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EDITED BY
Francesca Benassi,
University of Bologna, Italy

REVIEWED BY
Lorenzo Bastia,
University of Bologna, Italy

*CORRESPONDENCE
Sahar Saleh,
sahar.saleh@atu.ie,
sahar.abdulrazzaq.eng@aden-univ.net

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Overview of RF-based structural health monitoring of wind turbine blades

Sahar Saleh[1,2]*, Tale Saeidi[1], Nick Timmons[1], Faroq Razzaz[3] and Qusay Shihab Hamad[4]

[1]WiSAR Lab, Atlantic Technological University (ATU), Letterkenny, Ireland, [2]Department of Electronics and Communication Engineering, University of Aden, Aden, Yemen, [3]Electrical Engineering Department, Prince Sattam Bin Abdulaziz University, Al-Kharj, Saudi Arabia, [4]Quality Assurance Department, University of Information Technology and Communications (UoITC), Baghdad, Iraq

The structural health monitoring (SHM) of wind turbine blades is crucial for early failure identification, which subsequently reduces maintenance costs and ensures reliable operation in both onshore and offshore environments. Radio frequency (RF) and microwave radar technologies offer an effective non-contact and weather-resistant method for assessing wind turbine blade deflection. To achieve high-performance radar, various antenna types are offered in the literature, each with specific requirements and methodologies aimed at enhancing their performance to improve radar detection accuracy, such as high gain and narrow beam width. Among the different Doppler radars, Frequency Modulated Continuous Wave (FMCW) radar is preferred due to its enhanced spatial resolution, phase-based displacement sensitivity, and accurate fault localization. Additionally, radar performance can improve using advanced digital signal processing (DSP), improving signal strength, detection accuracy, and mitigating the multipath interference effect. This study examines RF-based solutions for wind turbine blade deflections, addressing various types of antennas, their placement on the blade at distinct frequencies (e.g., UWB and mmWave). It also tackles the primary limits of monitoring, including air attenuation, multipath effects, and resolution constraints. Challenges and future work for wind turbine monitoring based on RF were also mentioned. This overview establishes the fundamentals for the RF-based strategy in SHM of wind turbine blades.

KEYWORDS

structural health monitoring (SHM), wind turbine blade monitoring, modulated continuous wave (FMCW) radar, UWB, mmWave

1 Introduction

Structural health monitoring (SHM) is an important approach for infrastructure safety. This can be done directly using visual inspections, X-rays, or ultrasonic testing, which are considered very reliable and accurate; however, they are costly, require a large number of expensive sensor arrays, and data management can be complicated as a result (Li et al., 2017). To avoid this, indirect detection is cheaper and can detect small deflections, such as changes in stiffness or damping, with fewer sensors, but it is not as reliable. Ireland's 2030 goal of 80% renewable electricity depends on wind turbines (WTs); but, due to aging infrastructure and harsh climates (tropical heat, lightning, arctic cold, hail, and snow), blades and towers develop structural problems that cause fluctuating loads and diverse

operational stresses which initiate micro-cracks and fatigue and deflect their blades (WTB) (Heo and Na, 2025; Memari et al., 2025). As a result, this increases the maintenance cost by 40% of the operational costs (Herrasti et al., 2016). Early-stage damage is often subtle, making detection challenging. So, SHM has to find a compromise between cost and performance to minimize downtime. Efficient conventional condition-monitoring techniques (CMTs), used for wind turbine monitoring, include strain gauges, acoustic emission sensors, and fiber optics. However, these face problems such as difficult accessibility (especially in offshore farms), detaching sensors due to bad weather, and high costs (Tchakoua et al., 2014; Scholz et al., 2016). Wireless sensor networks (WSNs) are used as an alternative solution combining transducers, signal conditioning circuits, and processing software. However, they resulted in high sampling rates and synchronization, and this can be mitigated using advanced Digital signal processing (DSP) (Herrasti et al., 2016).

To overcome the previous detection method problems, RF-based radars with different antenna types and frequency bands are used, resulting in high-accuracy detection (et al., 2023). The antennas utilized for these radars are covered in Section 2, along with their limitations and potential future developments in Section 3, while Section 4 concludes the work.

2 Antenna technologies for radar-based wind turbine blade monitoring

WSNs considered as an effective method especially in collecting critical data such as temperature and oil conditions; however, they are practically costly and complex (high sampling rates and synchronization) (Herrasti et al., 2016). Authors in Zhang and Wei (2021) used eight 24 GHz mmWave sensors mounted on the tower to continuously measure the tower–blade-tip clearance. From each sensor's input into the nacelle rotation coordinate system and least-squares fitting, they computed the minimum clearance and utilized it in a feedforward pitch-control loop to increase clearance by 30% in field tests. This study shows that mmWave radar can follow blade deflection in real-world settings. Ng et al. (2024) developed a wireless IoT acoustic monitoring system for wind turbine blades to handle blade rotation, cabling, remote deployment, and antenna performance. Their field studies demonstrated that omnidirectional antennas are better since directional antennas lose communication when the blade moves. Recording acoustic and environmental data was effective, however sporadic signal loss highlighted the need for more reliable high-gain wireless connectivity. This shows the challenges of wireless communication on rotating turbine blades and the limitations of sensor-based SHM before radar-based techniques. A more robust sensing method is needed to overcome the high complexity of WSNs (Herrasti et al., 2016), the need for multiple distributed radars and coordinate transformations for clearance estimation (Zhang and Wei, 2021), and the wireless instability in rotating-blade IoT systems (Ng et al., 2024).

In Zhang et al. (2015), Zhang et al. (2016), Zhang et al. (2017); Zhang et al. (2018), Zhang et al. (2019), Franek et al. (2018); Franek et al. (2020), a tip antenna paired with root antennas was used to estimate blade tip–root distances and wind turbine blade deflection (WTBD) in the lower UWB frequency bands (2.82–4.97 GHz, 3.1–5.3 GHz, and 3.1–5 GHz). UWB is a low-power radio technology that utilizes a broad spectrum, generating extremely brief temporal pulses because of its extensive bandwidth. These short pulses provide precise determination of the initial signal's Time of Arrival (TOA), enabling localization within centimeters (Soumya et al., 2023). The lower band was chosen because RF components and pulse modules are cheaper, less lossy, and commercially available. Zhang et al. (2015), Zhang et al. (2016) used UWB (3.1–5.3 GHz) to sense wind-turbine blade deflection via two horn root antennas (receivers) and one internal corner reflected monopole (Zhang et al., 2015) and external Vivaldi (Zhang et al., 2016) tip antenna (transmitter) powered by pulse generator. The blade deflections were estimated via time-domain pulse measurements using delay-based distance estimation and triangulation. In Zhang et al. (2015), authors highlighted challenges for tip antennas, including near-field interactions, multipath, lightning protection, and aerodynamic constraints (low-profile to avoid aerodynamic drag and noise), and noted the need for high endfire gain toward the root. In Zhang et al. (2016), simulations optimized tip antenna polarization (y-axis) and root antenna positions to enhance signal strength and limit multipath interference in the lossy fiberglass blade. Practical wind turbine deployment positions all UWB electronics, including pulse generator and RF circuits, at the blade root, where power is available. The tip antenna receives signal from an internal connection. To protect the in-blade tip antenna, an external diverter strip sends lightning strike energy to a grounded receptor without affecting the radio link. Cross-turbine signal overlap is negligible due to highly directed tip and root antennas, low UWB transmit power, far dispersed turbines, and blade rotation and yawing. Zhang et al. (2017) evaluated in-blade UWB (3.1–5 GHz, Vivaldi) with dielectric lens tip antennas for multipath interference from surface and leaky waves and used C-RAM MT 26 to reduce multipath and improve pulse-front fidelity and tip–root distance precision (Zhang et al., 2017). In models and full-blade experiments with restricted in-blade space, lightning protection, ice, water, and temperature fluctuations, optimal absorber placement and thickness increase direct-pulse amplitude, stretch ratio, and multipath reduction. Zhang et al. (2018) recommend a high-gain tip antenna for UWB sensing accuracy and early detection of significant deflections to prevent tower strike (Zhang et al., 2018). However, Zhang et al. (2019) propose a vertical polarized tip antenna with metal directors or dependable pulse transmission along the blade with a capacitive feed and a long dielectric block to improve endfire gain and lightning protection (Zhang et al., 2019). In Franek et al. (2018), authors used the finite-difference time-domain (FDTD) numerical method to analyze UWB signal propagation along a 37.3-m wind turbine blade and compare simulations with real measurements to see how well FDTD predicts pulse magnitude and delay. The composite blade's composition reduces accuracy when the tip antenna is inside. FDTD simulation showed that multipath makes signal propagation over blades more complicated than ordinary wireless links due to directed waves and reflections (Franek et al., 2020). Recently, authors in (Maetz et al., 2023) developed a microwave SHM method for grouted connections of monopile-based offshore wind turbines, which are prone to cracking, particle washout, and long-term erosion. They monitored guided electromagnetic waves propagating along the grout and steel interface with a 100 MHz–2 GHz stepped-frequency CW (SFCW) UWB radar with permanently attached 2 Tx/3 Rx antennas to detect crack formation

and erosion during large-scale fatigue testing. Although useful for WTBD monitoring, UWB approaches have drawbacks. UWB frequency bands' longer wavelengths (28–96 mm) limit angular resolution, making it less effective at detecting small surface defects like cracks or corrosion, and its low power spectral density limits range to under 50 m, far below the 1–5 km needed to monitor Ireland's offshore wind farms. Their antennas are larger than that at mmWave frequency bands, making MIMO array beamforming for multi-target identification challenging.

Previous SHM investigations used Continuous Wave (CW) (Guan et al., 2014) and Doppler radar (Moll et al., 2014) at low or fixed frequencies to quantify vibration and required considerable offset calibration. These methods lacked imaging, range resolution, and internal defect localization/characterization. Munoz-Ferreras et al. (2016) conceptualized, simulated, and detected wind turbine Doppler fingerprints using C-band and K-band radars (Munoz-Ferreras et al., 2016). They found Doppler "flashes," tip halos, and curved spectrogram features, proving higher radar frequencies improve Doppler resolution. Researchers built and deployed short-range, fixed-position Doppler radars that measure velocity signatures only. Since they cannot provide range, deflection, deformation, or structural-localization information, they are unsuitable for continuous remote wind turbine monitoring. Research needs a hub-mounted, long-range mmWave FMCW radar that detects blade health, not Doppler velocity. Thus, mmWave FMCW radars are needed for true real-time remote SHM of turbine blades because FMCW detects range, velocity, and vibration with high penetration and resolution (Bruno et al., 2023). Thus, researchers are investigating mmWave frequencies for better monitoring and resolution. In order to increase image performance and eliminate sidelobes, authors in Arnold et al. (2017) designed a sparse mmWave antenna array (33.4–36 GHz) for radar-based SHM of WTBs with a Y-shaped transmit (one)–receive (nine) configuration. Sparse arrays localized faults cheaper and with less data than fully populated arrays using stepped-frequency CW (SFCW) radar and back-projection photography. The method involves powered on-blade antennae and demands a strong understanding of the blade's heterogeneous permittivity, which can cause large localization errors. It still requires powered on-blade antennae, making field deployment and maintenance challenging. Efforts have been made to explore the advanced techniques for designing suitable antennas at different frequency bands for FMCW-based SHM for wind turbine blades to improve detection accuracy and reliability. For the first time, mmWave imaging FMCW-based radar is used for SHM of WTBs using synthetic aperture imaging at Tx and Rx horn antennas (array) along the tower to project electromagnetic waves at the rotor blades It provides non-contact glass-fiber blade inspection and penetration at 24–25.6 GHz (B1:1600 MHz) and 24–24.25 GHz (B2: 250 MHz). Differential signal processing revealed corrosion and water in rotor tips. They found that larger bandwidth detects multipath reflections inside the blade, improving radar resolution over a narrow one that produces a single merged peak. In Scholz et al. (2016), a 24–25.6 GHz FMCW radar with 24 dBi horn antennas detected faults in a laboratory demonstrator utilizing spinning glass-fiber samples. Vertical scanning was possible while modifying rotor pitch and speed. The study revealed that typical surface faults may be remotely identified and that ambient elements like temperature change range profiles require future compensatory measures.

Later Moll et al. (2018a), they introduced permanent 24.05–24.55 GHz and 33.4–36.0 GHz FMCW radars with time-of-flight (TOF) range profiles and a simple root-mean-square (RMS) damage indicator for laboratory SHM with real structure damage in (Scholz et al., 2016) compared to the study with artificial defects. This progression shows a clear move from proof-of-concept imaging to more practical SHM methods, but both studies were lab-validated, used commercial horn antennas, and lacked field-level challenges like environmental changes, blade pitch variation, long-range deflection tracking, or continuous in-service monitoring. No turbine experiments were done, and the method relies on short-range radar mounts, controlled settings, and simple signal characteristics rather than structural-state estimation. They achieved the first in-field ISAR imaging of whirling blades by deploying two high-power FMCW radars (24 GHz and 33–36 GHz) on a 2-MW turbine tower (95 m heigh) (Moll et al., 2018c). They obtained radar pictures with front- and back-wall echoes using I/Q extraction and range-profile creation, indicating full blade penetration throughout operation. Tower-mounted radars see blades at large standoff distances, so rotation, pitch, and environmental fluctuation substantially affect their signals. The authors automated blade-passage detection using RMS curves and a moving-average filter to smooth the RMS signal and detect each blade as it crosses the radar beam, guaranteeing that only synchronized pictures are used for imaging. This work shows important viability, however the tower-mounted ISAR technique is noisy and geometrically unstable, requiring complicated synchronization filters and generating inconsistent findings across rotations. Authors in Moll et al. (2018b) found that embedded 57–64 GHz RadCom sensors in blade laminates enabled direct quality inspection and material-level SHM. 3D simulations optimized sensor placement and defect detection, including delamination and fiber failure, but full-scale and long-term deployment is untested.

In Bruno et al. (2023), a 77 GHz MIMO-SAR system was proposed to improve tower deformation measurements. Authors in Chen et al. (2024) utilized a 79 GHz circularly polarized microstrip array for tower collision detection, improving signal-to-noise ratio (SNR) and reducing interference via polarization. They combined the transmitting channel into one channel to increase the transmitted power to be focused and reach the tip, and to have a focused angle instead of higher azimuth resolution. Their proposed system is shown in Figure 1.

It should be noted that the mmWave radars face challenges such as atmospheric attenuation, multipath interference, and dynamic load effects in composites (Valerio de Queiroz Rodrigues, 2023). Internal antenna placement increases signal loss, and MIMO configurations raise costs. Environmental factors such as yaw misalignment, ice accumulation, and harsh weather, as well as drone inspection limitations, further challenge scalability (Yan et al., 2024).

Advanced Digital Signal Processing (DSP) along with machine learning (ML) is an important tool for improving detection by reducing noise and correcting displacement in low-SNR environments. ML enhances defect detection, with k-medoid clustering achieving 81.21% accuracy for micro-cracks in GFRP blades (Tang et al., 2023). In Shin Yee et al. (2024), Gaussian filters and k-medoids clustering are used to improve delamination detection, while phase-based algorithms are used to address high-frequency clutter and weather interference (Tang et al., 2021).

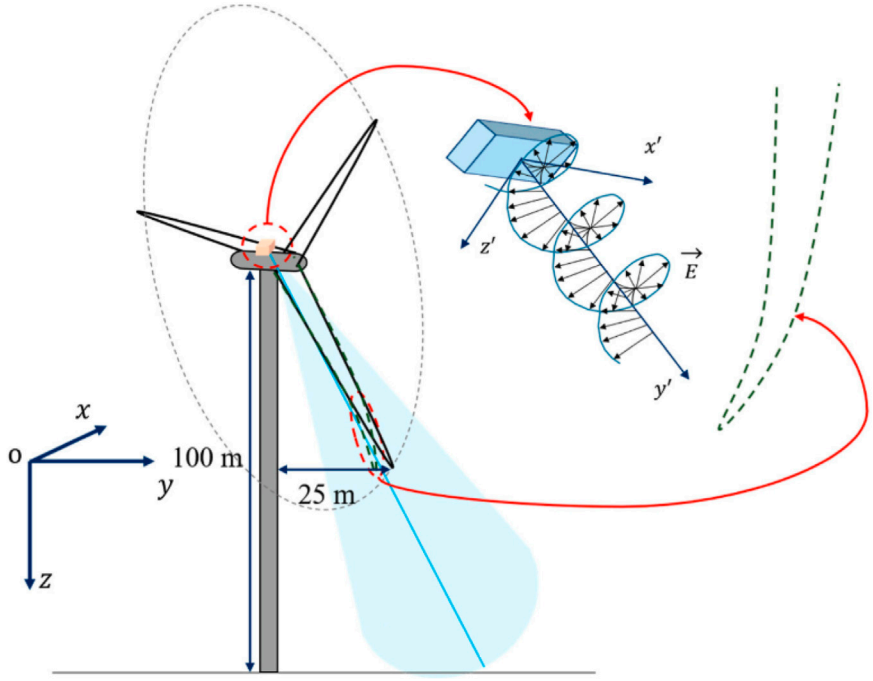

FIGURE 1
Radar installation diagram (Chen et al., 2024).

3 Discussion and future perspectives

RF-based radar systems, particularly FMCW radars in UWB and mmWave bands, offer a promising non-contact technique for WTBD. Vivaldi, horn, and microstrip array antennas have been tested to improve spatial resolution, beam focusing, and detection accuracy. Advanced DSP such as phase-based displacement estimation and machine learning can reduce noise, multipath interference, and environmental influences. Despite the advantages of UWB and mmWave FMCW radars for WTBD SHM, the following issues should be addressed.

- Radar performance can be degraded by atmospheric attenuation, harsh weather, and unpredictable operational circumstances, especially offshore.
- UWB systems have long-range coverage but low spatial resolution, while mmWave systems have higher resolution but are more attenuated.
- Selecting and optimizing antenna types, combinations, and positioning is essential for precise detection at low cost and complexity.

Future research may focus on:

- Real-time analysis of high-frequency radar data requires excellent DSP and ML algorithms, especially in dynamic operational contexts.
- Hybrid radar systems using UWB and mmWave bands or MIMO to improve detection accuracy and robustness.
- Designing compact, high-gain antennas, hybrid FMCW-MIMO radars, and low-power modular systems for scalable, reliable SHM of wind turbines.
- Real-time damage identification and classification in noisy and dynamic situations using sophisticated DSP and AI-based techniques.

In conclusion, RF-based radar can be used for non-contact wind turbine blade SHM. To be used in large-scale applications, environmental robustness, antenna optimization, and signal processing development must continue.

4 Conclusion

RF-based radar systems, combined with advanced antennas and DSP, provide a promising approach for accurate, non-contact SHM of wind turbine blades. While UWB and mmWave FMCW based radars offer good detection techniques, challenges remain in environmental robustness, range, and cost. Future work should focus on compact, high-gain antennas, hybrid FMCW-MIMO radars, and low-power modular systems for scalable, reliable SHM of wind turbines.

Author contributions

SS: Conceptualization, Resources, Writing – original draft, Writing – review and editing. TS: Writing – review and editing. NT: Funding acquisition, Writing – review and editing. FR: Writing – review and editing. QH: Writing – review and editing.

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