Overview of current methodologies for photovoltaic trackers park analysis

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SUMMARY
In today's renewable energy landscape, solar tracker systems have emerged as vital tools for harnessing solar radiation efficiently. While traditional fixed-tilt systems have received considerable attention and have been extensively studied, the industry is increasingly adopting tracking systems. To provide cost-effective solutions, designers face the challenge of minimizing structural resources while ensuring resistance to wind loads. This abstract provides an overview of existing methodologies in photovoltaic tracker design. The state of the art for wind tunnel tests on both solar parks and standalone trackers, and their integration with finite element models, are presented. Different numerical analyses can be implemented, ranging from simplified evaluation of equivalent static wind loads, to more complex structural response time-domain analyses. The latter presents an ideal starting point to develop more in-depth assessments of the expected service life due to fatigue damage, or to perform structural optimization to improve the cost-efficiency of the tracker design.

Keywords: single-axis photovoltaic trackers, solar park, wind tunnel, experimental testing

1. INTRODUCTION

The current push towards renewable energy has brought attention to the development of efficient systems for harnessing energy from solar radiation. While traditional fixed-tilt systems are well-addressed in literature, new technologies implementing movable dynamic mechanism are increasingly used in the industry due to their potential to produce more energy given the same covered area. To improve return of investment and maintain competitiveness, designers strive to minimize structural resources while ensuring a sufficient level of structural resources to withstand the expected environmental loads. Since solar parks are usually installed in large open areas, and the individual systems are characterized by large surfaces and low degrees of constraint, wind loads are anticipated to be the predominant load conditions. Under this premise it is of uttermost importance for the designer to estimate as accurately as possible the wind loads acting on the structure and identify the more efficient and cost-effective solution. The present abstract provides in the next section a brief review of the currently existing and developed procedures used to aid engineers in the design task, while in Section 3 the development of numerical procedures is discussed.

2. PROBLEM CHARACTERIZATION

An overview of the current methodologies for photovoltaic trackers park analysis is summarized in Figure 1 and the main items are described in the following.

2.1. Structural properties

Typically, the first key information for characterizing the structural response is the identification of its mechanical properties, that is the structural stiffness, mass and damping. While for the first two components the task is relatively easy due to ready availability of

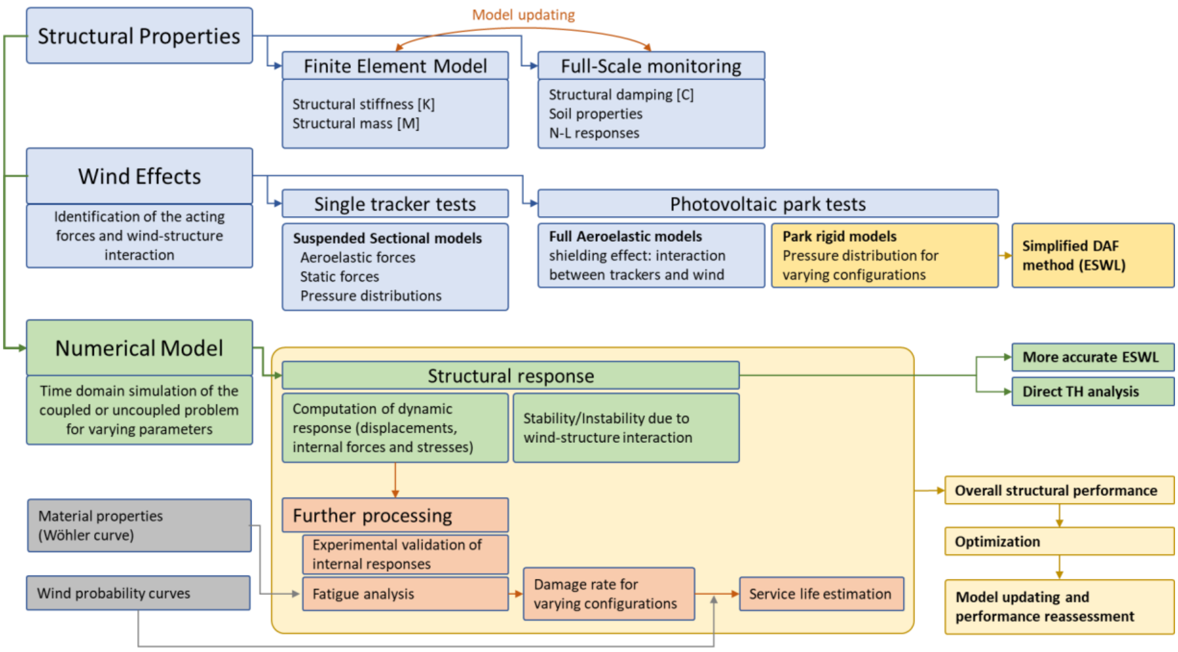

Figure 1. Schematic overview of the main activities concerning the design of PV systems against wind loads.

technical detailing and finite elements (FE) models, the evaluation of the damping ratio is more complicated. A conservative value of about 2%-5%, assuming no internal frictions and perfect connections between elements can be assumed; however, if a more accurate response is needed, it is possible to perform "Free Vibration Tests" (FVT) or monitoring in-situ.

2.2. Wind tunnel experimental tests

The second aspect analyzed concerns the structural response and interaction with the wind phenomena. For this purpose, wind tunnel experimental campaigns are a fundamental tool since they provide essential information for the structural design, optimization and verification of the mechanical systems. Moreover, wind tunnel tests allow for a cost-effective estimation of the response of PV system when interacting with the wind flow. Different typologies of experimental tests can be developed, and their results can be used jointly.

2.2.1. Rigid model of solar park

Rigid models of solar park were extensively adopted in literature and industry to investigate the response against wind actions of fixed-tilt PV panels for varying design parameters: for this reason, these models are well-established in current practice. A selection of the PV park, specifically the corner region which is the most affected by wind loads, is reproduced in model scale and instrumented with pressure taps fitted on the model surface, as shown in Figure 2a. The main results of this experiment are the buffeting loads acting on the tracker, that is the force due to the incoming mean wind and the associated fluctuations induced by turbulence. While in experimental campaigns the entire time histories of the phenomenon are acquired, in actual practice the design is carried out by means of simplified equivalent static wind loads (ESWL) derived from the application of a dynamic amplification factor approach (DAF) (Browne 2020). With this simplified methodology, the entirety of the pressure field is summarized in a distribution of normal force and torsional moment, and then further simplified in a coefficient representative of the extreme peak estimate and the associated dynamic amplification.

2.2.1. Aeroelastic model of solar park

A different type of experimental test that is possible to carry out in wind tunnel facilities involves the development of a fully-aeroelastic model reproduction of a portion of the PV park. This type of experimental investigation can provide more accurate reproduction of the shielding effect, the phenomenon that occurs when the leading perimetral trackers divert the incoming wind flow, reducing the wind speed observed in internal rows.

2.2.2. Aeroelastic sectional model of isolated tracker

A type of experimental tests that reproduce the response of an isolated tracker is given by the aeroelastic sectional model (Figure 2b). This type of test is well addressed in literature and is the approach adopted for the investigation of bridge aerodynamics to evaluate the coupled response between structural motion and wind flow. This test yields the trend of the aerodynamic derivatives, functions that allow the estimation of the self-excited response about a specific tracker's pitch angle (Taylor 2020, Frontini 2022, Cárdenas-Rondón 2023).

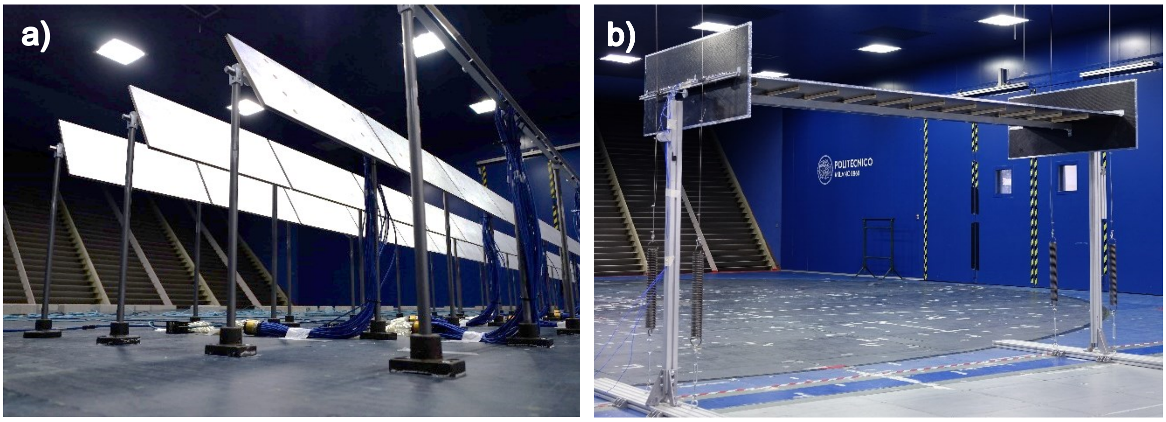

Figure 2. a) Rigid model of a PV park; b) Suspended sectional model of an isolated PV tracker.

3. STRUCTURAL PERFORMANCE EVALUATION

While the design and assessment of the full-scale structure is typically performed adopting ESWL deriving from the model experimentation of the rigid park, the same time histories can be used to develop an analysis in the time domain by means of a FEM approach. Following the schematics of Figure 1, the results of the structural properties identification are combined with the observed wind effects and, from this, the dynamic equilibrium of the single-axis tracker system can be defined. The solution of this governing equation provides the structural rotation and displacements, from which the internal actions and stresses can be derived (Figure 3a). By incorporating the coupled interaction between wind flow and structural motion (Taylor, 2020) into the problem formulation, a more precise structural response, which is also able to highlight potential unstable responses, is derived. This result is of uttermost importance for the tracker design, since for specific inclination ranges (10°-30°) experimental evidence shown that the aeroelastic response brings single axis tracker to be aerodynamically unstable (Taylor 2024), while at larger angles (50°-60°) the response tends to be more stable due to the same self-excited component.

3.1.1.Fatigue damage assessment

The knowledge of the structural response allows the designer to perform further analysis on the investigated system. The assessment of damage accumulation due to fatigue in structural elements typically subjected to large excursion in internal stress, such as the connections point (Frontini 2023), is particularly relevant. Processing the stress time histories with the rainflow method (Figure 3b) and combining the stress excursion distribution with the component Wöhler curve, a damage accumulation rate (specific of a given set of parameters) can be estimated. The resulting damage rate, combined with the wind probability curves, can be used to estimate a possible service life for the tracker's structural components.

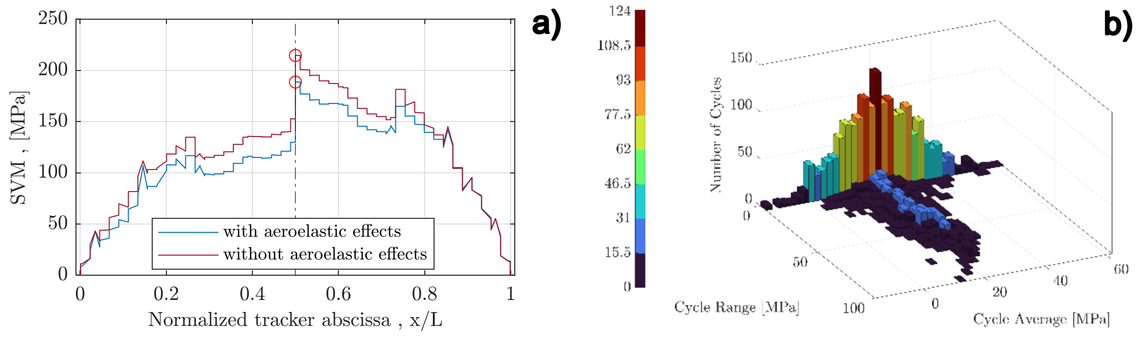

Figure 3. a) Envelope of an internal stress across all tracker's cross sections; b) Example of a rainflow distribution

4. FINAL REMARKS

In the present work an overview of the principal experimental and numerical procedures currently developed to analyze the PV trackers response has been presented. The methodologies are based on a hybrid approach that combines experimental measurements, numerical models, and eventually also full-scale monitoring (actual tracker installations, wind statistics). Several parameters concerning both the tracker's configuration (pitch angle, geometrical dimensions, structural damping and frequency), and the park layout (inter-row distance, position of individual trackers, effects of wind direction) have a relevant impact on the dynamic response and must be accurately analyzed. The presented time-domain procedures for the computation of the tracker response allow for a more accurate evaluation compared to what the simplified DAF approach can provide. It follows that the results can be used to develop more in-depth analyses, such as the estimation of the service life due to fatigue damage or the development of structural optimization procedures. The cost-effectiveness of the solution can be improved with an iterative procedure where the PV tracker (and the related park) is updated from time-to-time, consequently the solution is reassessed until a optimal level of performance (resistance, expected serviceability life) is reached.

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