A Step Forward Towards Radar Sensor Networks for Structural Health Monitoring of Wind Turbines

J.-M. Muñoz-Ferreras[1], Z. Peng[2], Y. Tang[2], R. Gómez-García[1], D. Liang[3], and C. Li[2]

[1]Dept. Signal Theory & Commun., University of Alcalá, Alcalá de Henares, 28871, Madrid, SPAIN

[2]Dept. Electrical & Computer Engineer., Texas Tech University, Lubbock, TX 79409, USA

[3]Dept. Civil, Environ., & Construction Engineer., Texas Tech University, Lubbock, TX 79409, USA

***Abstract*— Structural health monitoring (SHM) of wind turbines can be carried out through inexpensive noncontact radar systems. This paper reports the first steps for the proper deployment of a network of radar sensors around the wind turbine, which may provide useful information to reliably detect possible defects or malfunctioning. In particular, the echo features for a 50-m-height wind turbine when illuminated by a 24-GHz Doppler radar from different near positions are carefully studied and evaluated in a simulated scenario. The performed simulations are in close agreement with the experimental results obtained through a 24-GHz radar gun. As main conclusions, this analysis reveals the convenience of employing high-frequency radar systems for the sensor network and situating the radars on the ground.**

***Index Terms*— Doppler radars, remote sensing, spectrogram, structural health monitoring (SHM), wind turbine.**

I. Introduction

Ecologically-sustainable electrical power from wind is becoming an ever-increasing alternative to more traditional energy resources, such as petroleum, gas, or uranium. Wind farms are growing in size and number. In addition, the amount of wind turbines per wind farm and their physical dimensions are becoming larger and larger. As such, a wind turbine is a huge mechanical structure which requires continuous monitoring [1].

Structural health monitoring (SHM) of wind turbines by means of noncontact radar sensors can be a complementary alternative to other solutions, such as optical-fiber- or acoustic-emission-based systems (see [1] and cites therein). The authors previously showed an *ab-initio* field investigation of this approach in [1]. There, experimental results after illuminating a 50-m-height wind turbine with a 24-GHz handheld radar in the American Wind Power Center, Lubbock, TX, USA, were reported. The unique feature of the echoes is the appearance of periodic tilted flashes in the spectrogram (i.e., the Doppler-time map) [1].

The final long-term purpose of these investigations is the successful design of a network of radar sensors situated around the wind turbine to continuously monitor its structural health, enabling the maintenance or even shutting-down operations after the detection of an anomalous event—such as impairments in the periodicity and Doppler values of the flashes, or an excess of curvature in the tilted flashes. This work provides a first step towards this goal by conducting and analyzing simulations which also help to justify the experimental results shown in [1].

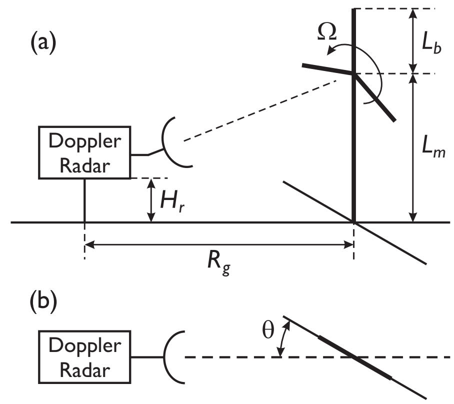

Fig. 1. Schematic representation of the acquisition scenario: a near Doppler radar illuminates a big wind turbine. (a) 3-D depiction. (b) Top view.

Near-field simulated and experimental tests for small wind turbines can be found in the technical literature (see [2] and cites therein). Also, some works related to big wind turbines in the far field can be encountered [3]–[5]. For the intended SHM context, the results detailed here permit to conclude that it is beneficial to use high-frequency radars and to deploy them on the ground around the wind turbine.

II. Simulation Scenario

Fig. 1 shows a schematic representation of the acquisition scenario. A 3-D view is given in Fig. 1(a), whereas a top view is provided in Fig. 1(b). The ground distance from the Doppler radar to the turbine is defined as R_g. The radar is situated at a height H_r above the ground. Regarding the wind turbine, L_m is the mast length and L_b is the length of the blades. The blades are rotating at a rate Ω. Note that the angle θ parameterizes the aspect orientation of the wind turbine with respect to the radar.

In the simulations, the Doppler radar is assumed to illuminate the entire wind turbine. In practice, it is important that the antenna beam covers all the blades, so that the unique features of the echoes (i.e., the flashes) can be obtained properly. The simulations have been accomplished by adding the returns of many point scatterers, which are assumed to be situated along straight lines for the blades

TABLE I

GEOMETRICAL PARAMETERS FOR THE ACQUISITION SCENARIO

Radar height (H_r)	0 m
Ground range from radar to turbine (R_g)	50 m
Mast length (L_m)	50 m
Blade length (L_b)	23.5 m

TABLE II

PARAMETERS FOR THE RADAR-SIGNAL SIMULATION

Transmitted CW frequency (f)	24 GHz
Acquisition time (T_a)	3 s
Sampling frequency (f_s)	20 kHz
Number of scatterers for the mast	500
Number of scatterers per blade	9400

and the mast. In particular, for the moving blades, the number of scatterers is chosen so that the spacing between them is set to be $\lambda/5$, where λ is the wavelength—note that $\lambda = c/f$, where c is the speed of light and f is the transmitted continuous-wave (CW) frequency. The simulation of a large number of scatterers—a big turbine and a high-frequency radar are assumed in this work—means a long computation time, but it is necessary if realistic results are desired to be obtained [2]. The complex analytic received signal $s(t)$ can be mathematically expressed as

$$s(t) = \sum_{k=1}^{K} \exp\left(-j\frac{4\pi}{\lambda}R_k(t)\right) \tag{1}$$

where t is the time, K is the total number of simulated scatterers, and $R_k(t)$ is the range history for the kth scatterer. Note that the same amplitude (i.e., the unity) is considered for each signal contribution of each scatterer.

III. SIMULATED RESULTS

Let it consider the scenario in Fig. 1. The parameters for the acquisition geometry are listed in Table I and correspond to a 660-kW Vestas V47 wind turbine [1]. As seen, the blade rotation rate is chosen to be $\Omega = 20$ revolutions per minute—i.e., the rotational period is $T = 3$ s—, which is a realistic value for wind turbines [5]. This means a speed for the blade tip of $v_t = 2\pi L_b/T = 49.2$ m/s.

The parameters for the radar-signal simulation are specified in Table II. The sampling frequency for the signal $s(t)$ in (1) has been selected to be $f_s = 20$ kHz, so that there are no Doppler ambiguities for the returned echoes—note that the maximum Doppler frequency is $f_{D,\max} = 2v_t/\lambda = 7.87$ kHz. The acquisition time is $T_a = 3$ s, which is identical to the rotational period T.

Next subsections show the simulation results for different aspect angles θ. The results reported there are interesting in relation to the proposed SHM radar network around the wind turbine. Note that, to make the study simpler, no white Gaussian noise has been added to the simulations.

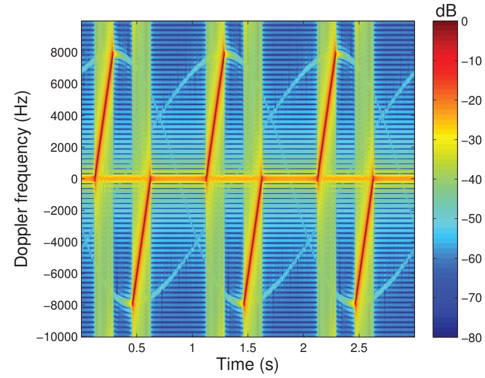

Fig. 2. Spectrogram for the simulation with $\theta = 0°$. Spectrogram parameters: uniform window of 64 samples and Fast Fourier Transform (FFT) of 512 points.

A. Simulated Results for an Aspect Angle $\theta = 0°$

When the orientation angle is zero ($\theta = 0°$), the maximum Doppler is observed by the radar. Fig. 2 shows the spectrogram for this case. As can be seen, energetic flashes appear when the blade is perpendicular to the propagation direction of the transmitted signal [2]–[5]. Three positive-Doppler flashes for the approaching blades and three negative-Doppler flashes for the receding blades are appreciated in this single simulated rotation period. The maximum Doppler ($f_{D,\max} = 7.87$ kHz) for the blade tips is also visible in Fig. 2, whereas the return in zero Doppler corresponds to the stationary mast.

A zoom-in for one flash of Fig. 2 is detailed in Fig. 3. A weak quasi-sinusoidal "halo" associated with the blade tip can be observed (see also Fig. 2), as described in [2]–[5]. The fact that these halos are much weaker here than those reported in past works comes from the use of a high-frequency radar. Indeed, this result justifies that the absence of halos in the experimental data in [1] is due to their masking by thermal noise.

One suitable explanation for the existence of sinusoidal halos and flashes is based on the constructive and destructive summing of the scatterer contributions in this human-made target [5]. A constructive interference occurs when the blade is perpendicular to the propagation direction of the signal. This explains the observed tilting of the flashes in Fig. 3. The time that the blade takes to go from angle α_1 to α_2 in Fig. 4 is the time during which the flash is ocurring in Fig. 3—$\alpha_1 = 45°$, $\alpha_2 = 64.41°$, and the aforementioned time is 161.8 ms in this simulation. This flash tilting is a near-field effect, not observed for far wind turbines [5], but clearly verified in our prior experiment in [1]. Besides, as clearly emphasized by the white line in Fig. 3, the flash is straight for this first case ($\theta = 0°$).

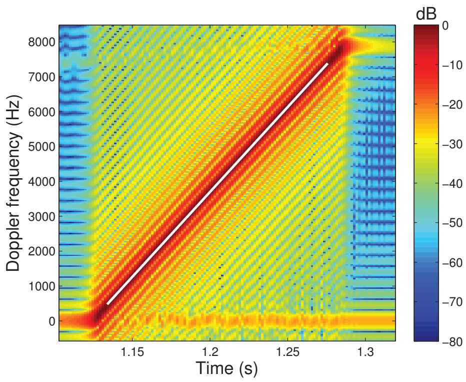

Fig. 3. A zoom-in for one flash of Fig. 2: a white line indicates that the flash is a straight tilted line in the Doppler-time map.

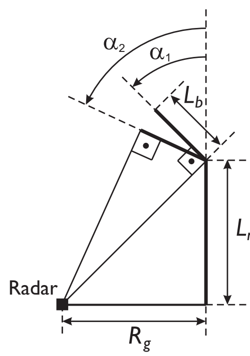

Fig. 4. Representation of an approaching blade at the instants when its base and tip are orthogonal to the transmitted signal.

B. Simulated Results for an Aspect Angle $\theta = 90°$

Fig. 5 shows a zoom-in for one flash of the simulated spectrogram when the orientation angle is $\theta = 90°$. Note that the parameters in Tables I and II have not changed.

As can be seen, the flashes have a lower Doppler excursion, which confirms the experimental results in [1] for $\theta = 90°$. For SHM purposes, this justifies a deployment of the radars on the ground. In fact, if the radar height is changed to $H_r = 50$ m, no flashes are observed—and, hence, SHM would not be possible. Additionally, the white line in Fig. 5 clearly indicates that the flash is not longer a straight line, but it possesses some curvature which happens when the aspect angle $\theta \neq 0°$.

IV. Discussion

Radar-based near-field SHM of wind turbines should use high frequencies, because the obtained results—both simulations and experiments [1]—have a better resolution than the ones reported for lower frequencies [2]–[5]. On the other hand, the radars should be deployed on the ground around the wind turbine, so that flashes are obtained regardless of the aspect angle θ—remember that wind turbines automatically change its bearing angle to adapt to wind direction. Analyzing the existing trade-off between the curvature observed in the flashes for $\theta > 0°$—a big curvature may lead to indicate that the blades are bending too much—and the number of radars needed around the wind turbine is the next step towards the successful design of the radar-based SHM system. Also, the fact that real blades are not perfect straight lines, along with their bending limits as well as their implications in the shape of flashes, are left as future research work.

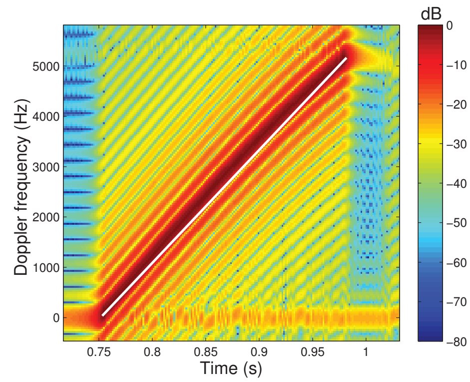

Fig. 5. Zoom-in for a flash of the simulated spectrogram with $\theta = 90°$: a white straight line emphasizes that the flash is curved. Spectrogram parameters: uniform window of 64 samples and FFT of 512 points.

V. Conclusion

A high-frequency on-ground radar sensor network deployed around a wind turbine is proposed for noncontact Doppler-based structural health monitoring (SHM). This paper has addressed some realistic simulated results, which validate some experimental data previously reported in the literature and provide the preliminary key design guidelines for the radar network.

Acknowledgment

This work was partially supported by the Spanish Government under Project TEC2014-54289-R.

References

[1] T. Nikoubin, J. M. Muñoz-Ferreras, R. Gómez-García, D. Liang, and C. Li, "Structural health monitoring of wind turbines using a low-cost portable K-band radar: An ab-initio field investigation," in *Proc. IEEE Topical Conf. Wireless Sensors Sensor Networks (WiSNet)*, San Diego, CA, USA, Jan. 2015, pp. 69–71.

[2] A. Naqvi and H. Ling, "Time-frequency and ISAR characteristics of wind turbines with higher order motions," *Prog. Electromagn. Res.*, vol. 143, pp. 331–347, 2013.

[3] B. M. Kent *et al.*, "Dynamic radar cross section and radar Doppler measurements of commercial general electric windmill power trubines, part 1—Predicted and measured radar signatures," *IEEE Antennas Propag. Mag.*, vol. 50, no. 2, pp. 211–219, Apr. 2008.

[4] A. Buterbaugh *et al.*, "Dynamic radar cross section and radar Doppler measurements of commercial general electric windmill power trubines, part 2—Predicted and measured Doppler signatures," in *Proc. Antenna Meas. Techn. Assoc. (AMTA) Symp.*, St. Louis, MO, USA, Nov. 2007, pp. 1–6.

[5] B. Gallardo-Hernando, J. M. Muñoz-Ferreras, F. Pérez-Martínez, and F. Aguado-Encabo, "Wind turbine clutter observations and theoretical validation for meteorological radar applications," *IET Radar Sonar Navig.*, vol. 5, no. 2, pp. 111–117, Feb. 2011.