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Research Article

# Research status and development trends of wind-induced vibration technology for photovoltaic support systems

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**Abstract.** Against the backdrop of global energy transition, photovoltaic (PV) power generation has witnessed rapid expansion, with China's newly installed capacity in 2024 accounting for 52.4% of global additions. However, PV support systems face significant wind-induced vibration challenges in complex scenarios. This study systematically reviews advances in wind-induced vibration mitigation technologies for PV supports. First, structural characteristics and failure mechanisms are analyzed for fixed-axis, single-/dual-axis tracking, cable-suspended flexible, and offshore PV support systems. Second, synergistic applications of wind tunnel tests, numerical simulations, and field monitoring are reviewed to reveal nonlinear dynamic mechanisms such as vortex-induced vibration (VIV) and flutter. Third, many important dominant factors, such as aerodynamic parameters, geometric parameters, structural parameters, topographic effects are analyzed in detail. And design strategies such as prestress optimization, damping enhancement, and stiffness assignment are used to mitigate wind-induced vibration response in practice. Current challenges are discussed including unclear dynamic aeroelastic coupling mechanisms, insufficient scaling model similarity, and lack of standards for diverse scenarios. In future, developing high-fidelity multi-physical models, intelligent vibration suppression technologies, and cross-disciplinary frameworks will be emphasized to enhance system robustness and cost-effectiveness under extreme climates, supporting the global scaling of PV deployment

**Keywords:** : finite element method, flutter, Photovoltaic support, vortex-induced vibration, wind-induced vibration, wind tunnel experiment



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## 1. Introduction

Under the global energy transition background, photovoltaic power generation has entered a phase of large-scale exponential expansion. According to statistics from China's National Energy Administration: In 2024, China added 277.57 GW of newly installed PV capacity, representing a year-on-year growth of approximately 28.3% (Wang, B.,2025). By the end of 2024, China's cumulative installed PV capacity had reached 886 GW(shown in Figure.1). Globally, new PV installations in 2024 amounted to 530 GW, marking a 35.9% increase year-on-year. Notably, China accounted for 52.4% of the world's newly installed PV capacity in 2024. The annual global photovoltaic installation capacity will increase rapidly year by year, as shown in Figure.2. As the core load-bearing structure of PV modules, the wind-induced vibration of PV support systems has become a critical focus of engineering safety research. Early PV supports predominantly employed fixed rigid structures, characterized by high stiffness and stability (Huang et al., 2022). However, with the growing complexity of application scenarios (e.g., integrated fishery and solar systems, mountainous terrain), large-span flexible supports have gained prominence (Guo, T.; Yang, Y. M.; Huang, G. Q.; et al,2023). While flexible supports offer advantages such as extended spans and enhanced terrain adaptability, they face challenges of low stiffness and natural vibration frequencies, making them susceptible to instability phenomena like flutter and vortex-induced vibrations (Zhou, R.; Wang, H.; Xu, Z. D.; et al,2024; Zhou, R.; Wang, H.; Xu, Z. D.2024); Zhang, X. B.2024).

In recent years, technological innovations in lightweight design and structural flexibility of photovoltaic systems have significantly increased their instability risks under extreme wind loads. According to statistics from the wind-induced vibration-triggered support system failures showed. Notable cases include:

- In 2022, Typhoon Chaba in Guangdong caused localized resonance fractures in the flexible support system of a 50MW aquavoltaic power station, resulting in direct economic losses exceeding ¥30 million.
- In 2022, collapse of a 100-megawatt photovoltaic array support in Xinjiang due to design strength deficiencies during severe winds, causing direct losses over ¥100 million.

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- In 2024, extreme gale weather struck regions including Ili and Tacheng in Xinjiang. Local photovoltaic power stations experienced incidents such as structural deformation of supports and solar modules being blown off, with some stations completely shut down due to structural damage.

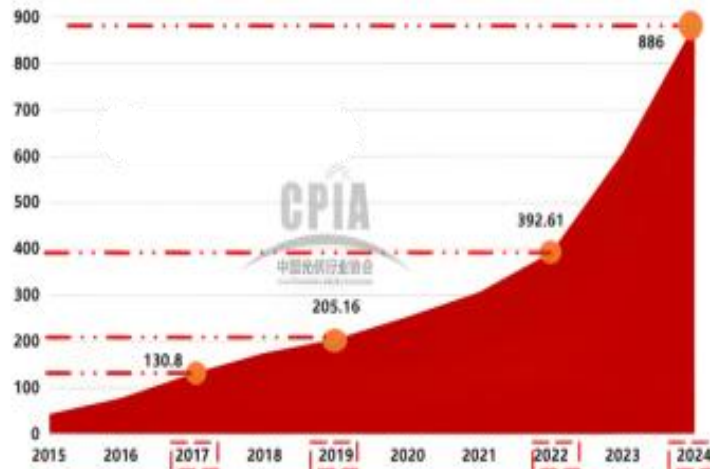


Figure 1 installed capacity of China's photovoltaic power (GW)

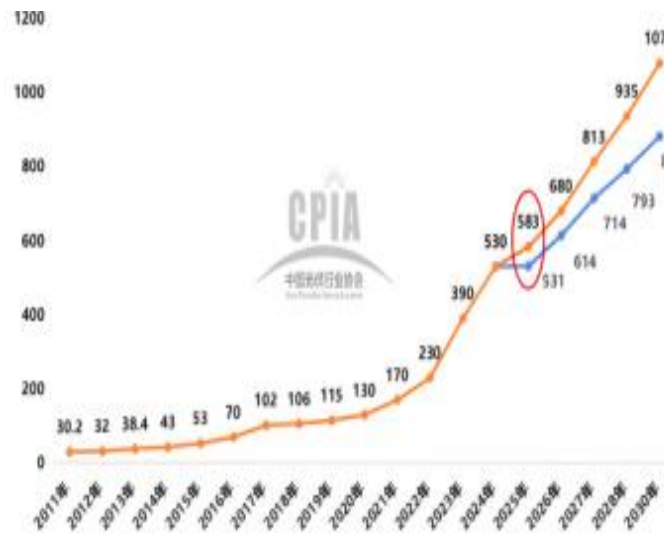


Figure.2 Annual global photovoltaic installation capacity (GW)

Through accident investigation, we found that despite significant advancements in photovoltaic (PV) support structure vibration research, critical challenges and unresolved issues persist in both theoretical and engineering practices. From the perspective of technological innovation, it is imperative to:

- Break Through Traditional Design Paradigms: Overcoming the limitations of the quasi-static wind load design framework and elucidating the nonlinear aeroelastic coupling mechanisms in flexible structures are pivotal.
- Develop Advanced Models: Constructing dynamic response models that account for turbulence scale effects will enable accurate prediction of the spatiotemporal evolution of wind-induced vibration coefficients. This addresses gaps in current codes, such as the neglect of dynamic parameters like mechanical admittance functions.

Therefore, this study systematically reviews the research progress in wind-induced vibration technologies for photovoltaic (PV) support structures. First, the structural characteristics and failure mechanisms of fixed-axis, single/dual-axis tracking, cable-suspended flexible, and offshore PV support systems are analyzed. Core challenges in wind-induced vibration lie in the anti-overturning design of fixed supports, torsional instability of tracking systems, and negative aerodynamic damping effects in flexible structures. Critical influencing factors encompass structural stiffness, system damping ratio, wind direction angle, and topographic features. Second, by synthesizing experimental and computational approaches—including wind tunnel testing, fluid-structure interaction simulations, and field monitoring. This work elucidates nonlinear dynamic mechanisms such as vortex-induced vibrations (VIV) and flutter in PV supports. Design strategies such as prestress adjustment, damping enhancement, and multi-objective collaborative optimization are proposed. Finally, addressing current limitations including insufficient understanding of dynamic aeroelastic coupling mechanisms,



**Figure 3** Accident scene of a photovoltaic power station in China due to strong winds

incomplete scaling model similarity, and lack of standardized multi-scenario guidelines, future research directions for technological advance

## 2. Types of PV Support Structures and Vibration Characteristics

PV support structures, as the core load-bearing components of photovoltaic systems, exhibit vibration behaviors influenced by complex environmental loads coupled with structural dynamic characteristics. This section first analyzes the structural properties of typical PV support systems and discusses their application scopes. Subsequently, it reviews the fundamental theories and developmental history of wind-induced vibrations in support structures, followed by a classification analysis of aerodynamic excitations based on distinct structural system characteristics.

### 2.1. Structural Characteristics of Typical PV Support Structures

Fixed PV support structures are rigid frameworks installed at fixed angles and orientations to secure photovoltaic modules. Their design requires comprehensive consideration of geographical location, climatic conditions (e.g., wind speed, snow load), and topographic features to maximize solar radiation absorption. Core components include vertical columns, main beams, purlins, and connectors, typically fabricated from corrosion-resistant materials such as steel or aluminum alloys. These fixed structures, whose angles and positions remain static post-installation, are suitable for diverse scenarios including rooftops, ground-mounted systems, and floating applications (Hu, B.; Wu, R.; Zhou, L.; et al.2022). Single-axis tracking structures rotate along a single axis (horizontal or tilted) to adjust the azimuth or elevation angle of PV modules for solar tracking. Representative configurations include horizontal single-axis and tilted single-axis types. Dual-axis tracking systems employ orthogonal dual-axes (azimuth and elevation) for omnidirectional spatial solar alignment, enhancing energy generation efficiency at the cost of increased mechanical complexity (Rodríguez-Casado, C.; Martínez-García, E.; Manzanares-Bercial, R.; et al.2024; Frontini, G.; Calamelli, F.; Muggiasca, Sara.; et al.2025; Bao, T.; Li Z.N.; Pu, O.; et al.2023).

Suspension cable-supported flexible structures utilize high-strength prestressed steel cables as primary load-bearing elements, fixing PV modules via suspension or inclined tension to form large-span (80–200 m) self-balancing systems. These structures consist of load-bearing cables (providing vertical stiffness), stabilizing cables (ensuring lateral stability), and adaptive anchoring systems. Characterized by out-of-plane low-stiffness characteristics (allowing 15°–25° vertical deflection) and high strength-to-weight ratios, they are particularly suitable for complex terrains (Guo, T.; Yang, Y. M.; Huang, G. Q.; et al.2023; Zhou, R.; Wang, H.; Xu, Z. D.; et al. 2024; Zhu, Y.F.; Huang, Y.; Xu, C.Z.; et al.2024; Wu, Y.; Wu, Y.Q.; Sun, X.Y.; et al.2025). Offshore PV support systems refer to structures deployed in nearshore or pelagic environments, adopting floating or pile-fixed configurations to withstand harsh marine conditions such as high-salt spray environments and intense wind-wave interactions. Core design considerations include coupled wave-wind load resistance and corrosion mitigation. Representative configurations encompass semi-submersible floating platforms, jacket pile foundation structures, and flexible tension-leg systems (Wang, B; Li, Y; Huang, L.; et al.2024; Djalab, A.; Djalab, Z.; Hammoumi, A.E.2024; Garrod, A.; Hussain, S.N; Ghosh, A.; et al.2024). The professional comparison of four photovoltaic mounting systems (fixed support, adjustable angle support, tracking support, flexible support) are listed in table 1, and corresponding on-site installation photo is shown in Figure.4 in detail.

**Table 1** Structural forms, advantages and disadvantages, and applicable ranges of various types of photovoltaic

Type	Structural Form	Advantages	Disadvantages	Applications
Fixed support	Rigid structure with columns, beams, and foundations; fixed tilt angle (typically south-facing).	Lowest cost Simple maintenance High stability	Lowest energy yield Inflexible angle adjustment	Ground-mounted systems Concrete/flat/tile roofs Low-latitude regions
Adjustable angle support	Single-column design with manual/mechanical adjustment mechanisms (e.g., arc beams, jacks, push rods).	5-10% higher yield than fixed systems Moderate cost Seasonal adaptability	Labor-intensive adjustments Higher maintenance frequency Limited adjustment	Seasonal irradiance regions Mid-to-high latitude areas
Tracking support	Motor-driven structures with rotating axes: Single-axis or Dual-axis	15-40% higher yield Optimal sun alignment Automated operation	High upfront and maintenance costs Complex installation Vulnerable to winds	Flat terrains High-irradiance regions Utility-scale plants
Flexible support	Cable-suspended system with steel columns, tensioned wires/cables, and stabilizing rods; spans large distances.	Adapts to complex terrains Minimal land disruption Low material usage High space utilization	Lower stability (wind/snow loads) Shorter lifespan Difficult maintenance	Mountainous areas Water surfaces Mining wastelands



Fixed support



Adjustable angle support



Tracking support



Flexible support

**Figure.4** Structural forms of different types of photovoltaic support system

2.2 Basic Principles of Wind-Induced Vibration in Support Structures

The dynamic response of photovoltaic (PV) support structures under wind loads is closely tied to structural safety, making vibration instability mechanisms dominated by aeroelastic effects a critical research topic in engineering. When wind speeds exceed a critical threshold, the support system may experience resonant responses due to periodic vortex shedding (vortex-induced vibration, VIV), where the frequency lock-in phenomenon significantly amplifies structural displacements. Concurrently, the flutter mechanism-triggered by fluid-structure interactions and characterized by nonlinear coupling between aerodynamic stiffness and structural damping, can lead to exponential growth in self-excited vibration amplitudes, resulting in catastrophic structural failure. Both dynamic instability phenomena stem fundamentally from interactions between unsteady aerodynamic loads and structural dynamic characteristics. Specifically, vortex-induced excitation forces govern the limited-amplitude vibrations in VIV, whereas flutter manifests as divergent instability driven by aerodynamic negative damping. The following sections briefly review the fundamental principles of vortex-induced vibration and flutter under wind load effects.

2.2.1 VIV Forces

Scanlan (Scanlan, R. H. 1981) proposed in 1981 a single-degree-of-freedom linear vortex-induced vibration self-excitation force model consisting of linear aerodynamic damping terms, linear aerodynamic stiffness terms, and forced loading terms. The model expression is as follows:

$$F_{viv} = \frac{1}{2} \rho U^2 D \left[ Y_1(K) \dot{y} + Y_2(K) \frac{y}{D} + C_L(K) \sin(\omega_s t + \phi) \right]$$

Where,  $Y_1$ ,  $Y_2$  and  $C_L$  are aerodynamic parameters related to reduced frequency;  $\phi$  is a model parameter; and  $\omega$  is the vortex shedding frequency.

To address the limitations of this linear model, Scanlan later modified it by introducing the Van der Pol oscillator to account for nonlinear effects in VIV

$$F_{viv} = \frac{1}{2} \rho U^2 D \left[ Y_1(K) \left( 1 - \varepsilon \frac{y^2}{D^2} \right) \frac{\dot{y}}{U} + Y_2(K) \frac{y}{D} + C_L(K) \sin(\omega_s t + \phi) \right]$$

where  $\varepsilon$  is a nonlinear parameter dependent on reduced frequency. This model uses a Van der Pol-type nonlinear aerodynamic damping term to capture the self-limiting amplitude characteristics of VIV. Due to its mathematical simplicity and ability to replicate key VIV response features, it remains the most widely adopted model.

### 2.2.2 Flutter Forces

Early studies on flutter focused on aircraft and bridge structures. Theodorsen theoretically analyzed the self-excited vibration of an idealized thin flat plate and derived an analytical expression for unsteady aerodynamic forces acting on a two-dimensional plate using potential flow theory (Zhang, X. B.2024). It is known as the Theodorsen force model. While this model effectively describes aerodynamic forces on thin wings or flat-plate cross-sections, it fails to apply to bluff bridge sections with significant flow separation. Through successive research generations, Sarkar et al. (Ehsan, F.; Scanlan, R. H.1990) extended the linear self-excited force model to three degrees of freedom (3DOF), with complete linear expressions for self-excited lift, drag, and pitching moment.

Scholars (Sarkar, P.; Jones, N. P.; Scanlan, R. H.1994) worldwide have developed various mathematical models to characterize aerodynamic non-linearity. Among these, the polynomial model stands out for its ability to describe nonlinear aerodynamic components through higher-order terms. It simulate unsteady aerodynamic effects using reduced frequency dependent parameters, and maintain mathematical simplicity with straightforward parameter identification., Wu et al. (Wu, B.; Wand, Q.; Liao, H., et al.2020) proposed SDOF torsional and 2DOF coupled bending-torsional nonlinear self-excited force models based on polynomial expansions. With advancements in computational techniques and artificial intelligence (AI), researchers are now exploring new methods to analyze and model nonlinear self-excited forces (Gao, G.; Zhu, L.; Han, W.; et al.2018).

## 2.3 Failure Characteristics of Photovoltaic Support Structures Under Wind Loads

### 2.3.1 Fixed Support Structures

Key wind resistance design are summarized as follows.

**Wind Pressure Distribution:** Scientific calculations are required to determine wind pressure distribution across the structure. Critical parameters, such as column spacing and crossbeam cross-sectional dimensions, are optimized to prevent overturning or structural failure under extreme wind speeds.

**Typhoon Resistance:** Coastal installations, for example, must comply with typhoon-resistant design standards.

**Composite Steel Systems:** Some designs utilize pre-assembled connection components to minimize welding points, enhancing structural integrity and reducing wind-induced vibration risks.

### 2.3.2 Single/Dual-Axis Tracking Support Structures

Wind load failure mechanisms are summarized as follows:

**Torsional Buckling:** Wind-induced torque causes buckling of the torque tube at critical wind speeds (30–40m/s). Aerodynamic flutter becomes significant at panel tilt angles of  $\pm 30^\circ$ , leading to structural fractures.

**Resonant Failure:** Overlap between low-order bending modes of the structure and dominant wind turbulence frequencies results in fatigue damage accumulation at weak bolt connections.

**Local Stress Concentration:** Unsteady flow separation at welded joints between support arms and torque tubes generates localized stress peaks exceeding the yield strength.

### 2.3.3 Suspension-Type Flexible Support Structures

Wind load failure mechanisms are summarized as follows:

**Aeroelastic Flutter:** The large-span, low-damping characteristics induce negative aerodynamic damping effects. Exponential growth in coupled vibrations between the main cable and components triggers strand slippage and fracture.

**Fatigue Failure:** Under long-term wind-induced pulsating loads, the stress amplitude in cables may exceed the fatigue limit of parallel steel wire cables, leading to cumulative damage.

**Node Loosening Failure:** Dynamic tensile-shear alternating loads at anchorages induce bolt connection loosening. Geometrical instability occurs when the prestress loss rate gradually increasing.

### 2.3.4 Offshore Photovoltaic (PV) Support Structures

Wind load failure mechanisms are summarized as follows:

**Structural Instability:** Wind-induced overturning moments exceed the structures' anti-overturning capacity under headwinds, causing complete collapse.

**Material Strength Failure:** Wind loads transmitted through PV panels generate bending stresses in critical load-bearing components. Exceeding the yield strength of materials results in plastic deformation or fracture. **Dynamic Fatigue Failure:** Coupling of high-frequency wind-induced vibrations and wave loads in marine environments excites structural oscillations. Long-term exposure leads to connector loosening or fatigue crack propagation. The offshore photovoltaic photo is shown in Figure.5.



Offshore fixed photovoltaic

Offshore floating photovoltaic

**Figure 5** Structural forms of offshore photovoltaic

### 3. Experimental and Numerical Research Methods and Techniques

Experimental methods (e.g., wind tunnel testing and field monitoring) utilize high-precision sensors to capture actual wind pressure distributions and vibration modes, providing baseline data for structural optimization. Numerical simulation techniques (e.g., CFD flow field analysis and finite element dynamic analysis) quantitatively reveal intrinsic relationships among key parameters such as vortex shedding frequency and aerodynamic damping through modeling.

#### 3.1. Experimental Research Methods

##### 3.1.1 Wind Tunnel Testing

Wind tunnel testing remains the most widely used technique for studying vibrations in photovoltaic (PV) support structures. Depending on the research objectives, three primary methods are employed:

##### 1. Rigid Model Pressure Measurement Testing

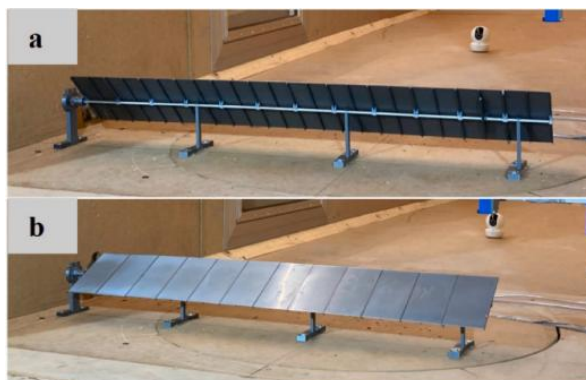
Pressure taps in high-precision wind tunnels collect surface wind pressure distribution data on PV modules to characterize static load behaviors. For example, Hang et al., (Du, H.; Xu, H. W.; Zhang, Y.; et al.2022) conducted rigid model pressure tests to systematically investigate the average and fluctuating wind pressure distribution on flexible supports across  $0^\circ$ – $180^\circ$  wind angles, guiding the optimization of wind vibration coefficients.

##### 2. Aeroelastic Model Testing

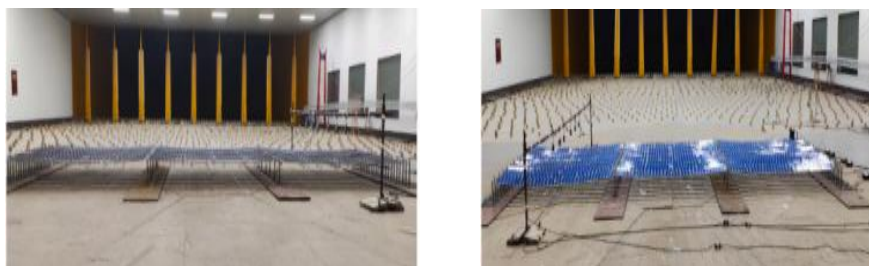
Models satisfying aeroelastic similarity ratios simulate structural dynamic properties, focusing on flutter and buffeting responses. For instance, Li et al., (Li, S.; Ma, J.; Liu, J.; et al.2024)] performed vibration measurements on elastically suspended sectional models at PV panel tilt angles of  $-39^\circ$  to  $+39^\circ$ , analyzing wind-induced responses under varying wind speeds. The study identified flutter critical wind speeds for flexible PV modules and evaluated two aerodynamic countermeasures to enhance flutter stability.

##### 3. Full Aeroelastic Model Testing

Full-scale or near-full-scale models authentically replicate fluid-structure interaction effects. Zhang et al., (Zhang, X. B.2024) used full aeroelastic models to reproduce torsional instability phenomena in single-axis PV supports at tilt angles of  $-45^\circ$  to  $45^\circ$ , clarifying trigger boundary conditions for vortex-induced vibration (VIV) and flutter. This work revealed interference mechanisms underlying large-amplitude torsional vibrations in PV array configurations. Wind tunnel testing of photovoltaic (PV) support systems requires meticulous model design to ensure aerodynamic and structural similarity to full-scale installations. The scaling of aeroelastic models must adhere to critical similitude criteria, including Reynolds number, Froude number, and damping ratios, to accurately capture fluid-structure interactions. Key considerations encompass: (1) Proper simulation of turbulence characteristics in boundary layer wind profiles to replicate site-specific wind conditions. (2) Precise scaling of PV module stiffness, mass distribution, and joint connections to preserve dynamic behaviors like vortex-induced vibrations and galloping instabilities. (3) Measurement protocol optimization for displacement/stress hotspots, particularly at cable anchorage zones and panel edges. Validated wind tunnel data forms the foundation for developing reliable wind-resistant design guidelines and fatigue life predictions. The setup of the single-axis solar trackers is shown in Figure.6, and setup of large-span flexible photovoltaic support structure is shown in Figure.7.



**Figure.6** Tracker setup in the test chamber by Rodríguez-Casado et al., (Rodríguez-Casado, C.; Martínez-García, E.2024)



**Figure.7** Aeroelastic model wind tunnel test by Zhou et al., (Zhou,Y; Peng, R.L.F.; Xiang,Y.; et al.2025)

In recent years, scholars have summarized the literature on the analysis of vibration characteristics of photovoltaic support using wind tunnel tests as follows in Table 2.

**Table 2** the research focus and main findings are listed by wind tunnel tests

Authors	Research Focus	Main Findings
Du, et al., (2022)	Rigid model pressure test	The system investigated the distribution patterns of mean wind pressure and fluctuating wind pressure of flexible supports across the full range of wind angles from 0° to 180°.
Li et al.(2024)	Key research on flutter and buffeting response	Reveals the flutter critical wind speed variation law of flexible stents within the ±39-degree tilt angle range
Estephan al.,(2022) et	Experimental and numerical method for peak wind load estimation of rooftop flexible photovoltaic system	Developing a modified PTS method combined with a dynamic resonance effect; A predictive framework for coupling low frequency turbulence and dynamic effects.
Rodríguez-Casado et al., (2024)	Three-dimensional pneumatic elastic-plastic benchmark model of uniaxial tracker	Establish standardized experimental model specifications; Generate a critical wind speed-tilt angle stability map
Xu et al.(2024)	Wind vibration mechanism of suspension cable support photovoltaic module	Establish the quadratic linear relationship between the amplitude and the wind speed; Proposed a gust load factor range
Sayegh et al., (2025]	Wind vibration mechanism of suspension cable support photovoltaic module	First full-size experimental verification; Optimize the wind deflector effect verification
Cai et al., (2024)	Vibration form evolution of large-span flexible photovoltaic gas bomb array	Realize the full array synchronous air bomb test; The law of reverse energy migration between rows is proposed;
Wu et al. (2025)	Test and evaluation of the new cable truss photovoltaic support system	Improve the structural vertical span ratio; Determine the critical stiffness parameters.
Liu et al.(2023]	Determination of critical wind speed of 33 m span flexible bracket	Determine the most unfavorable wind direction (0 / 180); Establish the calculation method of wind load factor.
Liu et al., (2024)	Experimental Study on Parameter Sensitivity of Flexible Support Structures	Determine the most adverse parameters (inclination> span); The optimized combination of vortex vibration suppression is proposed.
Zhou et al., (2025)	the wind tunnel test of large-span flexible photovoltaic support structure was studied, and the wind pressure distribution was determined	It owed that increasing PV module inclination angle (10 30) significantly enhances the longitudinal gradient distribution of wind pressure.
Fu., et al (2024)	The air pressure distribution characteristics of double-row flexible photovoltaic panels are studied	Study the wind pressure distribution characteristics of double-row flexible photovoltaic panels; The calculation method of the uneven wind pressure coefficient is proposed.
Koekemoer et al., (2024)	Full-size field measurement of the uni-axial tracker guide rail	The loading coefficient is found to be lower than the standard design value; Verify that there is no significant fatigue damage at low wind speed.

### 3.1.2 Field Measurements

Field measurements involve the installation of sensors (e.g., accelerometers, strain gauges) on operational photovoltaic (PV) arrays to monitor dynamic responses, validating numerical models. Field tests on a real-world PV project to investigate the effects of basic wind was conducted by Zhou et al., (Zhou, R.; Wang, H.; Xu, Z. D.; et al.2024; Zhou, R.; Wang, H.; Xu, Z. D.2024]. Speed, wind load direction, and support cable pre-tension on displacement responses and wind resistance reliability was discussed. Niu et al., (Niu, H. W.; Chen, Q.;Jiang, D.; et al.) carried out near-ground wind field measurements (below 10 m height) in Hanzhong, Shanxi Province, analyzing characteristic parameters such as mean wind speed, turbulence intensity, gust factor, turbulence integral scale, and wind power spectrum. Results were compared with values specified in design codes. Bao et al., (Bao,T.;Li, Z.N.; Pu, O. et al.2025) used field measurement data from a tracking PV power station near the Tengger Desert in Ningxia to study wind pressure interference effects on downstream rows in multi-row PV arrays. Main findings include: Most Significant Interference: Observed when wind direction was perpendicular to panel width, with downstream torque coefficients exceeding those of upstream rows at tilt angles above 30°. Vortex Shedding Frequency Shifts: High-frequency spectral peaks in fluctuating wind pressure were notably altered by upstream interference. Field Data Supplement: Established a wind pressure database for tracking PV arrays under real-world conditions, addressing limitations of wind tunnel tests and small-scale numerical simulations.

### 3.2. Numerical Simulation Methods

Numerical simulations for wind-induced vibration analysis of photovoltaic (PV) support structures primarily include finite element analysis (FEA) and fluid-structure interaction (FSI) modeling.

#### 3.2.1 Field Measurements

Finely detailed finite element models are developed using tools such as ANSYS and ABAQUS, coupled with dynamic time-history analysis or random vibration theory, to assess wind-induced vibrations or structural responses. Wang et al., (Wang, Z. G.; Zhao, F. F.; Ji, C. M.; et al.2020) modeled a 30-meter-span flexible PV support system (arranged in 3 transverse rows) using finite element software, analyzing its modal characteristics and vibration states under time-varying wind pressure loads. Du et al., (Du, H.; Xu, H. W.; Zhang, Y.; et al.2022) employed ANSYS based FEA to investigate wind-induced vibration responses of flexible PV supports, calculating corresponding wind vibration coefficients. Zhou et al., (Zhou, R.; Wang, H.; Xu, Z. D.; et al.2024; Zhou, R.; Wang, H.; Xu, Z. D.2024) combined finite element modeling with field measurement data and probability density evolution theory to study how basic wind speed, wind load direction, and support cable pre-tension influence displacement responses and wind resistance reliability.

#### 3.2.2 Fluid-Structure Interaction (FSI) Simulation Method

To address aerodynamic stiffness and aerodynamic damping effects, two-way coupling between computational fluid dynamics (CFD) and finite element methods (FEM) is employed to resolve interactions between complex flow fields and structural deformation. Key Studies are as follows: Zhang et al., (Zhang, C.; Huang, X. D.; Tao, T.; et al.2017) applied an FSI algorithm to analyze the time-history of wind-induced vibrations in PV support systems under pulsating wind loads. Results demonstrated that FSI-based simulations accurately capture wind vibration characteristics. Taking a tracking photovoltaic power system as the research object, a two-dimensional model of single-axis tracking photovoltaic structure is established (Li, Z. N., Wu, S. F.2024) Secondary development of Fluent through user-defined function (UDF) programming was investigated its torsional vibration under wind load conditions. A two-way FSI numerical simulation investigated the influence of ground anchor stiffness ratio (SR) on a system's dynamic response (Zhu, Y.F.; Huang, Y.; Xu, C.Z.; et al.2024). Quantitative evaluations of modal analysis, support reactions, displacements, and flow field variations clarified the comprehensive effects of anchor stiffness on wind vibration coefficients.

Focusing on pre-tensioned flexible cable-supported PV systems, a two-way FSI simulation quantified wind-induced vibration responses was studied (Zhu, Y F.; Huang, Y; Xu, C.Z. et al.2024), widely used in mountainous regions. Dynamic response characteristics were analyzed across varying tilt angles. The impact of initial cable pre-tension on wind-induced vibrations using two-way FSI coupling was evaluated (Zhu,Y.F.; Huang, Y.; Guo,Y.N. et al.2024). Simulations integrated equivalent models and Auto-Regressive (AR) models to generate pulsating wind speeds, significantly improving the accuracy of vibration response predictions.

### 3.3. Hybrid Research Methods

The wind-induced vibration mechanisms of photovoltaic (PV) support structures involve complex fluid-structure interactions (FSI) and nonlinear dynamic processes. Traditional single-method approaches struggle to fully resolve their dynamic response characteristics. Hybrid research methods, however, integrate the strengths of experimental validation and numerical inversion, such as calibrating turbulence models with field measurement data or refining aerodynamic admittance functions through sectional model tests. These integrations significantly enhance prediction accuracy for multi-field coupling problems. Together, they form a multi-scale research framework, providing a robust methodological foundation for stability assessment and wind-resistant design of PV supports in complex environments. Case Studies are as follows: Johnny Estephan et al., (Estephan, J.; Chowdhury, A. G.; Irwin,P.2022) Focused on the vulnerability of rooftop PV systems to extreme wind events. A novel hybrid experimental-numerical method was proposed to estimate peak wind loads by enhancing the Partial Turbulence Simulation (PTS) approach. Missing low-frequency turbulence effects and dynamic resonance phenomena (e.g., vortex-induced vibrations) were incorporated into the analysis. Fu et al., (Fu,X.;

Ren, R.X.; Li, J.; et al. 2024) Combined experimental and numerical analyses to study the aerodynamic characteristics of dual-row flexible PV supports. Key variables included wind direction, tilt angles, and structural parameters (e.g., ventilation gaps), with a focus on their impact on wind pressure distribution. Ma et al., (Ma, W. Y.; Chai, X. B.; Gao, F.; et al. 2023) Conducted sectional model tests to identify aerodynamic stiffness parameters and embedded them into finite element models to analyze axial forces in flexible PV support cables.

#### 4. Analysis of Key Influencing Factors

It is illustrated that aerodynamic parameters (e.g., wind direction angle, wind speed), geometric parameters (e.g., tilt angle, row spacing), and structural parameters (e.g., stiffness-damping ratio, prestress) are core factors driving vibrations in photovoltaic (PV) support structures. Additionally, shielding effects in multi-row arrays and complex terrain further amplify nonlinear response characteristics. The following sections briefly outline the dominant factors influencing PV structural vibrations and propose optimized design strategies tailored to specific challenges.

##### 4.1. Analysis of Key Influencing Factors

###### 4.1.1 Aerodynamic Parameters

Wind Speed and Turbulence Intensity:

Research indicates that the wind-induced vibration response of PV support structures is closely linked to turbulence characteristics. High turbulence intensity leads to the accumulation of high-frequency vibrational energy. Critical flutter wind speeds differ significantly across turbulence spectra. For instance, large flexible supports in uniform flow exhibit lower critical speeds compared to those in typical wind fields. Buffeting responses in flexible supports correlate positively with the square of wind speed, whereas high turbulence intensity suppresses flutter but exacerbates buffeting. Thus, wind speed remains the primary consideration in PV plant design.

###### 4.1.2 Aerodynamic Parameters

- **Tilt Angle:** Zhang et al., (Zhang, X. B. 2024) observed large-amplitude torsional vibrations in PV supports within a tilt range of  $-15^{\circ}$ – $15^{\circ}$ , with two vibration modes identified: At  $-15^{\circ}$ : Large torsional vibrations occur only within a specific reduced wind speed range, showing minor amplitude variations with speed changes. At  $-10^{\circ}$ – $15^{\circ}$ : Amplitudes increase sharply once reduced wind speed exceeds a critical threshold, resembling torsional flutter instability. No significant vibrations are observed at tilt angles  $>20^{\circ}$ , even under full test wind speeds. Niu et al., (Niu, H. W.; Chen, Q.; Jiang, D.; et al. 2024) investigated the effects of tilt angles ( $-60^{\circ}$  to  $60^{\circ}$ ), damping levels, and gap presence between PV modules on torsional flutter performance. main findings: Named 1V Condition: Pronounced torsional flutter occurs at tilt angles of  $-30^{\circ}$ – $30^{\circ}$ . Named 2V Condition: Distinct torsional flutter arises at  $\pm 10^{\circ}$ ,  $\pm 20^{\circ}$ , and  $\pm 30^{\circ}$  tilt angles. Zou et al., (Zou, L. H.; Wang, J.; Song, J.; et al. 2024) noted that variations in the tilt angle of PV modules significantly affect wind-induced vibrations in headwind conditions, with minimal impact in tailwind scenarios.
- **Spacing Ratio and Array Configuration:** Ma et al., (Ma, W. Y.; Chai, X. B.; Ma, C. C. 2021; Ma, W. Y.; Chai, X. B.; Zhao, H. Y.; et al. 2021) demonstrated that wind load variations with spacing ratio differ across tilt angles. Downstream PV modules are more sensitive to spacing ratio changes than upstream ones, with accelerated flows at the top and bottom regions increasing wind loads on mid-array modules. It is recommended that small spacing and large spans for flexible PV supports, optimizing stability by controlling spacing ratios below 0.1 (Ma, W. Y.; Chai, X. B.; Gao, F.; et al. 2023). Yang et al., (Yang, W. H.; Dai, J. H.; Chen, W. L. 2025) conducted wind tunnel tests on flexible PV arrays, analyzing VIV and flutter instability in single and triple row configurations under  $0^{\circ}$  and  $180^{\circ}$  wind directions. Findings revealed vertical VIV in multi-row arrays at low wind speeds, unseen in single rows, with maximum responses in middle rows.

###### 4.1.3 Structural Parameters

- **Cable Pre-Tension:** Zhou et al., (Zhou, R.; Wang, H.; Xu, Z. D.; et al. 2024; Zhou, R.; Wang, H.; Xu, Z. D. 2024) demonstrated that higher cable pre-tension enhances wind resistance reliability. However, the marginal benefit diminishes as pre-tension increases. Wang et al., (Wang, W.; Cao, J. X.; Cao, S. Y. 2024) found that reduced pre-tension in cables amplifies displacement amplitudes of PV panels across arrays, though the extent of increase varies with location. Cai et al., (Cai, Y.; Deng, H.; Li, B. Y. 2022) observed that increasing prestress in structural elements, with mid-span cables exhibiting the highest cable force, making them effective indicators of cable force variations under dynamic loads.
- **Stiffness and Damping Ratios:** Ma et al., (Ma, W. Y.; Kang, X. H.; Zhang, X. B.; et al. 2024) identified aerodynamic damping and aerodynamic stiffness as critical parameters influencing torsional instability in single-axis PV supports. Both parameters are sensitive to wind speed and tilt angle. Increasing torsional stiffness limits vibration amplitudes and raises critical wind speeds, particularly at specific tilt angles. At low tilt angles, vibration frequencies decrease with wind speed due to dominant aerodynamic stiffness effects, exhibiting distinct torsional flutter characteristics. Bao et al., (Bao, T.; Li, Z. N.; Pu, O.; et al. 2023) studied the dynamic properties (e.g., modal frequencies, mode shapes) of single-/dual-axis tracking PV systems. Stability under wind-induced vibrations depends heavily on tracking system natural frequencies, which are influenced by support stiffness, mass

distribution, and actuator constraints. Li et al. (Li, Z. N., Wu, S. F. 2024) observed soft flutter phenomena—steady periodic vibrations occurring above specific wind speeds. Damping ratios play a limited role in suppressing such torsional vibrations, aligning with empirical observations. Xu et al., (Xu, H. W.; Li, J. L.; He, X. H.; et al. 2024) highlighted the sensitivity of aerodynamic damping to wind direction angles. Increasing cable tension may significantly reduce aerodynamic damping ratios for flat-mounted modules at high wind speeds. Aerodynamic damping ratios generally decrease with wind speed, remaining positive at low speeds but transitioning to negative values under high-speed conditions.

#### 4.1.4 Topographic Effects

Mountainous and canyon terrain significantly alter local wind field characteristics, necessitating consideration of topographic effects in large-scale PV plant design. Xu et al., (Xu, H. W.; Li, J. L.; He, X. H.; et al. 2024) analyzed topographic impacts, revealing results are as follows. Larger terrain slopes diminish shielding effects between PV rows. Steep slopes accelerate airflow and redirect its path, causing downstream PV modules to experience negative wind pressure coefficients. When PV module tilt angles are smaller than terrain slopes, upward thrust forces develop on module backs. Larger tilt angles enhance wind resistance for mountain-based PV supports. Wind loads and wind-induced interference effects on PV arrays under 2D hilly terrain are studied (Xu, Y. Z.; Tian, R.; Li, B.; Jiang, F. L.; et al. 2024; Xu, A.; Ma, W. Y.; Yang, W. S.; et al. 2024), systematically revealing bidirectional aerodynamic impacts of slopes on wind loads and identifying critical slope angles. It highlights that near-summit areas within slope zones constitute critical design zones requiring prioritized assessment of wind direction variability and accelerated wind speed effects.

### 4.2. Vibration Design Optimization

#### 4.2.1 Cable Network Reinforcement

Zhou et al., (Zhou, R.; Xu, Z. D.; Wang, H. 2025) demonstrated that increasing the pre-tension of main bearing cables significantly elevates the first four natural frequencies of the structure. When pretension rises from 22 kN to 102 kN, the critical flutter wind speed increases from 17.1 m/s to 21.6 m/s. In contrast, pretension in stabilizing cables has minimal impact on natural frequencies or flutter critical speeds. For wind resistant design, prioritizing main cable pretension is recommended to enhance flutter performance. It is shown that increasing initial stiffness via main cable pretension has limited wind vibration suppression (He, X. H.; Ding, H.; Jing, H. Q.; et al. 2020; Li, W. J.; Ke, S. T.; Cai, Z. B.; et al. 2023). A novel lateral connection with stayed cable vibration control technique was proposed, offering direct engineering solutions for similar projects.

#### 4.2.2 Cable Network Reinforcement

Zhang et al., (Zhang, L.; Zhu, Z. L.; Luo, B. B.; et al. 2022) investigated the effects of beam spacing, number of columns, and front-rear column spacing on load-bearing capacity. Increasing columns distributes loads more evenly significantly boost capacity. Larger spacing reduces support effectiveness for central beams, increasing local deflection and reducing capacity. The addition of rigid rods to flexible PV support systems was studied (Wang, Z. G.; Zhao, F. F.; Ji, C. M.; et al. 2020). This modification stiffens the structure by altering natural vibration periods and coordinating displacements across upper, mid-upper, mid-lower, and lower chords. Such adjustments mitigate torsional responses and reduce oscillations, protecting PV modules.

## 5. Challenges and Technological Outlook

### 5.1. Key Challenges

Despite significant advancements in research on photovoltaic (PV) support structure vibrations (Cai, Q. G.; Ke, S. T.; Wang, L. S.; et al. 2024; Zhou, Y.; Peng, R. L. F.; Xiang, Y.; et al. 2025; Ren, H. H.; Liu, H. Y.; Wang, B. Y.; et al. 2025), critical theoretical and practical challenges persist primarily in the following areas:

#### (1) Unclear Multi-Scale Coupling Mechanisms of Aeroelastic Effects

Existing studies often oversimplify dynamic response modeling for PV systems. For instance, vortex-induced vibrations (VIV) depend on flow separation characteristics, yet their dynamics involve complex couplings of fluctuating wind pressure spectra, structural natural frequencies, and damping ratios. While improved Partial Turbulence Simulation (PTS) methods compensate for low frequency turbulence effects, frequency lock in mechanisms in higher order modes (e.g., torsional resonance) remain poorly understood. Experiments (e.g., on single-axis tracker arrays) reveal critical wind speeds highly sensitive to tilt angles, indicating strong dependence of aeroelastic instability boundaries on local flow separation. This is a phenomenon lacking universal theoretical fluid-structure interaction (FSI) models. Furthermore, negative aerodynamic damping in flexible PV supports in cable systems at specific tilts has been preliminarily observed, but its formation mechanisms and quantification criteria remain unclear for engineering applications.

#### (2) Scaling Model Dynamic Similarity Limitations

Current wind tunnel tests struggle with dynamic similarity errors: Reynolds Number Mismatch: Fluid separation in scaled models introduces Reynolds number discrepancies. Assumptions of Reynolds insensitive bluff-body aerodynamics may underestimate critical phenomena like vortex shedding frequency shifts. Damping Similarity Failure: Aeroelastic models mimic prototype damping by adjusting mass or stiffness, but reproducing precise aerodynamic-to-structural damping ratios is challenging. For example, fixed damping ratios in scaled models ignore real-world damping variations due to aging or loosened connections. Inadequate Flow Field Similarity: Most tests use uniform or quasi-static turbulent flows, failing to replicate real atmospheric boundary layers.

### (3) Insufficient Study of Multi-Row Array Flow Field Interactions

In large PV plants, wake interference between rows significantly alters local wind pressure distributions and vibration characteristics: Shielding Amplification: Wind tunnel tests report abrupt wind pressure surges in downstream rows (e.g., dual-row arrays), but no systematic studies exist for large scale arrays (>10 rows). Inter-Row Vibration Coupling: Field measurements show lower critical speeds for rear rows in triple-row tracking arrays with reversed torque distributions. Current numerical models struggle to resolve transient aeroelastic coupling. Terrain-Array Coupling: Studies neglect interactions between turbulent background flows and terrain roughness limiting structure optimization in high roughness environments.

### (4) Nonlinear Modeling Challenges in Hydro-Wind-Structure Coupling Floating PV systems face nonlinear multi-physics interactions (waves, wind, currents):

Shallow Water Nonlinearity: Time domain simulations often omit instantaneous wet surface variations (e.g., sudden draft changes). Potential flow approximations lack precision for extreme wave slamming or dynamic submersion effects. Hydrodynamic Interference Quantification: Diffraction/radiation effects between adjacent floaters are rarely modeled using viscous CFD, relying instead on indirect software couplings. For example, star-shaped floating arrays with flexible connectors optimize tension distribution but inadequately resolve fluid interactions. Long-Term Marine Load Effects: Existing studies focus on short-term regular waves, neglecting combined analyses of random wave spectra, wind-wave coupling, and typhoon transients. Fatigue models and time-frequency conversion algorithms require urgent validation.

## 5.2. Technological Outlook

To address the aforementioned challenges, future research should prioritize breakthroughs in the following directions:

### (1) Develop Multi-Physics Coupled Numerical Models

Cross-Scale Fluid-Structure Interaction (FSI) Algorithms: Integrate large eddy simulation (LES) with finite element methods to couple high-frequency turbulent fluctuations (e.g., detached eddy simulation, DES) with low frequency structural modes, enhancing prediction accuracy for vortex-induced vibrations (VIV) and flutter. Machine Learning Assisted Parameter Inversion: Leverage deep neural networks (DNNs) to extract feature mappings (e.g., aerodynamic admittance functions, damping ratios) from experimental data, reducing computational costs for numerical calibration.

### (2) Advance High-Fidelity Experimental Techniques and Full-Scale Validation

Composite Scaling Similarity Criteria: For flexible PV structures, establish hybrid scaling laws satisfying Reynolds and damping ratios. For example, 3D-printed aeroelastic materials (e.g., variable stiffness composites) are used to achieve multi-scale dynamic similarity. Realistic Turbulence Field Replication: Deploy active grids and perturbation jets in wind tunnels to match turbulence integral scales and energy spectra of target terrains (e.g., Category C plains, Category D mountains). Full-Scale In Situ Testing: Embed distributed sensor networks (e.g., FBG optical fibers, MEMS accelerometer) during PV plant construction, building life-cycle dynamic databases are used to full scale test.

### (3) Explore Novel Anti-Vibration Materials and Smart Control Technologies

Smart Dampers: Develop tunable dampers based on shape memory alloys (SMAs) or piezoelectric materials for real-time feedback control. For instance, embed active mass dampers (AMDs) are used in cable supported systems, based on optimized algorithms. Fiber-Reinforced Composites: Utilize carbon fiber-reinforced polymers (CFRP) to redesign PV supports with topologically optimized, ultralight high-stiffness structures.

### (4) Build Multi-Level Standardized Design Frameworks

Refined Dynamic Load Coefficients: Establish differentiated wind vibration coefficient tables based on array layout (single/multi-row), support type (rigid/flexible), and environment (mountain/floating), validated via Monte Carlo simulations. Standard Benchmark Model Libraries: Create open-access 3D aeroelastic model databases (e.g., solar tracker benchmarks) with key parameters (tilt, span, terrain), enabling numerical model calibration.

### (5) Deepen Extreme Climate and Long-Term Performance Studies

Typhoon/Hurricane Transient Response Prediction: Couple Weather Research and Forecasting (WRF) models with CFD to reconstruct transient extreme wind fields, analyzing nonlinear instability thresholds under unsteady wind angles. Digital Twin-Based Lifespan Prediction: Build digital twin platforms integrating real-time monitoring and degradation models to predict critical component lifespans and enable preventive maintenance.

## 6. Conclusion

This study systematically reviews advances and trend in wind-induced vibration mitigation technologies for supports. Currently, there are various types of photovoltaic mounting systems adapted to different application scenarios. Synergistic applications of wind tunnel tests, fluid-structure interaction simulations, and field monitoring are discussed by the authors. The results reveal the damage mechanics due to nonlinear dynamic mechanisms such as vortex-induced vibration (VIV) and flutter. Many important dominant factors, such as aerodynamic parameters, geometric parameters, structural parameters, topographic effects must be taken into account for photovoltaic power design. Current challenges are still existence, including unclear dynamic aeroelastic coupling mechanisms, insufficient scaling model similarity, and lack of standards for diverse scenarios. In the future, photovoltaic power still has immense potential for growth but will also face new challenges. Therefore, we need to plan for future development in advance. Such as we emphasize developing high fidelity multi-physics models, intelligent vibration suppression technologies, and cross-disciplinary standardization frameworks to enhance system robustness and cost-effectiveness under extreme climates, supporting the global scaling of PV deployment.

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