August 27-31, 2023
FLORENCE - ITALY
16th International Conference on Wind Engineering
ICWE 16

Dynamic loading of offshore wind turbine towers arranged in groups on port quaysides

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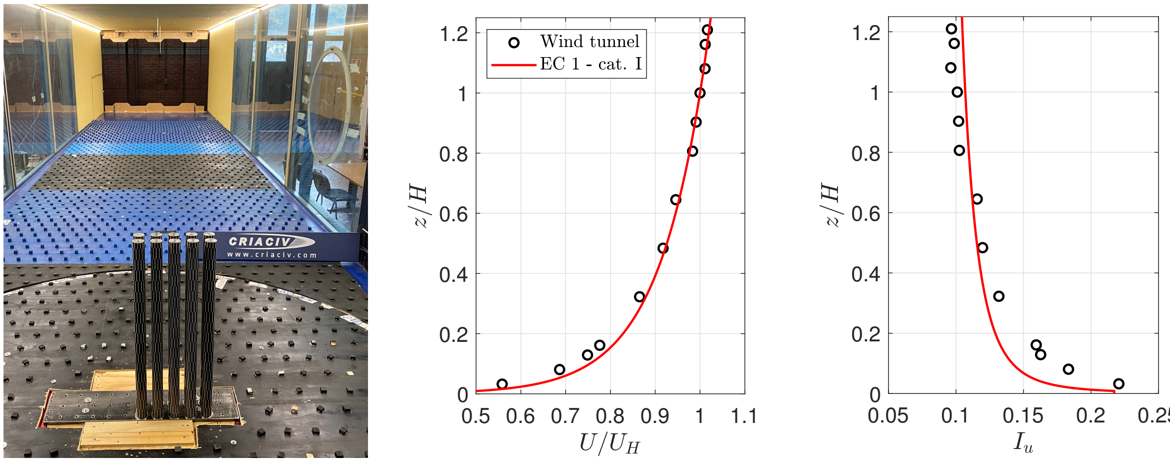
SUMMARY:
Offshore wind turbine towers temporarily arranged in groups on port quaysides for the pre-assembly operations are very sensitive to wind loads, and the large number of parameters make wind tunnel tests the main way to address the problem. On the other hand, the high Reynolds number expected for the towers at full scale represents the primary source of inaccuracy of experiments on scale models and may lead to a significant overestimation of the loads. For this reason, an original engineering solution based on discontinuous surface roughness was proposed and validated, and then applied to a variety of configurations. In the present work, the wind tunnel campaign results were revisited with the support of a simple mathematical model, aiming at estimating the effects of imperfect physical modelling. In particular, the paper outlines possible corrections of the dynamic wind loads due to turbulence integral length scale mismatch and finite stiffness of tower models.

Keywords: wind turbine towers, groups of finite-length cylinders, high Reynolds number

1. INTRODUCTION

Offshore wind turbine towers are usually temporarily placed on freestanding foundations on port quaysides for the pre-assembly operations prior to being loaded onto special vessels. Towers are arranged in square-grid groups at small centre-to-centre distance to facilitate crane operations. Typical examples of arrangements are groups of 2×2, 2×3 or 2×4 towers, or a line of a number of towers. Pre-assembly activities usually last 6 to 12 months. The resultant static and dynamic wind actions at the base of the towers are therefore of great engineering interest for the design of the foundations, and wind tunnel studies are at present the main way to address the problem (see, e.g., Kareem et al., 1998). 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. A surface technical roughness solution was proposed in Mannini et al. (2023) to simulate the high Reynolds number regime, and then used to determine the aerodynamic loads in a large number of configurations.

Various strategies can be followed to determine the design dynamic wind loads on the towers, but other issues may intervene when these are directly determined in the wind tunnel, such as



(a) (b) (c)

Figure 1. View of a group of ten towers placed in the wind tunnel with in the background all the devices placed upstream to simulate the turbulent boundary layer (a); vertical profile of the mean wind speed U (normalized with the mean wind speed at a height H corresponding to the tower top, U_H) (b) and longitudinal turbulence intensity I_u (c). EC 1 denotes the profiles provided by Eurocode 1 (EN 1991-1-4, 2010). See also Mannini et al. (2023).

the integral length scale of turbulence mismatch and the finite stiffness of wind tunnel models (Mannini et al., 2023). The current work revisits the results of a broad wind tunnel study with the support of a simple mathematical model that allows quantifying the effects of imperfect physical modelling and correcting design dynamic wind loads.

2. WIND TUNNEL STUDY

The towers considered in the current study have a height $H = 115$ m and a diameter varying from 7.0 m at the base to about 5 m at the top. However, finite-length cylinders with an equivalent constant diameter $D = 6.55$ m are studied for the sake of generality (Mannini et al., 2023). The centre-to-centre distance between the towers is always $d = 10$ m, leading to $d/D = 1.53$. 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 profile provided by Eurocode 1 (EN 1991-1-4, 2010) for terrain category I was assumed as a target; Figs. 1(b)-1(c) shows that it was satisfactorily reproduced both in terms of mean wind speed and turbulence intensity. Monolithic models of the towers were constructed in carbon-fibre (Fig. 1(a)). Moreover, a two-part model made of ABS was also 3D-printed and equipped with pressure taps. The measuring model was connected to a strain-gauge high-frequency force balance placed below the wind tunnel floor.

The discontinuous surface roughness solution used to simulate the very high Reynolds number expected at full scale is explained in details in Mannini et al. (2023). Measurement result examples in terms of resultant base moment coefficient (normalized with the mean velocity pressure at the height of the tower top times $0.5HD^2$) are shown in Fig. 2 for groups composed by two tower rows.

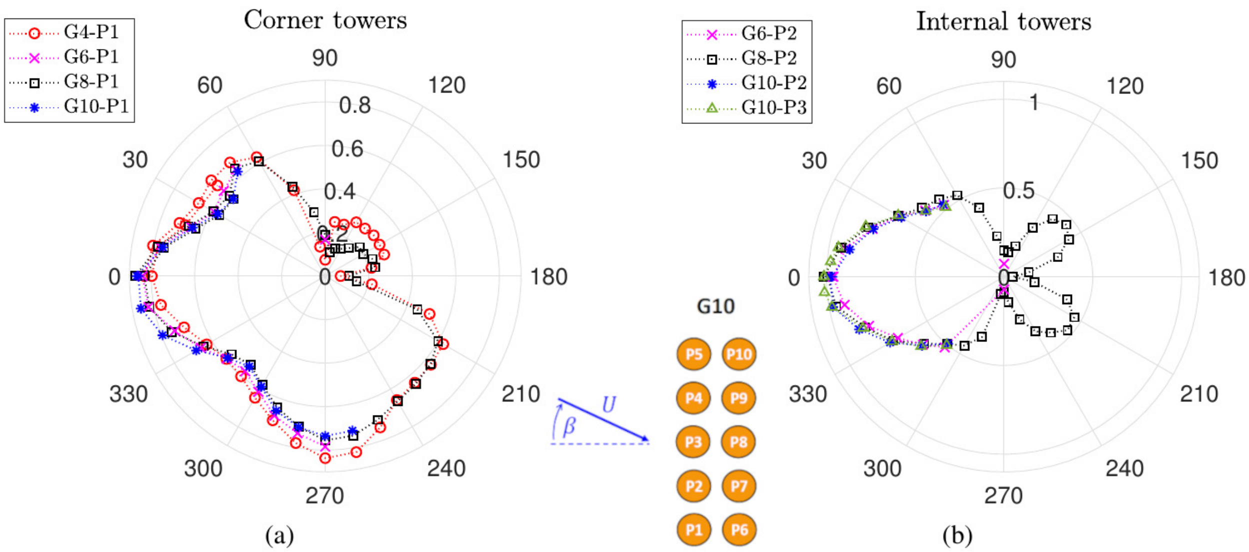


Figure 2. Comparison of mean resultant moment coefficients at the base of corner towers (a) and internal front towers (b) in double-row groups for different wind directions β (in deg). See also Mannini et al. (2023).

3. NUMERICAL ANALYSIS

The dynamic wind load at the base of the towers can be calculated invoking the strip assumption and the quasi-steady theory, that is considering that the forces per unit length at a given height z simply depend, instant by instant, on the velocity fluctuations at that height. Linearizing these buffeting forces, a straightforward calculation can be carried out in the frequency domain referring to the wind spectral properties either in the wind tunnel or at full scale.

To validate the model, the isolated tower is considered in a first step, limiting only to the along-wind force contribution. Fig. 3 shows the drag coefficient per unit length obtained from pressure measurements, which is one of the most important inputs of the calculations. Unfortunately, the velocity fluctuation cross-spectra at different heights were not measured in the wind tunnel; therefore, the classical exponential coherence function with the standard decay factor $C_{uz} = 10$ is ini-

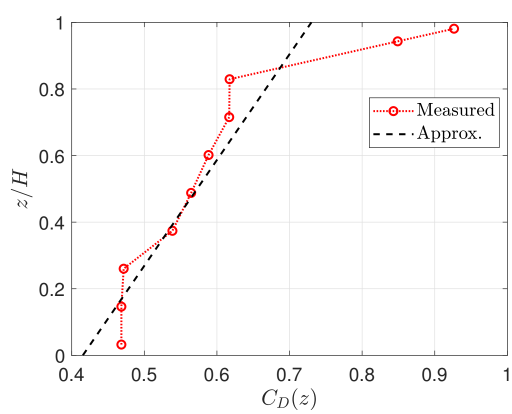
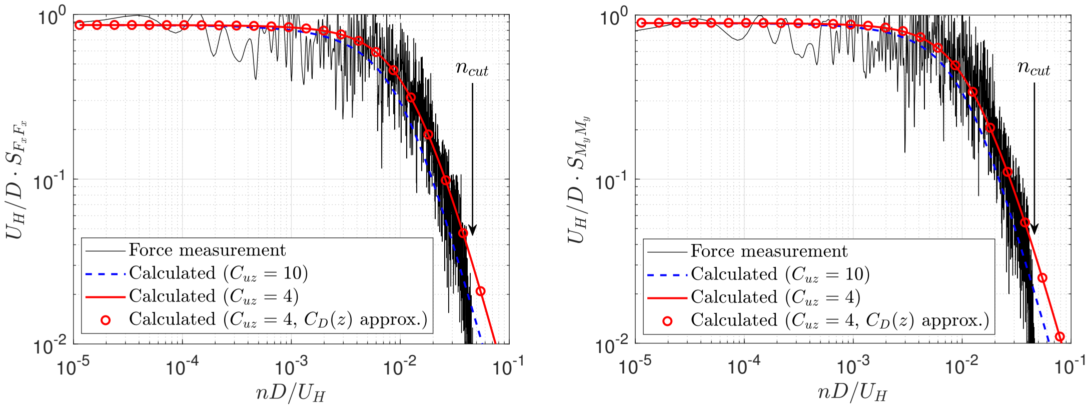


Figure 3. Mean drag force distribution along the isolated tower obtained from pressure measurements and corresponding linear approximation.



(a) (b)

Figure 4. Spectra of along-wind force coefficient (a) and associated overturning moment coefficient (b) at the base of the isolated tower. n_{cut} denotes the low-pass filter cut-off frequency of force measurement records.

tially assumed. As shown in Fig. 4, the agreement with experimental force measurement data is satisfactory, although the fluctuation energy is slightly underestimated in the high-frequency range. Bearing in mind that the cross-spectra were not measured and, above all, that the coherence of buffeting forces is expected to be higher than that of flow velocity fluctuations, in a second step the factor C_{uz} was calibrated against experiments. Setting $C_{uz} = 4$, and therefore increasing the coherence, the agreement with force measurement results is excellent. It is also worth noting in Fig. 4 that the calculation outcomes closely follow the experiments even assuming a linear approximation of the drag coefficient ("$C_D(z)$ approx." in Fig. 4).

The same approach was then applied to group configurations, considering both longitudinal and lateral turbulent fluctuations, either taking advantage of pressure measurements, where available, or determining the linear approximation of $C_D(z)$ based on the resultant forces and moments measured at the base of the towers.

4. CONCLUSIONS

The simple mathematical model outlined above allows revisiting the results of the broad wind tunnel test campaign on various tower group arrangements, estimating and correcting the effects of imperfect physical modelling. Considering the isolated tower as a paradigmatic example, the measured gust factor is underestimated by about 2% because of low-pass filtering required by the finite stiffness of the model, and by 2% for the turbulent integral length scale mismatch. A comprehensive overview of the results is provided in the full paper, focusing on tower group arrangements.

REFERENCES

EN 1991-1-4, 2010. *Eurocode 1 - Actions on structures - Part 1-4: General actions - Wind actions*.

Kareem, A., Kijewski, T., and Lu, P.-C., 1998. Investigation of interference effects for a group of finite cylinders. Journal of Wind Engineering and Industrial Aerodynamics 77-78, 503–520.

Mannini, C., Massai, T., Giachetti, A., and Giusti, A., 2023. Aerodynamic loads on groups of offshore wind turbine towers stored on quaysides during the pre-assembly phase. Engineering Structures. (under review).