

A novel numerical framework for efficient design of aerodynamic mitigators in solar tracker systems

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SUMMARY

Wind-induced torsional instabilities remain a major risk for single-axis solar trackers, and aerodynamic mitigators are a key means of reducing this vulnerability. Current methodologies rely either on quasi-steady models that cannot capture unsteady flow separation and wake effects, or on full 3D CFD-based fluid–structure interaction, which is too computationally expensive for iterative mitigator design. This work proposes a fast hybrid analysis framework that couples low-cost two-dimensional moving-mesh CFD at representative sections with a full three-dimensional finite-element model (FEM) of the tracker system through preCICE. The 3D FEM is essential because torsional instability depends on globally coupled torsion and bending response governed by nonuniform stiffness, mass distribution, and realistic support boundary conditions. The sectional CFD enables rapid screening and optimization of mitigator size, shape, and spanwise layout, including discrete and combined deployments. Both isolated-row and wake-influenced multi-row configurations are considered. Validation is planned against published and experimental benchmarks.

Keywords: *solar trackers, torsional flutter, 2D CFD-3D FEM coupling, aeroelastic instability, aerodynamic mitigation, wake interaction*

1. INTRODUCTION

Single-axis solar trackers are slender structures that can experience torsional instability during high-wind events, producing large-amplitude oscillations that may lead to low-cycle fatigue damage or system failure (Rohr et al., 2015; Valentín et al., 2022; Enshaei et al., 2023; Zhang et al., 2023; Taylor, 2024; Quintela et al., 2020). Predicting the onset condition of torsional instability and its dependence on operating tilt angles, commonly represented by a critical wind speed curve, is a key step in developing mitigating strategies (Rohr et al., 2015; Zhang et al., 2023; Taylor, 2024). Many existing approaches linearize the sectional aerodynamic torsional moment about a mean operating state using aerodynamic derivatives with respect to torsional rotation $\theta(t)$ and angular velocity $\dot{\theta}(t)$, typically identified from sectional measurements or simplified low-order models (Taylor, 2024; Quintela et al., 2020). While efficient, this representation can be insufficient when loads are governed by strongly unsteady separated flow and wake interactions, where the moment cannot be described well using only instantaneous θ and $\dot{\theta}$. To address these limitations, this work proposes a fast hybrid framework that couples 2D moving-mesh CFD with a full 3D finite-element tracker model for mitigator design. The key advancement is performing 2D CFD at selected representative sections along the span to generate unsteady load histories that are transferred and assembled as spanwise-distributed inputs to the 3D FEM, rather than applying one uniform sectional model across the span. Using the coupled time-domain response, the framework predicts the critical wind speed curve $U_{cr}(\alpha)$ for comparison and mitigator evaluation.

2. METHODS

2.1. Framework overview

Figure 1 summarizes the proposed workflow and the rationale for each module. Unsteady aerodynamic loading is obtained using 2D moving-mesh CFD at representative sections, where torsional rotation is prescribed and the resulting sectional force and torsional moment time histories are extracted. This step retains the dominant separated-flow physics responsible for instability onset, while keeping each aerodynamic evaluation computationally inexpensive compared with full 3D CFD-FSI. The structural response is computed using a full 3D FEM of the complete tracker, because torsional instability in a utility-scale system is governed by the true spanwise distribution of stiffness and mass and by discrete support constraints at bearings and piers, which together define how the structure deforms and how loads redistribute along the span. Coupling is implemented with preCICE in the time domain, where the 3D FEM provides the local torsional motion at each coupled spanwise station to drive the moving mesh in the corresponding 2D CFD simulation, and the 2D CFD returns the unsteady sectional forces and torsional moments, which are assembled as spanwise-distributed loads applied to the 3D FEM. This two-way exchange resolves interaction consistently without introducing reduced aerodynamic parameters, and the onset of instability is identified directly from the coupled time-domain response during a wind-speed sweep, where torsional oscillations transition from bounded motion to rapidly growing amplitude. Because the aerodynamic evaluation remains sectional and relatively inexpensive, the modular CFD-to-FEM architecture supports iterative design, including repeated evaluation of mitigator configurations defined by device shape, spanwise installation location, and discrete or combined layout patterns under explicit mass and cost constraints.

2.2. 2D CFD aerodynamic identification

Sectional aerodynamics are computed using URANS or LES with an AMI-based rotating mesh. Both isolated-row and wake-influenced configurations are simulated to represent baseline and array-interference conditions. The CFD outputs are used directly in the time domain without fitting flutter derivatives. Load time series are converted to dimensional loads per unit span and mapped to the 3D FEM using tributary-length assignment, with preCICE handling data exchange, time synchronization, and motion feedback when required.

2.3. 3D FEM structural dynamics and aeroelastic coupling

The structural module is a 3D FEM of the tracker assembly, including the torque tube, module rails, and support posts, with boundary conditions representing the discrete bearings and pier constraints that govern load redistribution and deformation along the span. The structural response is simulated in the time domain under the externally applied aerodynamic loading transferred from the 2D CFD simulation, so the coupled system is written in standard second-order form for the physical degrees of freedom, $M\dot{q}(t) + C\dot{q}(t) + Kq(t) = f_a(\theta, \dot{\theta}, U)$, where $q(t)$ denotes the nodal displacement and rotation vector and $f_a(t; U, \alpha)$ is the spanwise-distributed force and torsional moment history assembled from the sectional CFD results at wind speed U and mean tilt α . The resulting response provides U_{cr} for validation and design comparison.

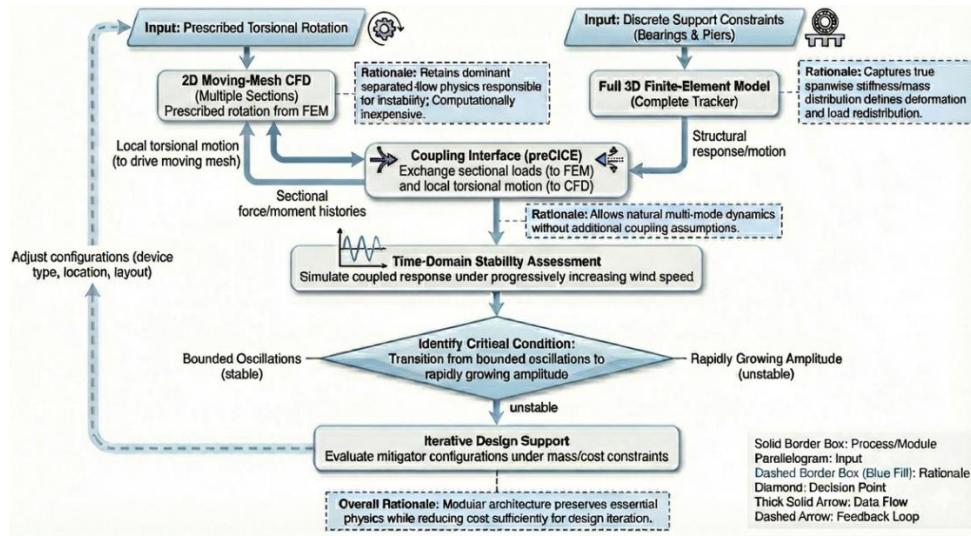


Figure 1: Schematic of the proposed 2D CFD-3D FEM coupling framework for aeroelastic instability prediction and mitigator screening.

2.4. Mitigator design with discrete and combined layouts

Mitigator design is formulated as a configuration-selection problem with design variables specifying (i) mitigator geometry parameters (size and shape), (ii) installation location along the tracker span, and (iii) the layout pattern, including discrete deployment over selected spanwise segments or combined layouts where multiple mitigator types are used together on the same segment or on different segments. For a given design, only the affected section geometries are reanalyzed at the corresponding CFD stations, the updated sectional load histories are coupled to the 3D FEM as in Section 2.2, and the resulting change in U_{cr} relative to the baseline configuration is used to rank candidate designs.

3. VALIDATION AND DEMONSTRATION

The validation plan is organized around the targets listed in Table 1 and is designed to verify the key outputs of the proposed 2D CFD-3D FEM framework. First, the framework will be validated for prediction of the isolated-row instability boundary by comparing the computed critical wind speed curve $U_{cr}(\text{tilt})$ against sectional experimental results obtained in the University at Buffalo wind tunnel, complemented by published sectional datasets and available CFD benchmarks over tilt angle and wind-speed sweeps. Second, the coupled response will be validated at the full-system level by benchmarking the predicted instability curve and response characteristics against full 3D aeroelastic experimental data obtained at the Wall of Wind facility at FIU, and by confirming that the 3D FEM reproduces representative structural dynamic characteristics for tracker assemblies under the same support conditions. Third, a mitigator demonstration will evaluate the framework as a screening tool by testing a set of mitigated configurations relative to a baseline section and comparing the resulting ΔU_{cr} trends and ranking consistency against sectional tests or sectional CFD with mitigators. Together, these validation items help assess the framework's ability to (i) reproduce the instability curve in a baseline configuration, (ii) maintain physically consistent full-structure response under spanwise distributed aerodynamic forcing, and (iii) provide robust

comparative assessment of mitigator size, shape, and layout decisions using a computationally efficient workflow.

Table 1: Planned validation matrix for the coupled 2D CFD-3D FEM framework.

Validation item	Reference data type	Parameters varied	Primary comparison
Isolated-row instability curve	UB wind tunnel sectional tests and sectional CFD	Tilt angle, wind speed	$U_{cr}(tilt)$
Coupling workflow benchmark	FIU Wall of Wind full 3D aeroelastic tests (benchmark)	Wind speed, tilt (if available)	$U_{cr}(tilt)$ trend
Mitigator screening demonstration	Sectional tests/CFD with mitigators	Size/shape, placement, combinations	ΔU_{cr} and ranking consistency

4. DISCUSSION

The proposed workflow bridges quasi-steady sectional models and full 3D CFD-FSI by retaining unsteady separated-flow physics in inexpensive sectional 2D CFD while resolving the global tracker response on a full 3D FEM with realistic spanwise properties and discrete supports. The main contribution is the preCICE-based, time-domain coupling of multiple CFD stations to the 3D structure, which preserves spatially varying aerodynamic forcing and enables systematic mitigator screening and optimization. The primary limitation is that inherently three-dimensional flow features and end effects are represented through sectional aerodynamics. Their influence will be assessed through sensitivity studies and targeted higher-fidelity spot checks where available.

5. CONCLUSIONS

A fast numerical framework is proposed to couple sectional 2D moving-mesh CFD with a full 3D finite-element tracker model for prediction of torsional aeroelastic instability in single-axis solar trackers. Multiple 2D CFD simulations provide unsteady sectional force and torsional moment histories that are exchanged with the 3D FEM through a preCICE-based time-domain coupling interface, yielding the critical wind speed curve U_{cr} used for comparison and mitigator ranking. The approach supports efficient screening and optimization of mitigator size, shape, and spanwise layout within practical computational budgets.

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