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ABSTRACT: The current paper deals with the aerodynamic loads acting on offshore wind turbine towers when these are temporarily placed at small distance in groups at the quayside of pre-assembly harbours. The importance of a correct simulation in wind tunnel tests of the high Reynolds number regime is emphasized. The results also suggest the possibility to simplify the geometry of the towers, running tests on cylindrical models with a properly chosen equivalent diameter. Finally, the work addresses the issue of a possible variation of the height of the towers.

Keywords: tower groups, high Reynolds number, wind tunnel tests, interference.

1. INTRODUCTION

The pre-assembly phase of wind turbine towers at the quayside in harbours presents configurations that are very sensitive to the wind action. Indeed, prior to being loaded onto special ships for the final offshore installation, the towers (without blades and nacelle) are placed close to each other, forming groups of up to 10-12 elements. These activities usually last 6-12 months, and an accurate estimate of static and dynamic wind loads in this temporary condition is crucial for the optimization of the design of the tower supporting structures (e.g., interfaces and foundation).

The literature does not adequately cover this important engineering problem, as most of the available results refer to groups of infinite circular cylinders in smooth flow (e.g., Price and Paidoussis, 1984; Sayers, 1988) rather than finite towers in turbulent shear flow. Moreover, the wind loads are strongly dependent on the specific geometric configuration of the group, especially in terms of number of towers, grid arrangement and centre-to-centre spacing, thus making the support of wind tunnel tests extremely important.

However, an obstacle to the experimental study of the aerodynamics of groups of towers is the very high Reynolds number expected at full scale for the design wind speed, which cannot be matched in the wind tunnel. This makes the laboratory results uncertain and probably overconservative.

In the present work, simplified cylindrical towers are considered in the interest of generality, and a high supercritical Reynolds number regime is simulated through surface technical roughness. The aerodynamic behaviour of various groups of towers of practical interest is investigated in terms of base force and moment coefficients. The effect of a variation of the height of the towers is also considered along with the influence of the actual shape of a realistic structure.

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2. EXPERIMENTAL SETTING

2.1. Facility and models

The baseline structures considered herein are finite-length cylinders having a full-scale height $H = 17.6\ D_{eq}$, where D_{eq} is an equivalent diameter calculated based on the real shape of modern offshore wind turbine towers (considering the equivalency of the base resultant moment, and assuming constant the drag coefficient per unit length along the tower). All group arrangements present a centre-to-centre nondimensional distance $d/D_{eq} = 1.53$. The tests were performed at a geometric scale 1:187.

The experimental campaign was carried out in the CRIACIV (Inter-University Research Centre on Building Aerodynamics and Wind Engineering) boundary layer wind tunnel (Fig. 1(a)). The turbulent wind profiles provided by Eurocode 1 (EN 1991-1-4, 2005) for terrain categories 0 and I were assumed as target; Figure 1(b)-(c) shows that they were satisfactorily reproduced both in terms of mean wind speed and turbulence intensity.

Monolithic models of the towers were reproduced in carbon-fibre (Fig. 1(a)). Moreover, a two-part model made of ABS was also fabricated and equipped with pressure taps. The measuring model was connected to a strain-gage high-frequency force balance placed below the wind tunnel floor. Nevertheless, when the overall dynamic load acting on the group of towers had to be measured, the models were all connected to a circular plate placed on the force balance flush with the floor.

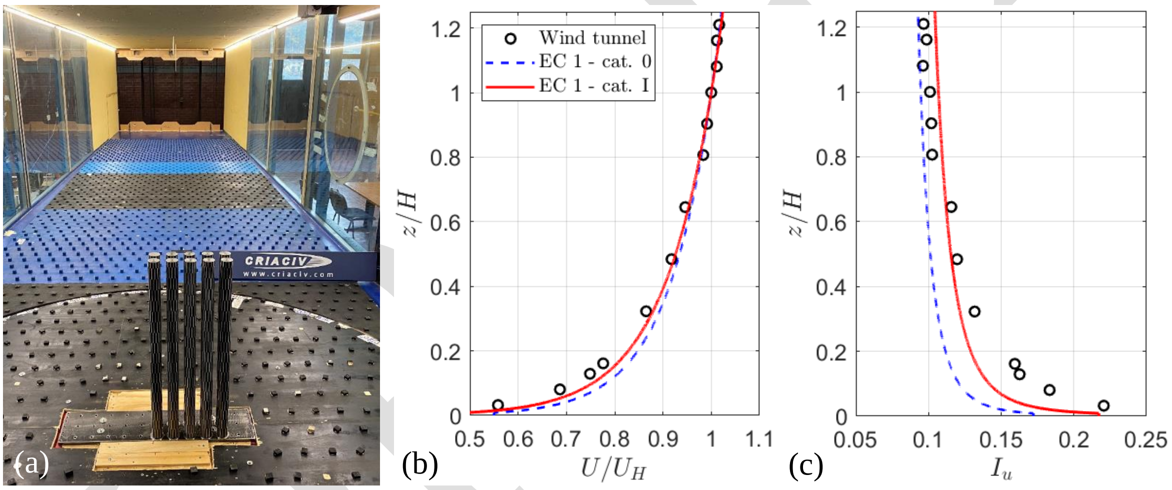

Figure 1. View of a group of ten towers mounted in the wind tunnel (a); comparison of measured and target mean wind velocity (b) and longitudinal turbulence intensity profiles (c)

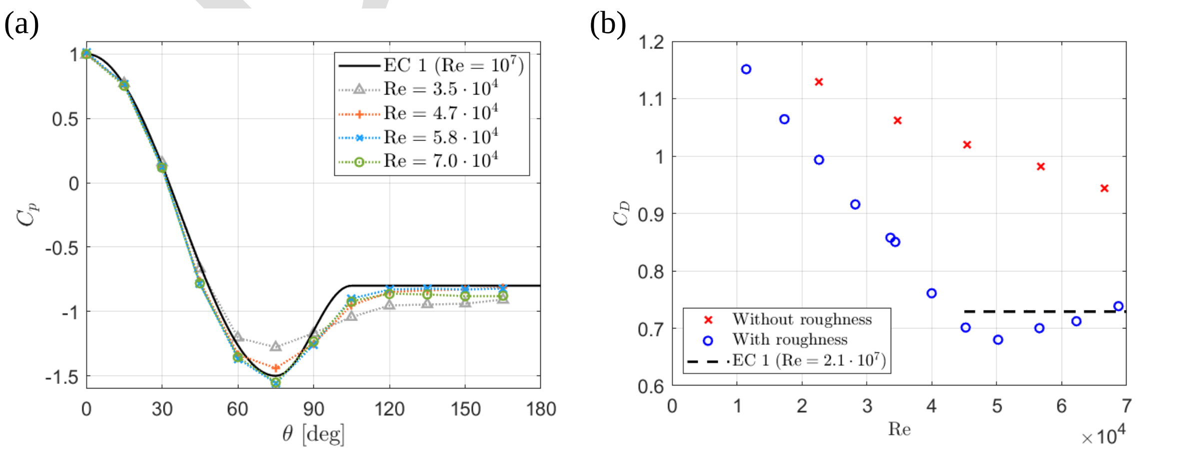

Figure 2. Pressure coefficient distribution (a) and integrated drag coefficient (b) for the confined turbulent flow configuration (circular cylinder)

2.2. Simulation of the supercritical Reynolds number regime

The crucial issue in this study was the simulation of the behaviour of the towers, either isolated or arranged in groups, at a Reynolds number of the order of $2 \cdot 10^7$ (based on the tower diameter), whereas in the wind tunnel it was possible to attain about $7 \cdot 10^4$. This was done by distributing small strips of sandpaper over the surface of the models. The effectiveness of this measure was verified by measuring the pressure distribution on a circular cylinder, for which a number of data are available for high Reynolds numbers. The test set-up was obtained by confining the turbulent flow in a region of the tower where the gradient of the incoming mean velocity is moderate. The results are reported in Figure 2(a) along with the target pressure distribution provided by Eurocode 1 (EN 1991-1-4, 2005). While a subcritical pressure coefficient pattern was found for the smooth cylinder (see e.g. Simiu and Yeo, 2009), in the high wind speed range (say, beyond a wind tunnel Reynolds number of about $5 \cdot 10^4$), the C_p-distribution is stable and very close to the target one. This is confirmed by the drag coefficient obtained through pressure integration and reported in Figure 2(b). It is worth noting that, even without surface roughness, free-stream turbulence contributes to a slight reduction of the subcritical drag coefficient value measured in smooth flow (see also Bell, 1983). It was also verified that the results were independent of the wind direction.

3. RESULTS

3.1 Baseline group configurations

The wind tunnel campaign was focused on mean and peak values of components and resultant of base shear force and moment coefficients. In particular, the latter is particularly important for design purposes, and is here defined as follows:

$$C_M = \frac{M}{q_H \int_0^H D(z)\, z\, dz} = \frac{2M}{q_H D_{eq} H^2} \qquad (1)$$

where M is the base resultant moment, q_H is the mean wind velocity pressure at the height of the top of the tower, and $D(z)$ denotes the diameter of the tower along its height.

For the isolated tower, a mean drag coefficient slightly higher than 0.6 and a moment coefficient of about 0.65 were measured. This is slightly higher than the value reported by Eurocode 1 for a tower having the same slenderness ratio (due to an overly small end-effect factor), and it is somewhat lower than 0.7 provided by CICIND (2002) Model Code.

All the tower group arrangements of practical interest were tested. Examples of results are reported in Figure 3 for the packs of four and eight towers for a full range of wind directions. Noteworthy is the good symmetry of the moment coefficient patterns. In contrast, nonsymmetric diagrams were obtained in some cases for the single row of two to five towers, where multiple flow configurations (either symmetric or biased) are possible (see also Sumner, 2010).

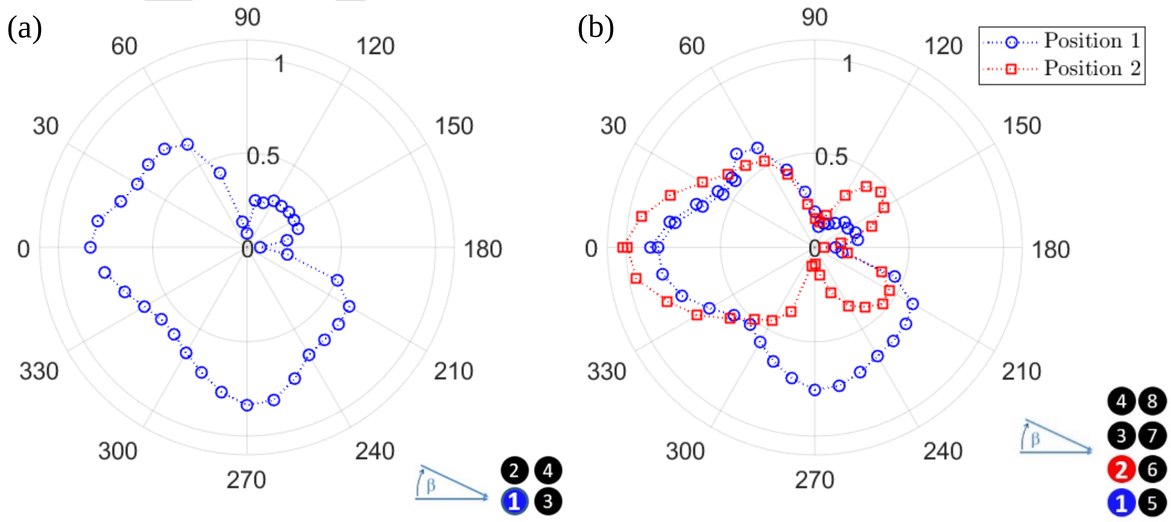

Figure 3. Mean resultant moment coefficient for various wind angles for the tower groups G4 (a) and G8 (b)

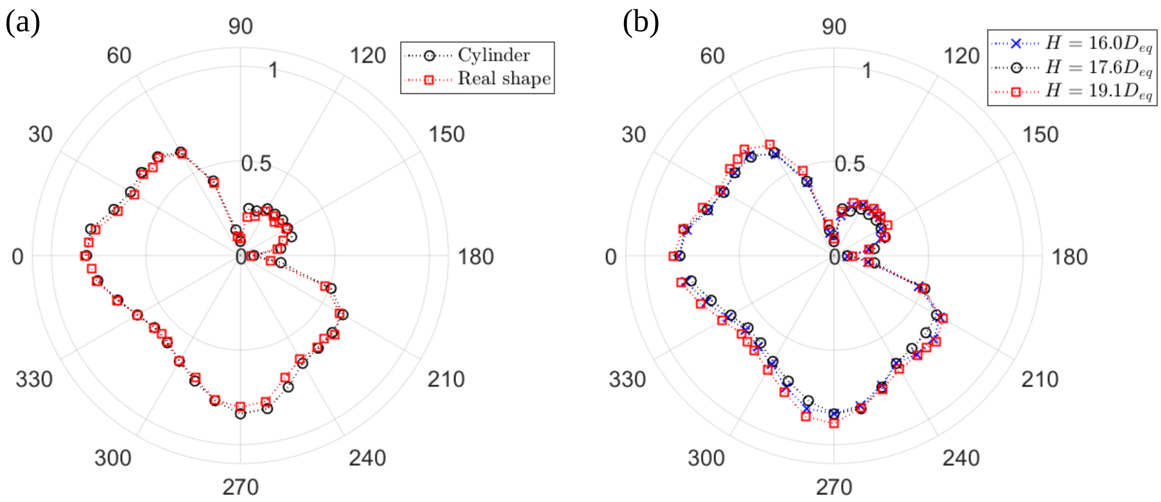

Figure 4. Mean resultant moment coefficient for various wind angles for the tower group G4: effect of tower shape (a) and height (b)

3.2 Effect of tower shape and height

The effect of the shape of the tower was investigated by comparing the results for the simplified cylindrical structure and for the real geometry, including all tapered portions. The results revealed that the difference in the two cases is very small both for the isolated tower and for the groups, especially in terms of base moment coefficient (Fig. 4(a)). This might corroborate the sensibleness of the choice of the equivalent diameter, which was based on the moment coefficient indeed.

Another extensive study was carried out about the effect of the height of the towers, shedding light on a behaviour slightly more complicated and less smooth than expected. From the practical engineering point of view, the results obtained for the isolated tower can be reasonably extended to the group configurations (at least for the directions where the loads are higher), defining a sort of correction coefficient. Figure 4(b) shows that the loads for the group of four towers are non-negligibly higher for the 19.1 D_{eq}-tall tower compared to the baseline one; in contrast, the moment coefficient only slightly changes reducing the height of the tower from 17.6 D_{eq} to 16.0 D_{eq}.

4. CONCLUSIONS

The results of this extensive experimental campaign on the aerodynamic behaviour of wind turbine towers arranged in groups at the quayside emphasized the importance of simulating the correct high Reynolds number regime for an accurate prediction of the loads. Moreover, the study revealed that a simplified cylindrical tower with an equivalent diameter can be used instead of the complex real geometry provided that the diameter is carefully chosen. Finally, particular attention must be devoted to possible variations of the height of the towers.

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