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WIND TURBINE BLADES VIBRATION: REVIEW

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Abstract

The rapid development of wind turbines and the elongation of their blades necessitate extensive studies to address higher loads, displacement and vibrational amplitude, nonlinearity in the geometry, nonlinear stiffness, and many other challenges. Moreover, as many countries are shifting towards wind energy due to its effectiveness and low environmental impact, there is a pressing need for comprehensive investigation. This review aims to explore diverse numerical and experimental methodologies used in analysing wind turbine blade models across various operating conditions, including turbulent flow or cold environments, as well as different geometries and sizes. Numerous proposed numerical methods demonstrate strong correlation with experimental results or similar results to alternative numerical techniques such as Finite Element Method (FEM), time or frequency domain methods, and direct simulation. Additionally, this paper encompasses various experimental findings, including modal model analysis, operational modal analysis, and structural health monitoring.

Keywords: *wind turbine, vibration, numerical solution, modal and operational analysis experiment, low and high orders of mode shapes, rotor dynamics*

1. Introduction

A shift from traditional sources of energy like fossil fuel is a necessity to ensure a reduction in pollution emissions and to protect the environment. Hence, the demand for different green energy sources such as wind turbines is increasing by the day. Unfortunately, these alternatives face challenges of their own. This review will focus on the vibrational challenges encountered by wind turbine blades. Moreover, recent years have seen a growing focus on stability issues in wind turbines due to the industrial trend towards larger and more flexible structures. The primary concern in this field which could result in the failure of the entire structure, is the edge-wise or flap-wise vibration, as illustrated in *Figure 1*. The deflection of wind turbine blades holds significant importance, particularly regarding aerodynamic loading and dynamic stability issues. For example, the flap-wise vibration might induce catastrophic results as high displacement at the tip of the blade could cause a collision between the blade and the tower.

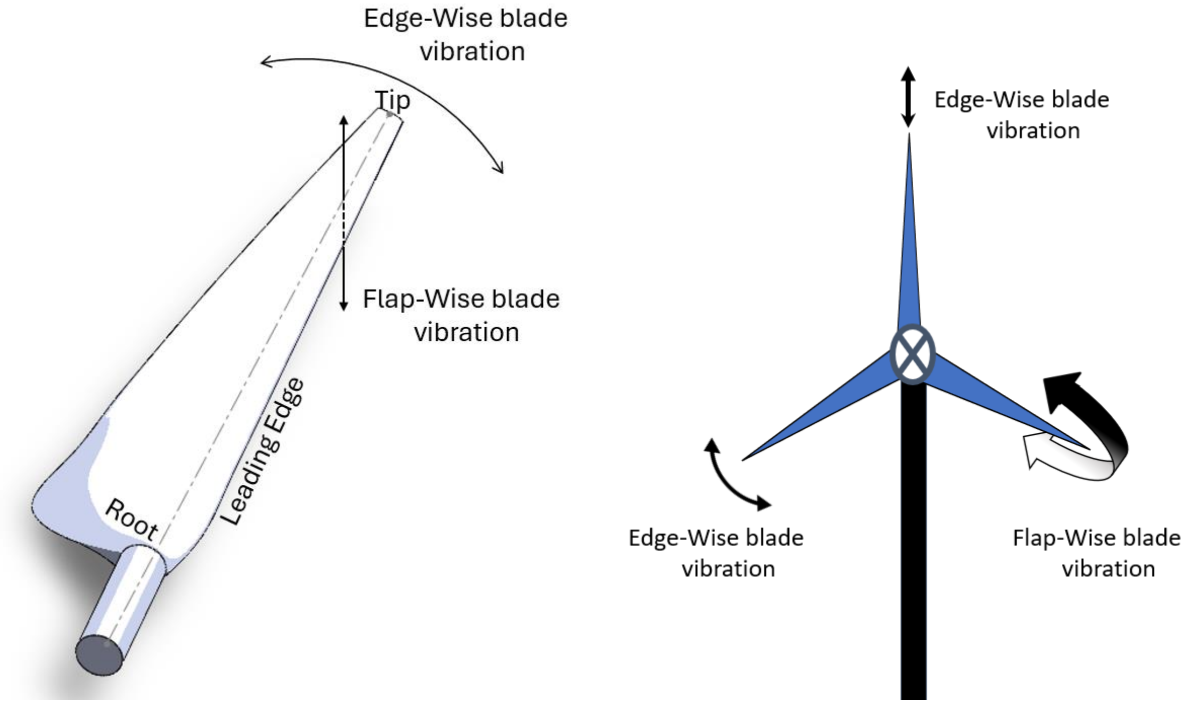

Figure 1. *Edgewise and Flap-Wise Vibration*

It is also important to introduce some of the primary equations and forces that govern the motion and aerodynamics of the blades. Four forces are acting on the wind turbine blades. These forces are the lift force, the drag force, the gravitational force, and the centrifugal force. While considering aerodynamics, it is possible to use Reynolds-averaged Navier–Stokes equations to simulate the nonlinearity around a vibrating blade which can be expressed as the following using the standard one-equation Spalart–Allmaras model (Naung et al., 2021).

$$\frac{\partial}{\partial t}\int Q \, \mathrm{d}\Omega + \int_{S} \vec{F}_1 \cdot \mathrm{d}\vec{S} + \int_{S} \vec{F}_v \cdot \mathrm{d}\vec{S} = \int_{\Omega} S_T \, d_\Omega \tag{1}$$

The domain is denoted by Ω, while the surface is represented by S. Q stands for the vectors of conventional parameters, and S_T is the source term. The inviscid and viscous terms are represented $\vec{F}_1$ and $\vec{F}_v$, respectively.

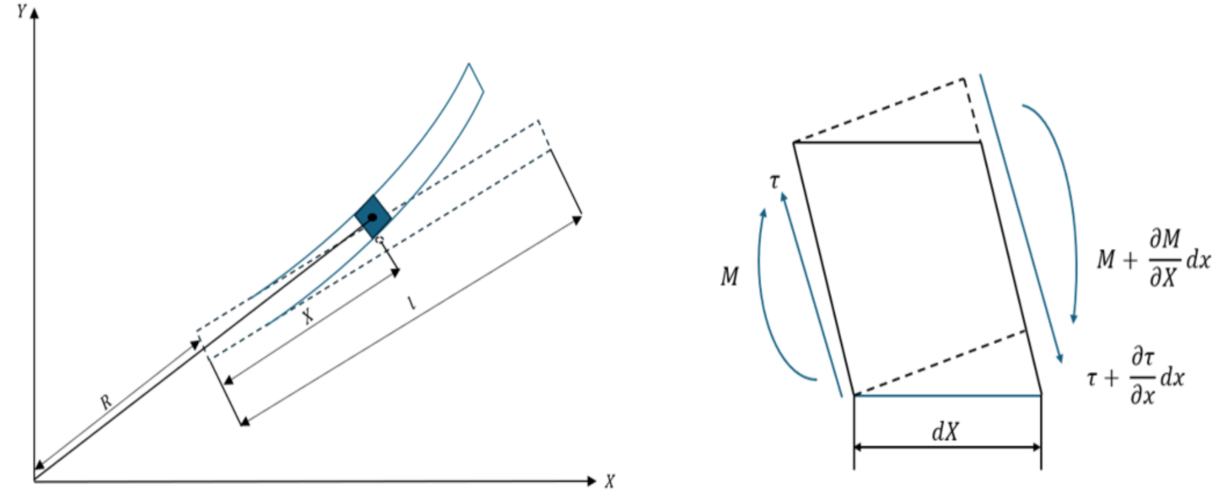

Figure 2. *Blade model and its element.*

While considering flap-wise vibration under large deformation, the equation of motion for the vibration of the blade can be expressed as:

$$\frac{\partial^2 M}{\partial x^2} + \rho A \frac{\partial^2 v}{\partial t^2} - \frac{\partial}{\partial x}\left(N \frac{\partial v}{\partial x}\right) = f(x,t) \tag{2}$$

In (2), *A* donates the cross-section area, *M* is the bending stiffness, *N* is the axial force, *v* is the displacement in the *y-axis* ρ is the density, and $f(x,t)$ is the excitation force.

The centrifugal force can be expressed as:

$$N_1 = \rho \omega^2 \int_x^L A(R+x)\,\mathrm{d}x \tag{3}$$

Here, ω represents the hub rotating speed, *R* is the radius of the hub and *l* is the length of the blade.

2. Experiments and numerical validation

It is crucial to validate the results of any research. The common approach involves comparing the experimental results with the numerical solution. Hence, most research in this field presents both experimental and numerical results. The modal analysis serves as the primary method to investigate the vibrational behavior of the blade. This method focuses on finding the natural frequencies, mode shapes, and damping characteristics of the structure by exciting the specimen using a shaker or a hammer. When the experiment is done while the specimen is under operation, it is called operational modal analysis. The operational modal experiment focuses on analyzing and investigating the amplitude, mainly at resonance or other operational conditions. This is all accompanied by the lack of data and the difficulty of conducting large-scale experiments in academia.

Because of the low operational speed of the rotor of the wind turbine, the first and the second resonance frequencies are the most crucial. Hence, most of the research concentrated on these frequencies. Reference (Chen et al., 2021) investigates higher orders of mode shapes and mode coupling experimentally and numerically for a complex curvature. Various tests were applied to the blades. Two of the tests involve impact excitation and utilize accelerometers. One test was conducted on the whole rotor while the other was on a single blade. Additionally, a third test was conducted using a laser as a sensor and a shaker for excitation. These tests demonstrated a high correlation with the FEM results, showing the possibility of using FEM for similar cases.

An experiment discussed in (Marulo et al., n.d.). examined the impact of local failures on the dynamic characteristics of wind turbine blades, while considering their structural integrity for early-stage design. The study investigated modal parameters during operation before and after failure where the failure was reached under a static test. The study concluded that Operational Modal Analysis demonstrated a strong correlation with numerical simulations. Additionally, a numerical analysis was performed to assess the influence of centrifugal stiffness induced by rotational speed on blade vibration and aeroelastic behavior. The results indicate that changing rotational speed can significantly affect the aeroelastic behavior of wind turbine blades.

Reference (Pacheco-Chérrez and Probst, 2022) introduced an operational test to identify damage caused by wind excitation. The test employs the NREL FAST tool and QBlade (for blade aerodynamics simulations) for dynamic response simulation, ANSYS Workbench for transient analysis, and the Frequency Domain Decomposition (FDD) algorithm for extracting modal parameters. The NREL FAST tool, developed by the US National Renewable Energy Laboratory, analyzes various wind turbine blade configurations. By comparing modal properties of undamaged and damaged blades, it identifies longitudinal crack-type damage in the upper part of the blade. This method shows potential for cost-effective monitoring of wind turbine blades and rotors using only wind-induced blade accelerations.

Operational modal analysis is usually done under actual operating conditions, or when it is difficult or impossible to use excitation devices like a shaker or a hammer. Researchers published a benchmark for employing vibration-based structural health monitoring methods on wind turbine blades in (Ou et al., 2021). They investigated different environmental conditions as well as the blade in a healthy state and a damaged state.

3. Numerical analysis

This section will focus on papers proposing novel numerical methods. A variety of numerical methods can be applied to the vibration analysis of wind turbine blades. Vibration may occur linearly or nonlinearly under different airflow conditions. Wind turbines operate in diverse real-life conditions that change with the time of day, day of the year, and their geographical location, necessitating the use of different numerical models. Although modeling the blade as a lumped mass (mass-spring-damper) is possible, it is often used for control analysis in studies, such as the five-mass model detailed in (Lindeberg et al., 2012). Additionally, many of these lumped models can be found in the literature review (Xie and Aly, 2020). However, to accurately capture the higher mode shapes and natural frequencies for complex geometry and different boundary conditions, the Finite Element Method is the primary numerical technique utilized in this field. Different studies tried to show the effectiveness of using FEM in this field, such as (Boudounit et al., 2019) where the numerical results were compared to the experimental results for the higher mode shapes and resonance values.

A Finite Element Method (FEM) study investigated the behavior of a wind turbine blade under uniform pressure, obtaining the force at the root and the displacement at the tip numerically in (Navadeh et al., 2021). The study employed two cases of applied force: one involved a half-sine (simulating wind gust force) combined with a uniform pressure pulse, while the other utilized a step-wise (simulating impact or blast force) combined with a uniform pressure pulse. In general, the results exhibited nonlinearity at high-pressure values. Also, the study found three effects of geometrical nonlinearity: increased flap deflection with higher pressure, a gradual time shift in nodal displacements, and a shivering effect observed at the root of the membrane forces.

Reference (Lang et al., 2024) employed various methods and compared them to Finite Element Method (FEM) results using Campbell diagram analysis of blade vibration. One approach was the simplification of the blade into an Euler-Bernoulli beam to capture the flap-wise nonlinear vibration. Another approach involves considering the nonlinear term from the centrifugal force to derive an equation of motion that captures the large deflection flap-wise vibration. Finally, the Galerkin method was employed and analyzed semi-analytically using the multi-scale analysis method, with the Runge–Kutta numerical method. The results of the paper are summarized in three main points. Firstly, the effect of changing hub speed on blade vibration amplitude varies significantly with time. Secondly, maintaining rated speed while adding harmonic external excitation results in a 71% amplification ratio for the maximum amplitude. The amplitude-frequency response shows two peaks influenced by excitation amplitude. A 1-unit increase results in a 10-fold increase in vibration response. The frequency of the first peak remains unchanged, while the second peak slightly decreases by 18%. Finally, with fluctuations in the external excitation frequency, the spatial evolution trajectory of blade vibration changes, reducing the maximum response by a 36% decrease.

The validity and computational efficiency of the Time Domain Method and the Frequency Domain Method were investigated and compared to experimental results in (Naung et al., 2021). The paper aimed to investigate the behavior of an oscillating wind turbine. The experiment used NACA0012 airfoil. The experiment utilized the NACA0012 airfoil, representing the mid-section of the blade, in wind tunnel AF10. Additionally, the hexahedral element type was used in a quasi-3D model which is a two-dimensional model with span-wise extension. Comparison with the nonlinear frequency-domain method revealed that as the angle of attack increased, the difference in unsteady pressure distributions between airfoil surfaces also increased. Also, extensive validations between the frequency-domain and time-domain solution methods confirm the high agreement between the two methods. Additionally, Comparison with the nonlinear frequency-domain method revealed that as the angle of attack increased, the disparity in unsteady pressure distributions between airfoil surfaces also increased.

An alternative approach is to actively vibrate the blade to study the airflow around it. Reference (Nakhchi et al., 2022) employed the direct numerical simulation method to model airflow behavior at the separation point for a blade subjected to active harmonic vibration during unsteady flow conditions, blade vibration augmented the separation bubbles within the separation region, leading to additional distortion in the flow.

Furthermore, the harmonic oscillation of the blade generates periodic pressure signals, with pressure fluctuations amplified by the oscillation, especially in the flow separation region.

4. Icing in cold environment

Wind turbines face many challenges in cold environments. The snow and rain will generate an imbalance at impact. The ice accretion will have a significant effect on the generated energy and the lifetime of the blades because it changes the aerodynamics around the blade and its shape. Additionally, the new body of the ice and the blade will have different natural frequencies.

Reference (Blades, 2016) investigates the effects of ice accumulation on wind turbine blades in cold climates, focusing on structural and aerodynamic changes. Using aeroelastic equations and finite element analysis, it examines how ice mass distribution influences blade vibrations, natural frequencies, and damping factors. Results show that ice reduces natural frequencies and alters damping factors, potentially leading to unstable vibrations and decreased turbine power output. The conclusion emphasizes the impact of ice shapes on performance, suggesting that certain shapes can significantly reduce power output and induce instability, necessitating turbine shutdown and deicing for safety. It underscores the need for robust turbine design to withstand icing conditions and ensure safe operation in cold climates.

Another reference (Gantasala, n.d.) that uses nacelle accelerometer data and power analysis to detect icing, enabling timely de-icing or shutdown. Employing k-nearest neighbor (kNN) method on vibration and power data validates icing detection. Tower oscillation during icing is studied, with lateral vibrations increasing, matched to rotor speed. These factors, along with the month, detect ice formation, demonstrated on data from a winter wind park.

A study investigated icing on wind turbine blades in (Dai et al., 2023), focusing on the vibration performance of the blade tip area. Using an S8025 airfoil blade, it analyzes the impact of different loads on vibration characteristics. Results indicate that ice accumulation at the blade tip increases mass and stiffness, altering vibration frequencies. Centrifugal force load significantly affects vibration performance. The study suggests deicing treatment for optimal wind turbine operation. It emphasizes the importance of addressing the icing of the blade tip for efficient wind power utilization in cold regions.

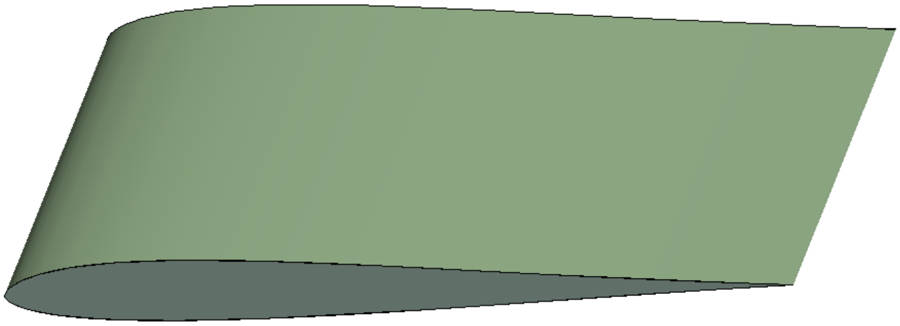

Figure 3. *S8025 airfoil*

5. Summary and conclusion

In conclusion, the combination of experimental and numerical approaches is vital for understanding wind turbine blade dynamics. Operational and non-operational modal analysis offers valuable insights. Recent studies demonstrate its effectiveness in validating results and detecting damage caused by wind excitation. These findings show the cost-effectiveness of monitoring blade integrity, driving progress in vibration-based structural health monitoring methods for wind energy applications. Additionally, applying numerical methods for wind turbine blade vibration analysis shows insights into both linear and nonlinear behavior under various airflow conditions. While simplified models like the lumped mass system are common for control analysis, the Finite Element Method (FEM) remains paramount for capturing complex geometries and boundary conditions. Recent studies have revealed insights into phenomena such as nonlinear behavior under uniform pressure and the effects of changing hub speed and external excitation on blade vibration. Moreover, comparisons between Time Domain and Frequency Domain Methods validate high agreement between methods, enhancing confidence in numerical simulations. Innovative approaches, such as actively vibrating blades, offer unique perspectives on airflow behavior and flow separation, collectively advancing our understanding of wind turbine blade dynamics and contributing to the optimization of wind energy systems. There are still several unresolved issues necessitating further study and investigation. These include examining the impact of uneven loads arising from wind fluctuations, ice accretion, or the added weight from the accumulating ice, either through experimentation, numerical analysis, or a combination of different force sources. While extensive research has been conducted on airfoils and blade geometry regarding drag and lift forces, there has been relatively little focus on their vibrational behavior under varying environmental conditions. Moreover, most vibrational studies have only analyzed the behavior of individual blades, with limited attention given to the entire rotor. This is due to the complexity of the problem which contributes to the high costs of conducting experiments or numerical analyses on these issues. Simpler prototypes or methodologies that discuss such problems are needed for further development of the field.

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