Effects of flow accelerations typical of thunderstorm outflows on the vortex-shedding from a square cylinder

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SUMMARY:
Accelerating flows acting on a sectional model of a sharp-edged square cylinder are reproduced through the action of a multiple-fan wind tunnel. The model is equipped with 94 pressure sensors, while the wind flow around the body is characterized through three Pitot-static tubes. The accelerations generated by the 72 individually controlled fans of the facility are compatible with those typical of thunderstorm outflows. Particular attention is devoted to the acquisition of signals associated with vortex-shedding, for which tailored time-frequency analyses, based on the continuous wavelet and Hilbert transforms, are proposed. Time intervals in which the shedding frequency is constant, separated by discontinuities, are found during the transients. The number and magnitude of such discontinuities seem to be connected with the flow acceleration. The appearance of constant-frequency time cells is not strictly repetitive; moreover, the Strouhal number is seen to decrease for higher levels of acceleration.

Keywords: Transient aerodynamics; vortex-shedding in accelerating flows; constant-frequency time cells

1. INTRODUCTION

The main source of fluctuating cross-wind forces acting on slender structures is the alternate shedding of vortices in their wakes (e.g., Solari, 1985). Research on this phenomenon, which is typical of bluff bodies, has been carried out since the second part of the last century and the description of its main features has been the subject of several reviews (e.g., Buresti 1998). An adequate level of knowledge of bluff-body aerodynamics allowed the definition of sets of pressure and force coefficients which were estimated for a large range of design configurations. These were essential for the design of structures, since they could be treated as constant quantities and combined with the knowledge of the dynamic pressure in order to derive the full-scale aerodynamic loading. This procedure is possible by invoking the strip and quasi-steady theory (Kawai, 1983), whose applicability is well-consolidated when studying effects on structures induced by synoptic winds, which have indeed steady characteristics in both wind speed and direction. On the other hand, its application might be subverted by the transient nature of thunderstorm outflows. These are non-stationary phenomena occurring at the mesoscale, whose duration may be limited and whose flow direction might exhibit remarkable irregularities (e.g., Solari, 2019). A transient condition is expected to affect the vortex-shedding development, as well as the pressure and force coefficients, which depend on the regularity and configuration of the shedding of the vortices (Buresti, 2012). However, the available literature on transient aerodynamics is often not relevant for thunderstorm outflows. Indeed, the pioneering work proposed by Sarpkaya (1963, 1966) was conducted for accelerations which are too high to be considered representative of thunderstorm outflows.

The present work, collocated within the framework of the ERC Project THUNDERR, proposes the results of a wind tunnel test campaign carried out at the multiple-fan wind tunnel of the Tamkang University (TKU-MFWT), in Taipei. A sectional model of a sharp-edged square cylinder has been subjected to the action of accelerating flows, whose magnitude was calibrated to be consistent with full-scale thunderstorm outflows (Brusco et al., 2022). The analyses herein reported focus on the temporal variation of the shedding frequency during the transients, which is studied through tailored time-frequency analyses.

2. WIND TUNNEL TEST CAMPAIGN

The TKU-MFWT is equipped with 72 individually controlled fans, arranged in a 12 x 6 matrix. The test chamber is 1.32 m x 1.32 m in cross section and no roughness elements are used to develop the velocity profile, so that all the internal surfaces are smooth. The contraction rate is 2:1 and is obtained by reducing the vertical dimension only. The total length of the facility is 10.43 m and the contraction beyond the wall of fans covers 4.39 m of this dimension. The maximum speed is about 16 m/s. The average turbulence intensity in the TKU-MFWT has been estimated as approximately 2.5 %, being higher for low levels of wind velocity and lower for higher wind velocities. The sectional wind tunnel model has a side of 6 cm, spans the entire width of the test section, and is equipped with 94 pressure taps. In particular, 46 of them are installed in correspondence of its mid-span section. Two circular end-plates, whose diameter is 40 cm, are installed 60 cm apart, leading the model to a slender ratio equal to 10.

The wind tunnel test campaign has been articulated in two different phases. The first one regarded the simulation of steady flows, employing the multiple-fan wind tunnel as a traditional facility. As far as the simulation of unsteady flows is concerned, a total of 13 different conditions have been simulated, each one characterized by a number of repeats equal or higher than 30. The baseline test UF1 (UF = unsteady flow) has been reproduced for a total of 90 repeats, and the signal of the reference velocity of one of them is presented in Fig. 1 (in black). In the following, preliminary results from a selected repeat of UF1 will be analyzed. The other 12 unsteady conditions have been reproduced by setting different values of the flow parameters, such as the flow acceleration, initial and target wind velocity and the time length between the ramp-up and the ramp-down (see Brusco, 2021 for further details). Amongst these, another case of interest is represented by test UF6 (Fig. 1, in grey), which follows the same path as UF1, but with a lower flow acceleration.

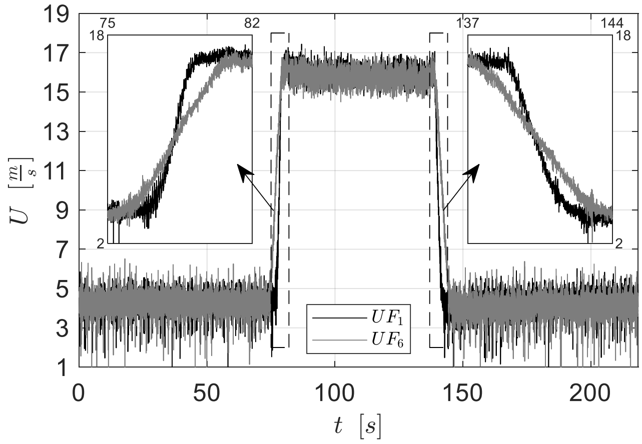

Figure 1. Comparison between the freestream velocity time histories of single repeats of UF_1 and UF_6.

Great attention is devoted to the non-dimensional coefficient linked with vortex-shedding in transient conditions, $c_{\Delta P_L}$, which is connected with the pressure difference between upper and lower model surfaces. Fig. 2 shows one of the relevant ramp-up time-histories.

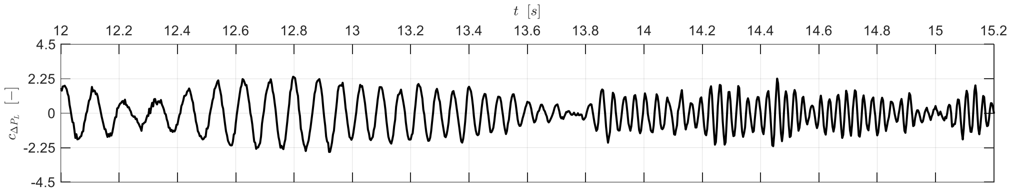

Figure 2. Time-history of $c_{\Delta P_L}$ from one repeat of UF_1, focusing on the ramp-up.

From a visual inspection of the signal, the variation of the shedding frequency evidently appears not to be always regular. The passage from one condition to another seems to occur either with a regular pattern or through phases in which the frequency is quite constant, interspersed with abrupt changes. These are characterized by a sudden decrease of the signal amplitude and correspond to a local violation of the Strouhal law, so that the shedding frequency does not vary with the same trend as the incoming velocity. The time-histories acquired in the ramp-down case point out the same outcome. Inspired by these initial remarks, time-frequency analyses based on the continuous wavelet and Hilbert transforms have been carried out, discussing the suitability of the relevant parameters.

3. TIME-FREQUENCY ANALYSES AND PRELIMINARY RESULTS

As for the continuous wavelet transform, the complex Morlet wavelet is employed, since it provides an excellent compromise between time and frequency resolution. The crucial parameter to be set is the central frequency ω_0, whose increase improves the frequency resolution, whereas its reduction produces an enhancement of the temporal one. Therefore, different cases are considered and analyses are carried out by assuming ω_0 equal to 2π, 4π and 6π. The relevant energy maps are treated to extract the corresponding ridges, which are the curves that follow the time-variation of the instantaneous dominating frequency of the signal. Figures 3a and 3b report some results obtained from such time-frequency analyses applied to the time-history of the signal $c_{\Delta P_L}$. In particular, Fig. 3a displays the corresponding wavelet energy map, evaluated by adopting ω_0 equal to 6π, on which the white line represents the ridge. Further, Fig. 3b shows the time-histories of the ridges extracted from the different energy maps evaluated with three values of ω_0. The dash-dotted line provides the theoretical variation of the frequency following the Strouhal frequency-velocity law. Finally, the black dots indicate the estimates of the instantaneous frequency obtained from the temporal spacing between the maxima. The entire set of techniques shows a satisfactory level of similarity with the theoretical curve for low levels of acceleration, whereas time intervals in which the frequency remains constant (denoted as constant-frequency time cells) are observed when the highest level of flow acceleration are achieved. The passage from one cell to another occurs with discontinuities, which become even more evident by studying the time-varying Strouhal number, which points out the violation of the Strouhal law. The conclusion that may be drawn from the analysis of these results is 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 careful analysis of all the repeats and conditions considered in the present campaign, it is possible to observe that the number of constant-frequency cells, as well as the timing of their occurrence, are not completely regular. Finally, when analyzing the mean behavior of the variation of the shedding frequency, it is possible to observe that the shedding frequency at a certain instantaneous velocity appears to be similar to or definitely lower than its steady counterpart.

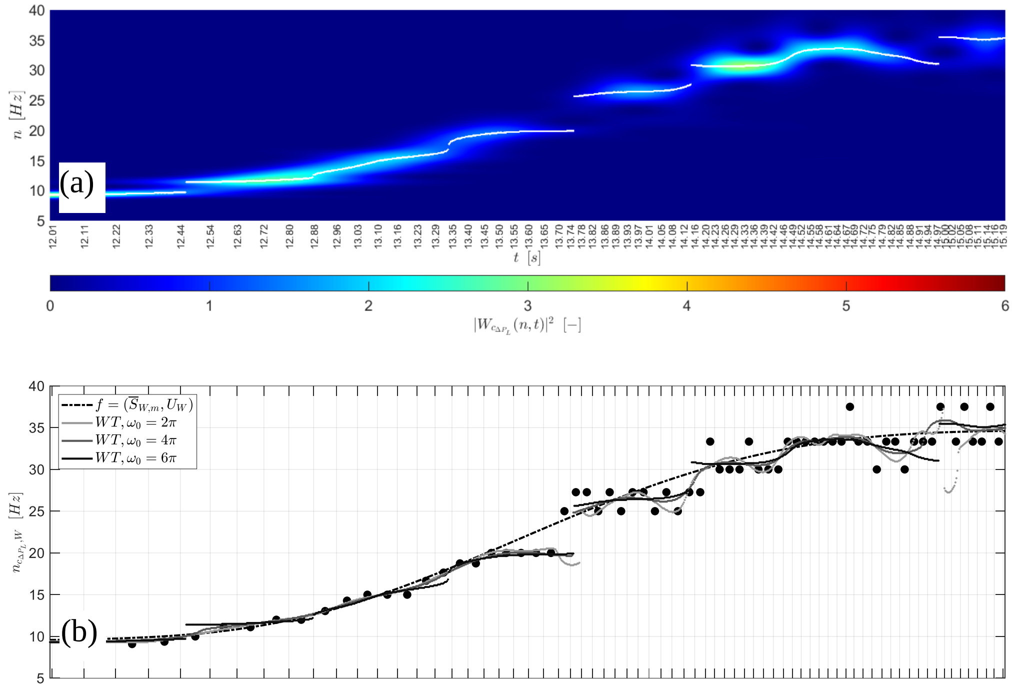

Figure 3. Time-frequency analyses carried out on the signal $c_{\Delta P_L}$ (Fig. 2): (a) $\left|W_{c_{\Delta P_L}}\right|^2$, $\omega_0 = 6\pi$, (b) variation of the shedding frequency in the transient.

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REFERENCES

Brusco, S., 2021. Transient phenomena induced by thunderstorm outflows on slender structures. PhD Thesis, University of Genoa.

Brusco, S., Buresti, G. and Piccardo, G., 2022. Thunderstorm-induced means wind velocities and accelerations through the continuous wavelet transform. Journal of Wind Engineering and Industrial Aerodynamics, 221, 104886.

Buresti, G., 1998. Vortex shedding from bluff bodies. In: "Wind Effects on Buildings and Structures" (Riera, J. D., Davenport, A. G., Eds.), Balkema, Rotterdam, 61-95.

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

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.

Sarpkaya, T., 1963. Lift, drag, and mass coefficients for a circular cylinder immersed in time dependent flow. Journal of Applied Mechanics, 30, 13-15.

Sarpkaya, T., 1966. Separated flow about lifting bodies and impulsive flow about cylinders. AIAA J4, 414-420.

Solari, G., 1985. Mathematical model to predict 3-D wind loading on buildings. Journal of Engineering Mechanics, 111(2), 254-276.

Solari, G., 2019. Wind Science and Engineering, Springer Nature Switzerland.