Chapter 3
Effects of Environmental and Operational Variables on the Modal Properties of Wind Turbines Blades

Felipe Bravo and Rodrigo Astroza

Abstract This research addresses the influence of environmental and operational variables on modal properties of wind turbine blades by employing a vibration-based structural health monitoring approach. Three triaxial sensors were placed in a mock-up resin/epoxy wind turbine blade and exposed to different rotor speeds, mass additions, and progressive damage under actual environmental conditions. Modal properties were identified with an input-output state-space system identification algorithm and an automated modal tracking approach. The findings reveal that higher rotor speeds increase the natural frequency of the first flapwise mode, attributed to greater blade stiffness. In contrast, higher temperatures significantly decrease the natural frequency, particularly at higher speeds, while added mass lowers natural frequency, with diminishing effects at increased speeds. Notably, although temperature has a pronounced impact on frequency in early damage stages, progressive damage did not significantly influence damping ratios or mode shapes. These insights underscore the intricate relationship between environmental and operational variables and blade performance, highlighting the necessity for improved monitoring strategies in operational modal analysis.

Keywords Structural Health Monitoring · Wind Turbine Blades · Environmental and Operational Variability · Modal Analysis

Introduction

Wind energy is increasingly recognized as a key player in the transition towards sustainable energy systems, providing a clean and renewable source of energy and being one of the fastest-growing forms of renewable energy. Despite the advancements in wind energy technology, wind turbine blade failures remain a prevalent issue [1], leading to significant economic losses, reduced operational efficiency, and serious safety concerns. Blade failures can result from a variety of factors, including material fatigue, manufacturing defects, and environmental stressors [2]. The economic implications of such failures are substantial, often involving costly repairs, downtime, and potential legal liabilities. Moreover, failures can compromise safety, posing risks to maintenance personnel and nearby communities. Addressing these challenges is imperative to ensure the continued growth and viability of wind energy as a primary energy source.

While there is a growing body of literature on wind turbine blade performance, there remains a significant gap in comprehensive studies examining how environmental and operational variables affect blade performance and durability. Most existing research has focused on isolated factors or laboratory conditions [3], failing to account for the complex interplay of multiple variables encountered in real-world operating environments. This lack of holistic understanding hampers the development of effective monitoring and maintenance strategies, which are crucial for enhancing blade longevity and reliability.

This research investigates the influence of key environmental and operational variables—specifically temperature, rotor speed, and mass changes—on the modal parameters of wind turbine blades. By employing a vibration-based methodology, this study aims to identify how these variables interact and affect the structural integrity of the blades. Ultimately, the findings of this research will contribute to a deeper understanding of the factors influencing blade performance, facilitating the development of improved monitoring and maintenance practices to enhance the reliability and longevity of wind turbine systems.

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Background

Vibration-based structural health monitoring (SHM) approaches employing modal parameters—such as natural frequencies, damping ratios, and mode shapes—are essential for assessing environmental and operational variables (EOVs) and damage-sensitive features used in damage detection [4, 5]. SHM leverages these modal parameters as critical indicators of structural integrity, particularly in wind turbine blades, which are subjected to dynamic loads and varying environmental conditions. Research has demonstrated that variables such as temperature [1], rotor speed [2], and ambient noise [6] significantly affect the modal parameters of wind turbine structures, particularly of blades. Both numerical and experimental studies have revealed how damage impacts these modal parameters [7], complicating damage detection through vibration analysis alone. This complexity can lead to misdiagnosis, resulting in unnecessary maintenance or, conversely, unaddressed structural issues that could compromise safety.

Operational modal analysis (OMA) must navigate the complexities arising from the interaction of EOVs, as the influence of damage on modal parameters can be confounded by these environmental factors. For instance, high ambient noise levels can mask significant changes in modal parameters, making it difficult to detect damage reliably. Mitigating the impact of EOVs on modal parameters is critical for effective OMA, especially since damage diagnosis and prognosis models—such as the one developed by Jaramillo et al. [8]—often rely on natural frequencies as key inputs. Natural frequencies are particularly significant, as they serve as the primary indicators for assessing structural health and predicting potential failures.

Data acquisition on wind turbines presents its own challenges. While the tower structure is generally easier to sensorise [9], obtaining reliable data from the blades remains problematic. Factors such as blade shape, material properties, and environmental exposure contribute to the difficulty in effective sensor deployment. Most existing data has been collected under laboratory conditions, simulations [6, 10], or through methodologies that are too invasive to replicate [11]. These limitations raise concerns about the applicability of the findings in real-world settings, where environmental conditions vary widely.

This study proposes a vibration-based methodology for accurately identifying modal parameters using input-output system identification and effectively clustering these parameters under varying EOVs. By integrating these factors, this research aims to improve the reliability of damage detection models and inform maintenance strategies. It presents a data framework that accounts for variations in the modal parameters of wind turbine blades due to changes in temperature and rotor speed and describes the combined effects of these variables on the first and second modes of the blades. Additionally, this study examines the influence of progressive damage on the modal parameters of a small-scale wind turbine blade. The findings could provide significant insights for the wind energy sector, contributing to enhanced monitoring practices and longer turbine lifespans.

Analysis

Acceleration measurements were captured from a 2.4 m long glass-fiber/epoxy-resin wind turbine blade from a wind turbine mock-up designed specifically for this study. A 3-meter-tall steel tube with a 1 hp motor attached to the top, controlled by a frequency regulator, and equipped with a hexagonal steel rotor allowed for better control of the operational variables. This setup facilitated precise adjustments, as illustrated in Fig. 1.

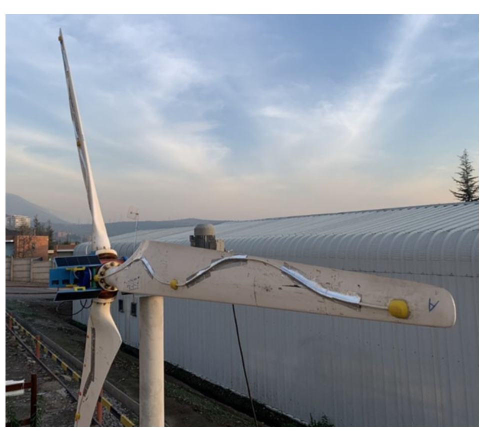

Fig. 1 Experimental Wind Turbine Setup

Three strategically deployed ADXL345 accelerometers, featuring an amplitude range of ±8 g and a sensitivity of 2 mg/LSB, were installed on the blade, as shown in Fig. 2. A monitoring device located in the center of the wind turbine's rotor captured temperature and acceleration data at a sampling rate of 200 Hz. Measurements were taken every 10 minutes under various scenarios, including healthy states, changes due to mass additions, and progressively induced artificial damage while exposing the blade to varying rotor speeds. These scenarios were analyzed to assess the impact of EOVs on the wind turbine blade, represented in Fig. 3.

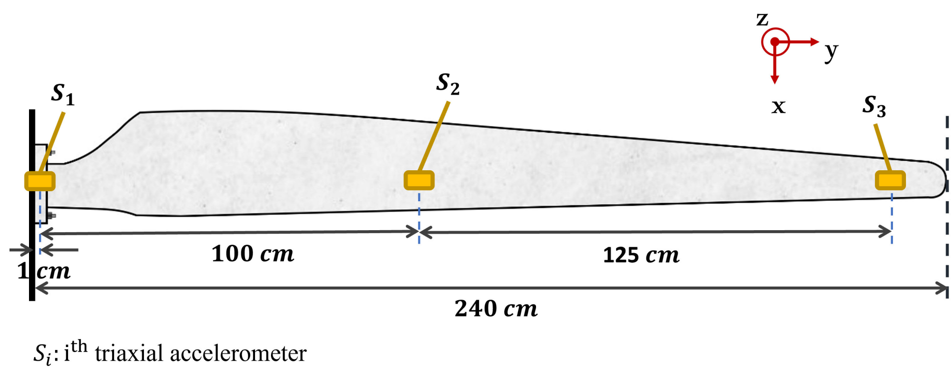

Fig. 2 Accelerometer deployment on the blade

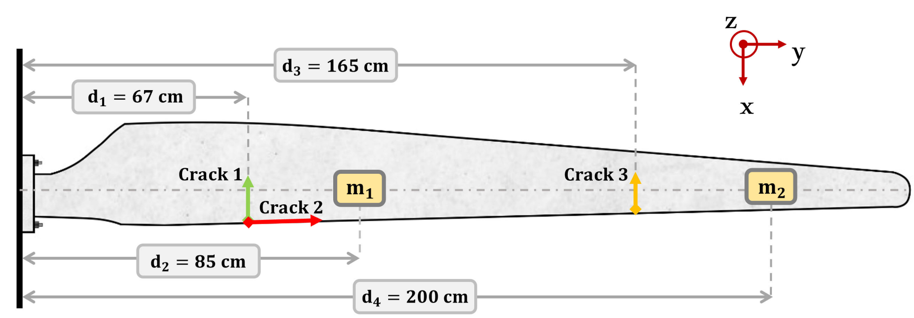

Fig. 3 Scenarios for testing EOVs

An input-output system identification method, specifically the Deterministic-Stochastic Identification (DSI) algorithm [10], was employed to estimate the modal parameters, including natural frequency, damping ratio, and mode shape of the wind turbine blade. An automated modal tracking algorithm then enabled accurate tracking of the blade's modal properties throughout the different tested scenarios over several days of data collection, capturing a diverse range of temperature fluctuations and ambient conditions.

A significant ascending trend in the natural frequency of the first flapwise mode was observed as the rotor speed increased (Fig. 4). This effect is attributed to heightened blade deformation and increased stiffness at higher speeds due to nonlinear geometry effects. The damping ratio exhibited a slight increase at lower speeds ($\leq$ 45 rpm) but showed a substantial rise at 60 rpm. Despite these changes in frequency and damping, no significant variation in mode shape was detected across different rotor speeds.

Higher temperatures resulted in a decrease in the natural frequency of the first flapwise mode, with steeper slopes observed at increasing rotor speeds (Fig. 5). The damping ratios exhibited a stronger temperature influence at speeds above 15 rpm. At lower speeds, other factors appeared to outweigh the temperature effects on damping behavior (Fig. 5). The addition of mass significantly lowered the natural frequency of the blade, with this effect becoming less pronounced at higher rotor speeds due to compensation effects (Fig. 6).

In the earlier stages of damage, temperature had a more pronounced effect on the natural frequency, allowing for noticeable damage influences. However, in later stages of damage, a significant decline in frequency was observed as damage progressed as rigidity tends to decrease over damage progresses. Despite visible frequency effects, no clear influence of damage on the damping ratio or mode shape was detected (Fig. 7).

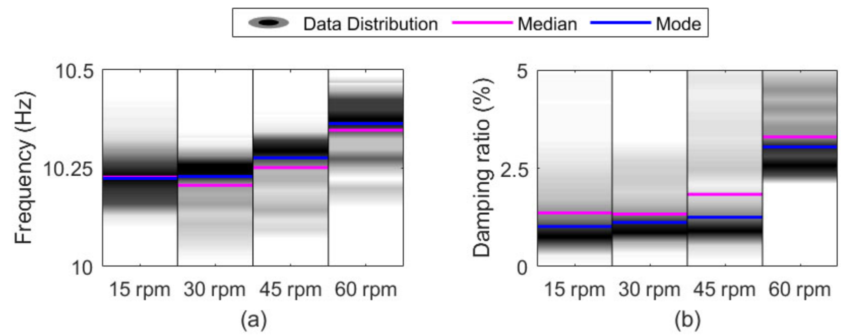

Fig. 4 (a) Identified frequency and (b) damping ratio at rotating speed scenarios

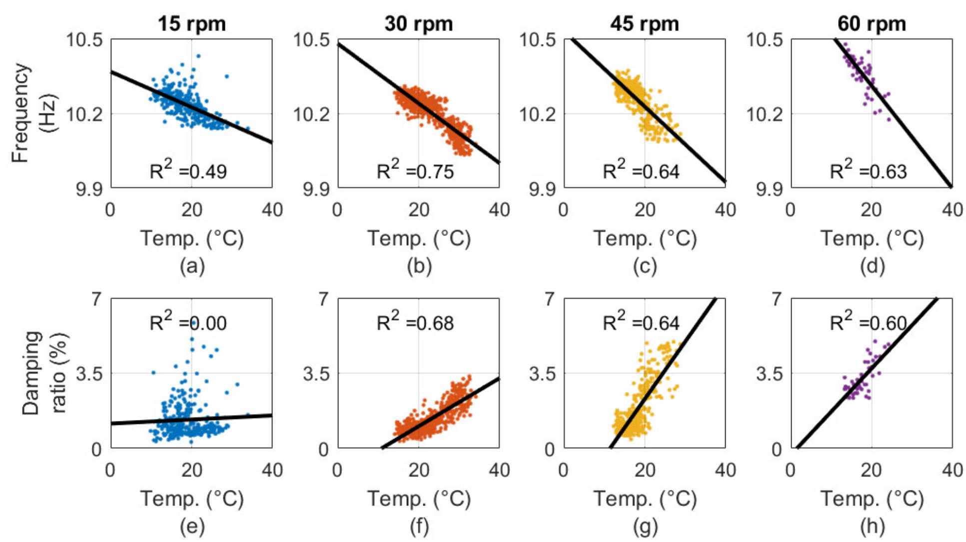

Fig. 5 Identified frequency at four rotating speed scenarios (a), (b), (c) and (d) and identified damping ratio at four rotating speed scenarios (e), (f), (g) and (h)

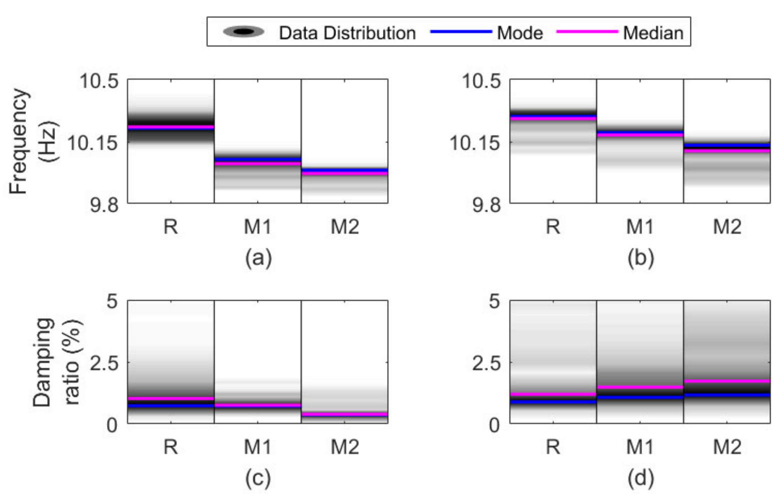

Fig. 6 Identified frequency considering reference and mass addition scenarios at 15 rpm (a) and 45 rpm (b) and identified damping ratio considering reference and mass addition scenarios at 15 rpm (c) and 45 rpm (d)

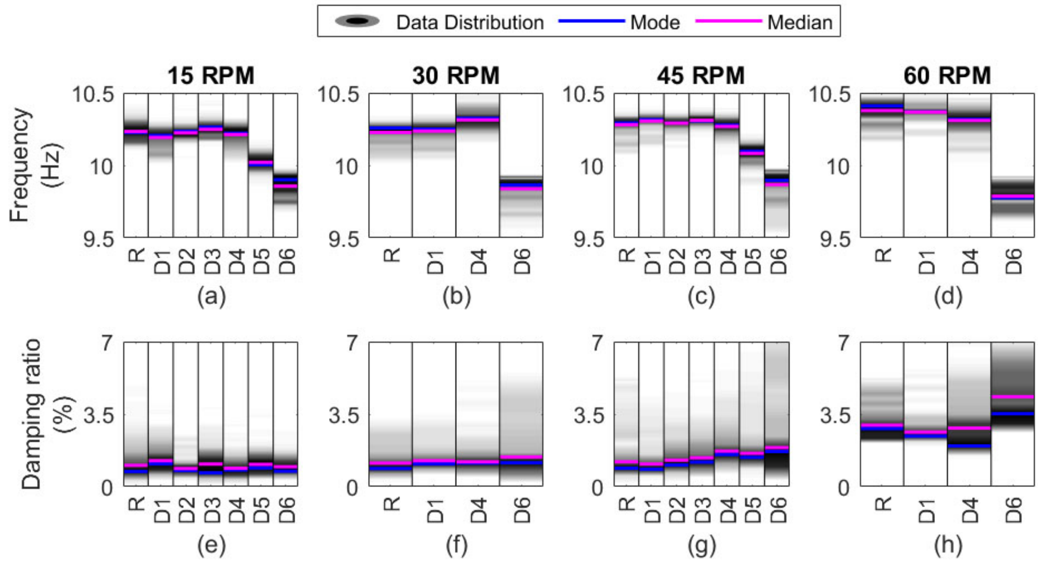

Fig. 7 Identified frequency at four rotating speed scenarios (a), (b), (c) and (d) and identified damping ratio at four rotating speed scenarios (e), (f), (g) and (h) considering progressive damage

The results align with the established physics related to material behavior and corroborate findings from previous research on damage progression in rotor blades [6]. These insights into the relationship between modal properties and EOVs are crucial for enhancing OMA. Algorithms based on modal properties could benefit from these findings to better understand, compensate, and disaggregate the effects of each environmental and operational variable, allowing for improved isolation of the real effects on wind turbine performance.

Conclusion

This study has established significant correlations between environmental and operational variables and the modal parameters of wind turbine blades. Key findings include that the natural frequency of the first flapwise mode increases with rotor speed, reflecting enhanced stiffness due to nonlinear geometric effects. Conversely, elevated temperatures have been shown to decrease natural frequency, especially at higher rotor speeds. The addition of mass to the blades significantly reduces natural frequency, although this effect becomes less pronounced at higher speeds. Additionally, while temperature influences the modal parameters during the early stages of damage, no substantial impact on damping ratios or mode shapes was observed as damage progressed. These findings highlight the complex interplay between environmental and operational variables and the structural dynamics of wind turbine blades.

Understanding how environmental and operational variables affect modal properties, maintenance strategies can be optimized, leading to more effective monitoring and timely interventions. Improved damage detection methods that incorporate these variables can help prevent catastrophic failures, thereby ensuring operational efficiency and reducing maintenance costs. This research contributes to the development of more robust operational modal analysis frameworks that account for the variability introduced by EOVs, ultimately supporting the sustainable operation of wind energy systems.

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