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FLOW FLUCTUATIONS AND VORTICITY DYNAMICS IN THE NEAR-WAKE OF A TRIANGULAR PRISM IN CROSS-FLOW

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1 INTRODUCTION

In previous investigations ([1], [2], [3]), the fluctuating wake flow field of a prism with equilateral triangular cross-section, aspect-ratio $h/w = 3$ (where h and w are the prism height and width, respectively), and placed vertically on a plane with its apex edge against the incoming flow (see Fig. (1)), was characterized. For this body shape and this flow direction, two strong counter-rotating vortices were found to detach from the free-end, and to significantly influence all the upper-wake flow field. Furthermore, fluctuations at three prevailing frequencies were singled out, with different relative intensities depending on the wake regions.

In particular, the frequency connected to alternate vortex shedding from the lateral vertical edges of the prism, corresponding to a Strouhal number $St = fw/U \cong 0.16$ (HF in the following), was found to dominate in the regions just outside the lateral boundary of the wake, for vertical positions below $z/h = 0.9$. A lower frequency, at $St \cong 0.05$ (LF), was found to prevail in the velocity fluctuations on the whole upper wake, and in particular above $z/h = 1.0$ for downstream distances $x/w \geq 1.5$. Fluctuations with a dominating frequency significantly below that of the vortex shedding had already been detected in the upper portions of the wake of finite circular cylinders with higher aspect-ratio ([4], [5]), and had been suggested to be related to oscillations of the tip vortices. By using time-frequency techniques for component extraction and cross-correlation analysis (see [6]), it was shown in [1] that the LF found in the prism near-wake is indeed associated with a vertical, in-phase, oscillation of the vorticity structures detaching from the free-end. A LES simulation of the same flow configuration, described in [7], confirmed the connection between the LF and the oscillation of the counter-rotating axial vortices detaching from the body tip, and highlighted the complex topology of the upper near-wake produced by the vorticity sheets shed from all the edges of the prism.

In [2] wake velocity fluctuations were also observed at an intermediate frequency $St \cong 0.09$ (IF), and were found to prevail in the symmetry plane $y/w = 0$, in positions corresponding to different downstream distances depending on the value of z/h. By using as a reference the numerical information provided by the abovementioned LES simulation, it was suggested that they may be caused by a flag-like oscillation of the sheet of transversal vorticity shed from the rear edge of the body free-end, and approximately lying along the downstream boundary of the recirculation region in the central part of the near wake.

In the present paper the results are described of experiments carried out to further investigate on the connection between the wake flow fluctuations and the dynamics of the different vorticity structures. Flow visualizations, hot-wire velocity surveys and pressure measurements are analysed for the model in the original configuration and with geometrical modifications along its edges, conceived in order to interfere with the evolution of the various vorticity structures. The forces acting on the various models were also measured and compared.

2 EXPERIMENTAL SET-UP AND PROCEDURES

The tests were carried out in the subsonic wind tunnel of the Department of Aerospace Engineering of the University of Pisa, and the experimental set-up is sketched in Fig. (1), where the used reference frame is also shown. The model has an equilateral triangular cross-section, an aspect ratio $h/w = 3$ (with a base width $w = 90$ mm), and is positioned vertically on a plane, where the boundary layer thickness is below 10 mm, and may thus confidently be assumed not to affect the flow in the upper wake region. The wind-tunnel turbulence level is about 0.9%, and most of the tests were carried out at a Reynolds number $Re = Uw/\nu = 1.5 \cdot 10^5$.

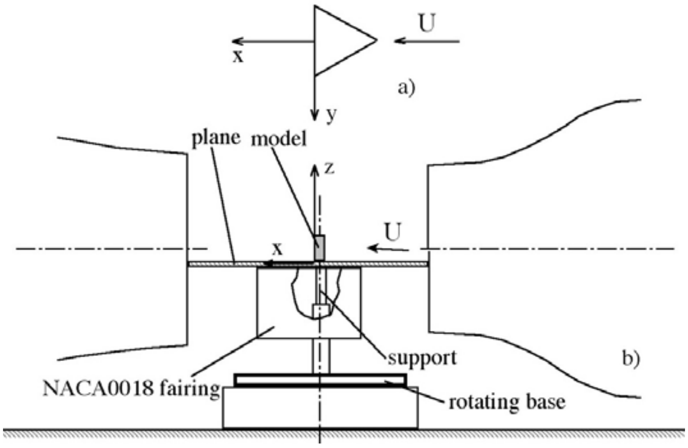


Figure 1: Experimental set-up: a) model orientation; b) test lay-out.

The flow visualizations were performed using a laser light sheet and injecting smoke upstream of the model with a probe. The pressure measurements were carried out using two electronic pressure scanners, each with 16 ports and transducers. From each port, signals comprising 2^{16} samples were acquired with a sampling rate of 2 kHz. For the velocity measurements, single-component hot-wire probes were used, with a sampling frequency of 2 kHz and a time-length of approximately 33 s; the probes could be moved in the axial, vertical and transversal directions using a computer-controlled traversing support rig, which allowed detailed characterizations of the wake flow field to be obtained. For the force measurements, the model was connected to a six-component strain-gage balance, positioned below the plane and inside a fairing, which replaced the support shown in Fig. (1).

The signals obtained in all the measurements were highly intermittent and with significant modulations, both in amplitude and frequency; therefore, they were analysed using a procedure based on the wavelet and Hilbert transforms, described in detail in [6], which allows the dominating spectral components to be extracted and demodulated, in order to obtain the time-variation of their amplitude and of their instantaneous frequency.

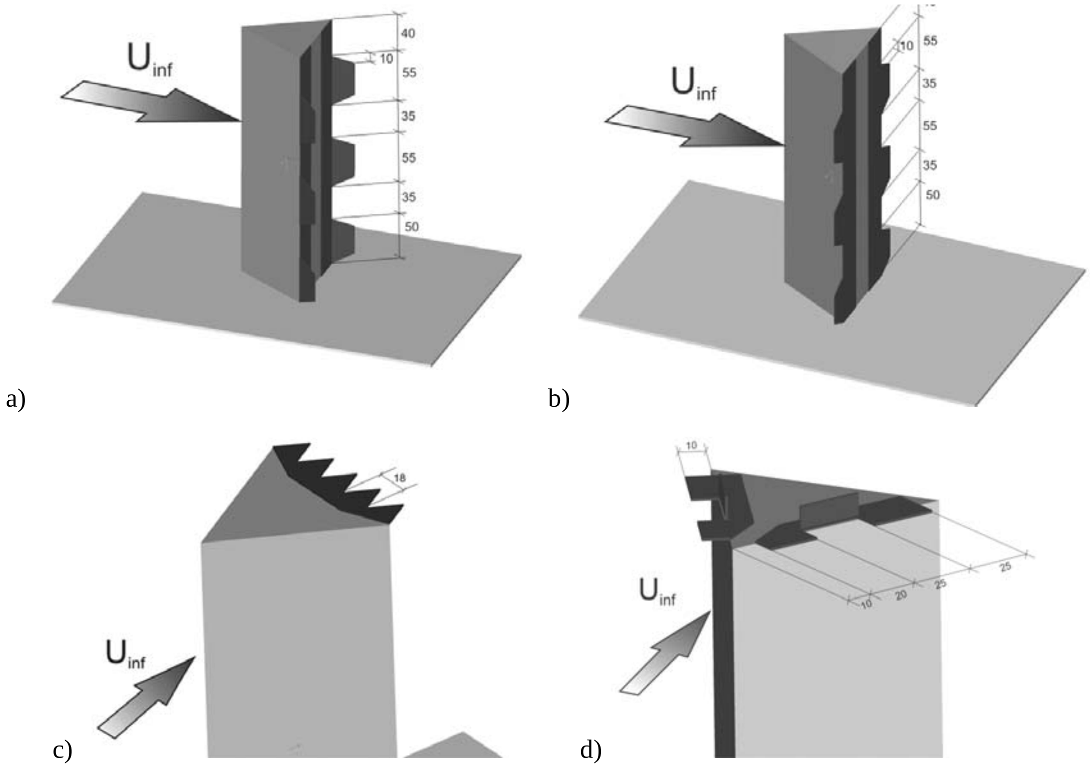
3 RESULTS

The flow visualizations confirmed the complex topology of the upper part of the near wake; in particular, the shear layers from the upstream surfaces are seen to wrap around two counter-rotating vortices detaching from the front inclined edges of the free-end, and to produce a significant difference between the vertical position of the middle and lateral parts of the upper boundary of the wake. Furthermore, in the central portion of the near wake a recirculation region is present, and is bounded by the shear layer formed by the transversal vorticity shed from the rear edge of the free-end.

Measurements of the mean and fluctuating pressures over the upper and rear surfaces of the model completely confirmed the suggestion that the origin of the IF may be an oscillation of the transversal vorticity sheet bounding the recirculation region behind the body. Peaks at this frequency were indeed found to dominate in the spectra of the pressure signals acquired both near the rear edge of the free-end and on the rear surface, below the reattachment line; over the latter region the corresponding fluctuations were also found to be in phase.

The geometrical modifications to the lateral edges of the model that were introduced to alter the dynamics of the wake vorticity structures (Figs. (2a) and (2b)) produced a lowering of the HF, which may be directly related to the increase of the mean wake width. Simultaneously, the IF was found to follow a similar decreasing trend as the HF, which may be explained by considering that the intermediate frequency is connected with oscillations of the recirculation region, whose size variations due to the widening of the wake are likely to have an influence. Conversely, the LF fluctuations present in the upper part of the wake remained unaltered.

On the other hand, the indentations along the rear edge of the model free-end (Fig. (2c)), which were added to try to directly influence the structure of the shear layer bounding the recirculation zone, had negligible influence on the wake morphology and on the frequency and intensity of all the detected components.



a) b) c) d)

Figure 2: Modified models.

Finally, when small plates were introduced along the front edges of the model free-end (Fig. (2d)), in order to directly interfere with the physical mechanism originating the LF fluctuations, no variation was again found in the frequency, energy and regularity of the fluctuations in the upper part of the wake. As suggested by the flow visualizations, this rather surprising result probably derives from the fact that, in spite of the highly irregular free-end edge, the mechanism of roll-up of the vorticity shed from the sides of the plates is still strong enough to be able to generate the axial vortices, even if with a different formation process.

From all these results it may then be concluded that the observed LF fluctuations are not influenced by the values of the frequencies of the remaining wake fluctuations, and are probably strictly connected with an autonomous instability of the counter-rotating axial vortices detaching from the body tip and of the sheets of vorticity wrapped around them.

As for the force measurements, no significant difference was found between the values of the mean drag force coefficient, based on the effective cross-flow area, of the original model and of the modified model shown in Fig. (2a). Conversely, a significantly higher value of this coefficient characterized the model of Fig. (2b); this result may be due not only to the considerably wider wake of this model, but also to the intense vortex shedding that was still detected, in spite of the strong irregularities introduced along the vertical lateral edges.

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