Parametric evaluation of the wind induced response in photovoltaic solar trackers using a simplified equivalent wind loads approach

Filippo Calamelli [1], Tommaso Argentini [2], Giorgio Frontini [3], Sara Muggiasca [4]

[1]*Politecnico di Milano, Milan, Italy, filippo.calamelli@polimi.it*
[2]*Politecnico di Milano, Milan, Italy, tommaso.argentini@polimi.it*
[3]*Politecnico di Milano, Milan, Italy, giorgio.frontini@polimi.it*
[4]*Politecnico di Milano, Milan, Italy, sara.muggiasca@polimi.it*

SUMMARY
Nowadays, the improvement of the structural performances of the photovoltaic solar trackers led to the development of lightweight and slender systems, significantly susceptible to turbulent winds. In the current design practice, the wind effects on these kind of structures are typically taken into account with a simplified approach which defines equivalent static wind loads employing the so called Dynamic Amplification Factors (DAFs). Despite its simplicity, the aforementioned procedure is characterized by several drawbacks which restrict its scope of application. In this paper the DAF methodology is compared with a more refined approach varying several parameters to assess its capability to predict the wind induced response, with the main purpose of defining practical design guidelines.

Keywords: Photovoltaic solar trackers, Equivalent wind loads, Dynamic amplification factors, Wind tunnel.

1. INTRODUCTION

In the recent years, the use of Photovoltaic (PV) systems with tracking mechanism significantly increased. These structures are characterized by a longitudinal torque tube to which the solar panel modules are bounded. Furthermore, a series of motor drives allows the panels to align towards the Sun during the day, leading to a greater efficiency with respect to more traditional stationary systems.

Beside the energy efficiency, the structural optimization of the PV trackers led to systems more and more lightweight and slender, significantly sensitive to turbulent wind. Specifically, in the current design procedures, wind effects are taken into account by defining equivalent loads which are statically applied to the structure (Chen and Kareem (2001)). Moreover, it is possible to assess the dynamic response to turbulent wind including in the definition of the equivalent loads the so called Dynamic Amplification Factors (DAFs) (Browne et al. (2020), Taylor and Browne (2020)). This simplified approach requires the knowledge of the spectrum related to the unsteady wind pressures acting on the tracker panels, estimated with wind tunnel tests, and a limited set of structural parameters, i.e. the damping and the frequency of just one modal shape, typically defined employing numerical models.

From a design point of view, the main advantage of the DAF application is the possibility of avoiding more complex and computationally expansive methods which are alternatively required to determine the structural response due to the incoming turbulent wind. Nevertheless, despite its simplicity, the DAF procedure has several drawbacks. First of all it is a method that, to assess the equivalent wind loads, accounts for just one modal frequency, typically the one related to the modal shape more excited by the incoming turbulent wind. In addition, as wind tunnel tests are generally performed on rigid models of the solar trackers, the experimental results can be considered reliable assuming small wind-induced deflection and thus, that the structure is not predisposed to aeroelastic instabilities. Therefore, a comparison with a more refined approach could be useful to investigate the scope of application of the DAF method whose definition, for the aforementioned reasons, is not straightforward.

In this paper, based on a wind tunnel study, the results obtained applying the simplified DAF formulation are compared with those derived by performing numerical simulations which, with a modal approach, directly loads the structure with the experimental time histories of sectional force and torque. Specifically, the comparison is carried out varying a set of parameters, i.e. the structural damping, the inclination angle of the panels with respect to the horizontal (commonly named pitch angle), the exposure of the panels to the incoming wind as well as the spacing between the rows of the PV trackers park. The main purpose of the analysis is to validate the applicability of the DAF approach with the final aim of providing reasonable guidelines for the designers.

2. METHODOLOGY

2.1. DAF approach

In the design practice the wind effects on a structure can be taken into account defining equivalent static wind loads which must take into account both the static action, associated to the mean wind speed, and the dynamic response, mainly due to the resonance effect that occurs when the modal frequencies of the structure approach the range of frequencies of the incoming wind turbulence. The latter can be included in the definition of the equivalent static wind loads adopting the so called DAF methodology. Specifically, integrating the experimental pressures, measured during wind tunnel tests, on a specific surface area of the solar panels, it is possible to assess the time histories of the normal force $F(t)$ and of the torsional moment $M(t)$ applied to the torque tube of the PV trackers. Subsequently, for both of the aforementioned internal forces, the total coefficients related to the equivalent static wind loads are defined as

$$C_{F,\text{total}} = C_{F,\text{static}} \pm C_{F,\text{dynamic}} \tag{1}$$

$$C_{M,\text{total}} = C_{M,\text{static}} \pm C_{M,\text{dynamic}} \tag{2}$$

where $C_{F,\text{static}}$ and $C_{M,\text{static}}$ are derived directly from the time histories and are representative of the mean wind loads and of the background component caused by the pressure fluctuations while, $C_{F,\text{dynamic}}$ and $C_{M,\text{dynamic}}$ take into account the resonant effects and are defined using the DAFs, which are evaluated with the following formulation:

$$DAF = \sqrt{1 + \frac{\pi}{4\zeta}\frac{fS(f)}{\sigma^2}} \tag{3}$$

where ζ is the structural damping, f is the natural frequency of the mode selected, $S(f)$ is the power spectral density associated to the time-varying normal force or torsional moment and σ^2 is the related variance. Afterwards, from the knowledge of these coefficients, it is possible to evaluate the equivalent static wind loads necessary for the design of the PV trackers.

2.2. Numerical simulations

To investigate the applicability of the equivalent static wind loads assessed employing the DAF approach, a modal analysis was performed applying the experimental time histories of the internal forces and of the torsional moments directly to a numerical model of a PV tracker. Specifically, the equations of motion governing the problem can be distinguished in a mean and in a fluctuating component. Gathering the structural parameters from a FE model of a solar tracker, the problem can be easily solved, in modal coordinates, numerically integrating the dynamic equilibrium. As a final results, the total structural response can be defined from the sum of the static and the time-variant dynamic displacements.

2.3. Wind tunnel tests

The experimental data presented in this paper were obtained carrying out tests in the wind tunnel of the Politecnico di Milano. Specifically, the wind pressure distributions acting on the panels surface were evaluated employing rigid models of the structures arranged in a typical configuration of a PV trackers park. Furthermore, the measurements were performed taking into account the variation of different parameters, i.e. the pitch angle of the trackers, the exposure of the panels to the incoming wind and the spacing between the rows of the park. Figure 24depicts a typical experimental configuration.

Figure 24. Experimental setup of the PV trackers in the wind tunnel of the Politecnico di Milano.

3. RESULTS AND CONCLUSIONS

The main purpose of the current research is to perform a parametric analysis to assess the scope of application of the simplified DAF methodology. Specifically, the aforementioned method is compared with a more refined approach varying a set of significant parameters, i.e. the structural damping, the pitch and the exposure angles of the panels and the spacing between the rows of the array. To illustrate the parametric analysis, a selection of cases of particular interest is presented. Specifically, Figure 25 depicts the comparison between the results coming from the application of the DAF approach (continuous lines) and those of the numerical simulations (dotted lines) in terms of Von Mises stresses along the longitudinal development of the torque tube. Two reference trackers were selected, i.e. the second one of the first row (R1C2) and the second one of the second row (R2C2), and the variation of several parameters is taken into account. First of all, the plots presented are the outcome of an envelope procedure over the all the incoming wind directions. Furthermore, Figure 25(a) shows the results for a pitch angle equal to 30° and a Ground Cover Ratio (GCR, defined as the ratio of the distance between two rows and the chord of the panels) of 2.65. With respect to Figure 25(a), the pitch angle is varied to 60° in Figure 25(b) while, in Figure 25(c), the GCR is increased to 4. At last, two levels of damping ratio are report, i.e. 2% and 10%.

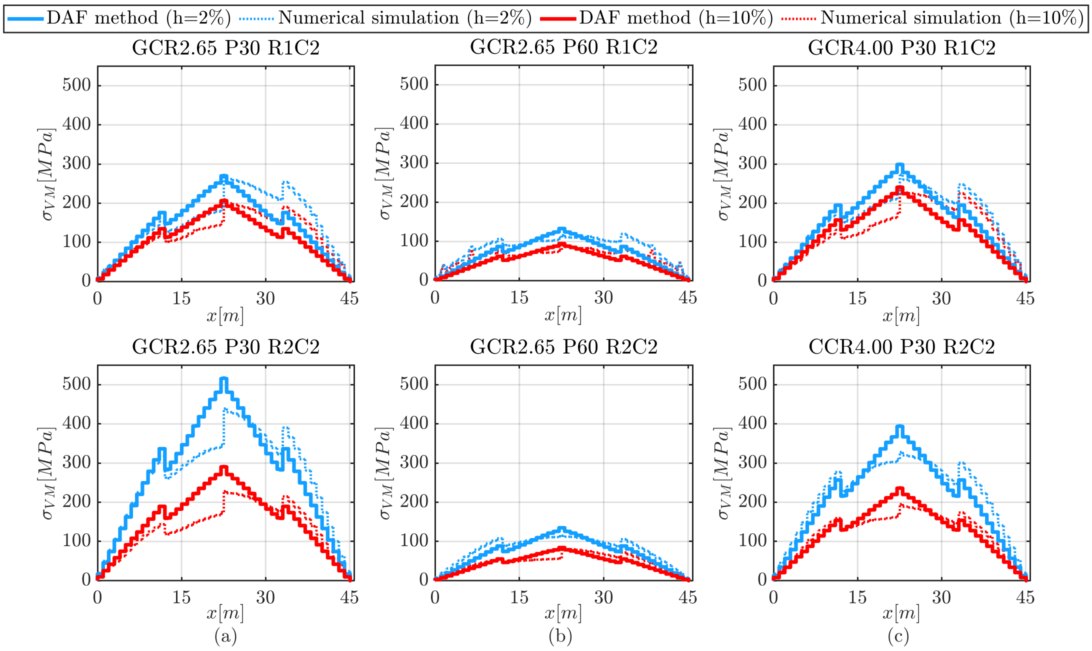

Figure 25. Comparison between the results of the DAF approach and of the numerical simulations, reported in terms of the Von Mises stresses along the torque tube of two solar panels taken as reference case.

As shown in the figures, the DAF approach tends to be conservative, with respect to the numerical simulations, in correspondence of the peak values of the stresses located in the center of the torque tube. Nevertheless, this is not necessarily true for all the sections along the longitudinal development of the structure. As for the pitch angles, the 30° configuration appears to be more critical, mainly in the second row of the array, where the dynamic effects are enhanced by the turbulence generated by the previous row. Indeed, the shielding effect due to the perimetral PV trackers is intensified increasing the value of the pitch angle. Moreover, as confirmed in Figure 25(c), the increase of the GCR seems to have a beneficial effect reducing the stresses in the tracker of the second row. As expected, raising the value of the structural damping, the stresses reduces.

The results reported show that the DAF approach is deemed to be adequate for a rough pre-dimensioning of the structure based on the peak stress values. Nevertheless, to optimize the design of the solar panels, the employment of more accurate approaches would be desirable. However, since alternative methods are often computationally too expansive, a different possibility could be to consider combinations of more localized equivalent wind loads assessed using DAFs coefficients obtained integrating the experimental pressures on different areas, i.e. on the full, half or quarter surface of the solar panels. In the full version of the paper, the set of results will be extended also investigating the effect of different integration surfaces, with the main purpose of defining more detailed and not over-conservative design procedures.

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