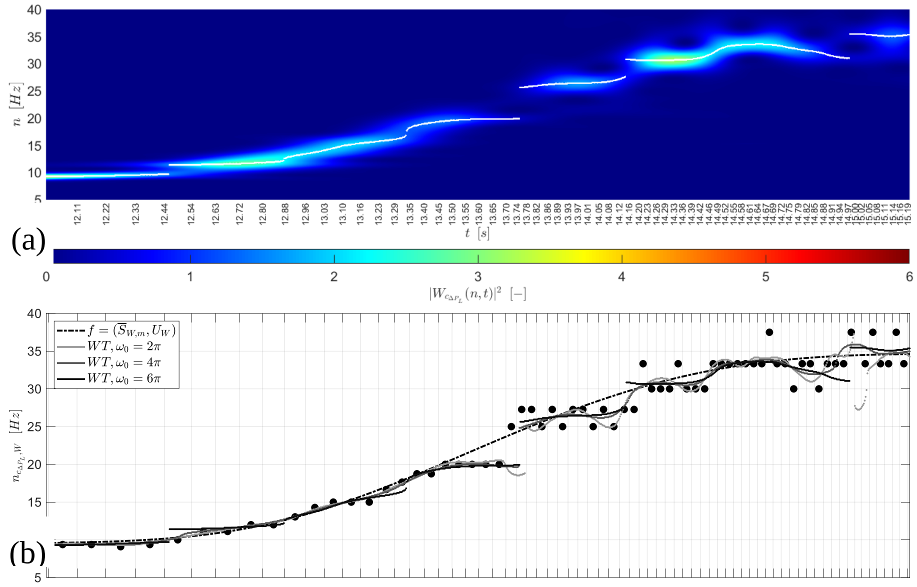

Figure 3. Time-frequency analyses carried out on the signal $c_{\Delta P_L}$ (Fig. 2): (a) energy map, $\omega_0 = 6\pi$, (b) temporal variation of the shedding frequency in the transient.

Acknowledgments

This research has been financially supported by the European Research Council under the European Union's Horizon 2020 research and innovation program (grant agreement No. 741273) for the project THUNDERR - Detection, simulation, modelling and loading of thunderstorm outflows to design wind safer and cost-efficient structures – through an Advanced Grant 2016.

The authors sincerely acknowledge the memory of Professor Giovanni Solari, PI of the THUNDERR Project and main promoter of the collaboration between the University of Genoa and Tamkang University. His passion, love for science and dedication to his students are still vivid and will always be an inspiration for those who were lucky enough to meet him.

References

Brusco S, Buresti G, Piccardo G (2022). Thunderstorm-induced means wind velocities and accelerations through the continuous wavelet transform. Journal of Wind Engineering and Industrial Aerodynamics, 221: 104886. https://doi.org/10.1016/j.jweia.2021.104886

Buresti G (2012). Elements of Fluid Dynamics, Imperial College Press.

Choi ECC (2000). Wind characteristics of tropical thunderstorms. Journal of Wind Engineering and Industrial Aerodynamics, 84(2): 215-226. https://doi.org/10.1016/S0167-6105(99)00054-9

Kawai H (1983). Pressure fluctuations on square prisms – Applicability of strip and quasi-steady theories Journal of Wind Engineering and Industrial Aerodynamics, 13: 197-208. https://doi.org/10.1016/0167-6105(83)90141-1

Sarpkaya T, Kline H (1982). Impulsively-started flow about four types of bluff body. Journal of Fluids Engineering, 104: 207–213. https://doi.org/10.1115/1.3241809

Solari G (2014). Emerging issues and new frameworks for wind loading on structures in mixed climates. Wind and Structures, 19: 295-320. https://doi.org/10.12989/was.2014.19.3.295

Solari G (2020). Thunderstorm downburst and wind loading of structures: progress and prospect. Frontiers in Built Environment, 6(63): 1–24. https://doi.org/10.3389/fbuil.2020.00063