Novel non-contact deformation health monitoring of towers and rotating composite based wind turbine blades using interferometric ground-based radar

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Key words: deflections, radar, wind, blades, monitoring

SUMMARY

This paper describes the use of non-contact quasi monostatic ground-based radar (GBR) for system health monitoring (SHM) of the blades of wind turbines. It focusses on the deflection monitoring of these blades and validates the results from the design parameters extracted from numerical simulations during the design stage.

Using a 3-tier SHM framework, acquisition of deflection in the time-domain is done by the GBR. These results are then transformed into the frequency-domain using a fast Fourier transform (FFT) to obtain the resonant frequencies as second step in the 3-step SHM framework. The third step of validation / hypothesis testing of the measured results with initial simulated design parameter is then effected to demonstrate that the GBR can be used for deformation health monitoring of composite blades and towers.

The work demonstrates that the GBR can be deployed as a non-contact, real-time monitor that can measure deflections and natural-vibration frequencies of wind turbines blades. This enables smart monitoring of dynamic structures in urban and non-urban settings.

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1 INTRODUCTION

To increase the installed capacity of a wind turbine, the blades are made longer[1][2, 3]. This has the effect of increasing the effective area available for extraction of wind power. The impact of longer blades means their optimisations towards lesser weight, to make more slender, lighter and flexible blades. For this, use of composites materials are used. This will however result in the blade experiencing more significant vibrations and deflections in the in-plane and out-plane directions during operations.

In order to meet the stringent demands for blades that are lightweight, with high strength and excellent fatigue resistance capabilities, the use of composite materials has been on the increase. Use of Composites has however meant that the previous design approaches (fatigue and ultimate strength) for blades be extended from the static and fatigue classes to also include aeroelasticity analysis [5] (*Figure 1*). This is due to two factors: (a) neglecting aeroelasticity analysis leads to over-estimation of annual energy produced and (b) it exposes the blade designer to ignoring blade flutter – a dynamic aeroelastic instability occurring in large flexible structures [5], as commonly seen in the ever increasing composite blades.

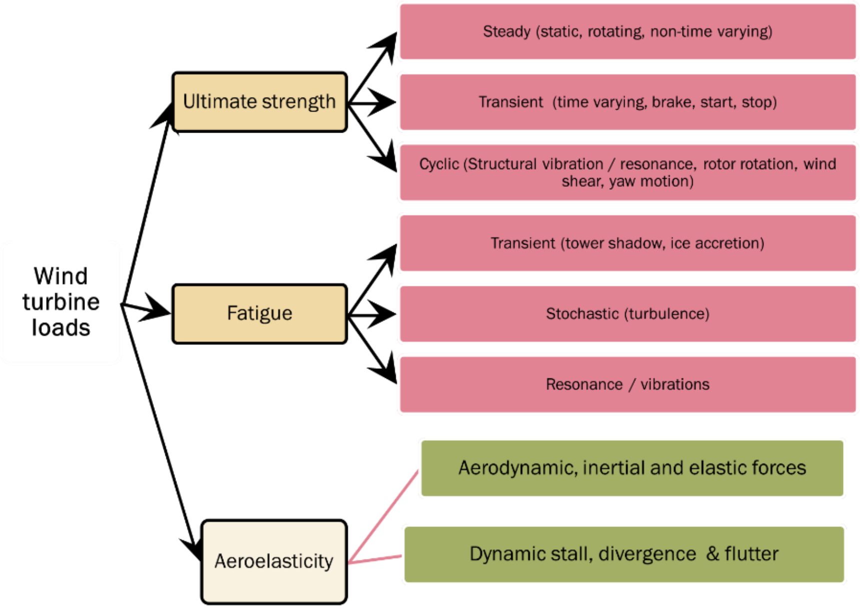

Figure 1: Parametric load analysis for design & SHM for Wind turbines

Current industry practices for the transient design modelling of the aeroelastic effects is by numerical simulation of the wind flow over blades, their dynamic behaviour and effects on the structure [6]. Integral to the aeroelasticity modelling are the complex deflections made by the rotor blades, tower and nacelle (Figure 3). These consist of the to- and fro- deflections of the blades (Δd_{blades}), tower deflections (Δd_{tow}) and the nacelle whirling movements. The nacelle whirl is where the hub centre of the rotor deflects in an elliptical orbit around its rest position.

Wind turbine blades, unlike commercial aircraft blades are fatigue critical structures. The design is dictated not only by fatigue but as previously noted by aeroelastic considerations. Design of aircraft blades will mainly consider ultimate strength while for wind turbine blades, fatigue is the major consideration. When being designed, the wind turbine blades with approximately 100 million design cycle loads over its lifetime have several orders of magnitude more cycles in testing than for aircrafts blades (1 million lifetime design cycles). This makes wind turbines blades testing and design extremely expensive. The approach normally used is for physical testing for some orders of magnitudes and the residual is achieved by simulations.

For homogenous materials this would be in order, however, the use of composites presents a challenge, especially at locations where the composites transit from compression to tensile failure modes [13]. This has already been noted almost a decade earlier in [14] wherein it was realized that while fatigue damage information of composites glass fibre reinforced plastics (GFRP) at micro- and macro scale exists, the transfer of such information onto a full-scale for certification purposes is not trivial. The study [13] suggests the round robin comparisons of different numerical methods to attain a sound understanding of the fatigue lifetime.

In addition to the design challenges, the environmental and operating conditions (EoCs) of wind turbines are transients (non-periodic), consequently the potential deflections during design and in real life operating conditions are based on simulations in the time-domain. This provides the minimum and maximum limits for the deflections and for which various sensors within the tower, and nacelle monitor. However, exact values are not easily determined for proper real-time system health monitoring.

This paper thus demonstrates that using a GBR for determination of fatigue lifetime can be achieved for operating wind turbines as well as during testing of wind turbines during design and this fed back to the numerical systems to better enhance the design process.

2 GBR THEORY AND STATE OF ART

To determine the deflection of blade, a quasi-monostatic GBR, emits radio waves from one of its antenna and then recieves the returned backscattered / echoed waves. The different delays/ranges of the backscattered waves, distinguish them from each other allowing sections of the blade or tower to be identified in the corresponding 1D or range profile (distance from GBR to the wind turbine blade) i.e. profile versus time (t). This is obtained by match-filtering the backscattered signals with the transmitted signals or stretch processing. Consequently, the maximum range (R_{max}) for this quasi-monostatic radar. [25, 26] is given by equation (1).

$$R_{max} = \sqrt[4]{\left(\frac{P_t G_t G_r \lambda^2 \sigma}{(4\pi)^3 \mathrm{P}_{r\_min}}\right)} \qquad (1)$$

where P_{r_min} is the minimum received power in Watts at the receiver antenna that would allow target detection, P_t is the transmitted power in Watts at the transmitter antenna, G_r and G_t are the antenna gains for the receiver and the transmitter respectively, while λ is the radar signal wavelength in metres and σ the radar cross-section area in square metres. To measure deflection the radar will distinguish the two maximum points OP1 and OP2 as the blade oscillates back and forth, similarly also for the nacelle.

Further using Doppler shift in the GBR backscattered signal, a distinction between moving and stationary targets as well as determining the radial velocity (deflection velocity, v) of a target can be made [27]. The Doppler information can only be extracted by recovering the phase history of the signal over time and therefore requires the GBR receiver to be coherent [28]. In [29], the displacement/deflection along the line of sight (Def_{LOS}) of a structure when the GBR is at an incident angle θ (angle between the line of sight and ground) is provided by the equation (2).

$$Def_{LOS} = \Delta S \, \frac{L}{r} = \Delta S \, . \cos(\theta) \qquad (2)$$

where L is the distance between the radar position and the structure, r is the slant range as given in equation (1), and ΔS is the actual deflection measured by radar. Def_{LOS} is the structures' deflection along the slant range r with θ being the elevation angle with respect to the horizon.

A number of studies have been undertaken where GBR was used to determine the deflections of blades of an operating wind turbine [15-22]. Analysis of these studies indicate two key research gaps. First the studies have not attempted either not monitored an actual operating wind turbine and/or use the GBR within a robust framework of System health monitoring (SHM). Secondly, the studies has attempted to validate the results of the GBR with commonly used approaches in the wind energy sector used for acquisition of deflection and resonant frequencies. Such approaches include use of accelerometers, Fibre Bragg gratings (FBG) and use of numerical results like finite element analysis (FEA). This paper has thus sought to address these two gaps.

3 EXPERIMENTAL METHOD

To address the aforementioned research gaps, a SHM framework employing 3 sequential steps or tiers has been incorported into the GBR monitoring. The tiers are (a) data normalization, (b) feature extraction using condition parameters (CP) and lastly (c) health validation by way of hypothesis testing (HT) [23, 24]. To begin the data collection within the 3 tier SHM framework, the GBR was placed at almost 90 degrees to the broad side of the Wind turbine 1 (WT1) nacelle (Figure 2), and data collection done in periods of 80 seconds spans.

The GBR had first its main lobe focussed at the blade tips near the middle of the tower in order to obtain the out-of-plane blade deflection as it moves from OP1 to OP2 (Figure 3), thereafter it was focussed at the mid-nacelle to obtain the tower deflection and also the nacelle whirl. Natural frequencies for the 3 data sets were obtained from analysis of the range information in the time-domain spectra.

Figure 2: GBR placed orthogonally to WT1

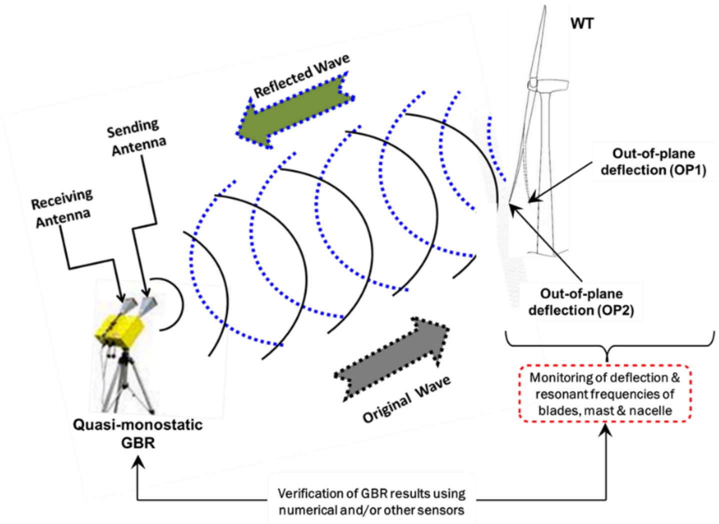

Figure 3: In-plane deflection monitoring of the blade

4 RESULTS AND ANALYSIS

Focussing the main lobe from the GBR to the blade tip resulted in acquisition of a high signal to noise ratio (SNR) value of 54.88 dB at a distance of 62.76 m. Using a surveyors tape measure the actual distance was validated and found to be 62.7meters, indicating good congruency with the GBR measurement. It was necessary as noted in [20] that the SNR values for the flat sided rectangular wind turbines nacelle, should be greater than 40 dB. In the experiment, the SNR value when GBR centre beam was pointed directly at the blade was 54.88 dB. Having validated the distance and the SNR, application of the GBR within the 3 tier SHM proceeded.

4.1 Data acquisition and normalisation

The first step was the acquisition of the time-frequency data. Located at a distance of 62.7 meters from the WT1 (Figure 5), the emitted electro-magnetic radio waves from the GBR were aimed at the mid-tower region and the reflection acquired by the receiving antenna to provide a time-domain results along the line of sight (LoS) of the GBR's central beam, which was then normalised and clustered into wind speed bins (Figure 4) .

An average displacement for the blades was determined by obtaining the difference between a set of peaks and the troughs, and averaging it over the total number of sets. The displacement range was 4.28m to 5.85m and with an average of 5.03m at an average wind speed of 6.4 m/s.

This was found to be in order when compared to the design value of 10.5m. It is expected however as the wind speed increases the deflection will also increase but should never surpass the design value – of 10.5m in the case of this WT1.

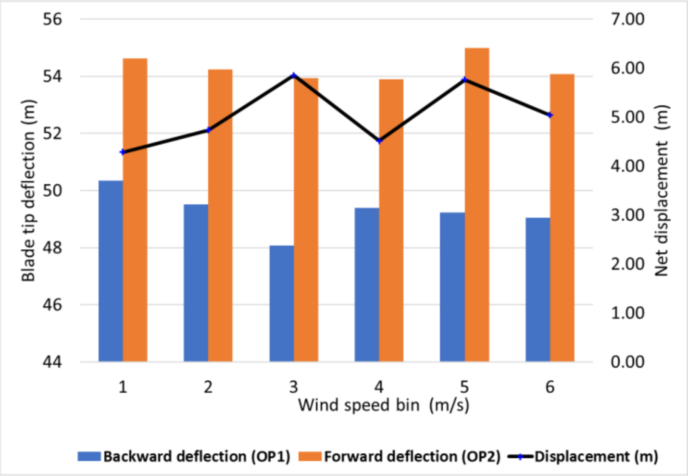

Figure 4: Forward and backward blade tip deflection

4.2 Extraction of condition parameters (CP)

To obtain condition parameters of the blades (resonant frequencies), a fast Fourier transform (FFT) was applied on the time-domain deflection results to obtain CP values in the frequency domain. The results however were for both flexural and torsional frequencies, Thus, to accurately identify which modal frequency is correct and relates to which component, either a numerical simulation will will need to be done or a comparison of the results is done with results from undamaged wind turbine values (normally by way of using blade's resonant frequencies as provided by the manufacturer). This forms the third part of the SHM framework.

The first modal frequencies (1P) for the tower is identified at 0.28 Hz (not shown), while the first and second modal frequencies for the blade tips are identified at 0.4489 Hz and 0.8728Hz (Figure 5). The CP extraction tends to extract both flexural and torsional frequencies for both tower and blade.

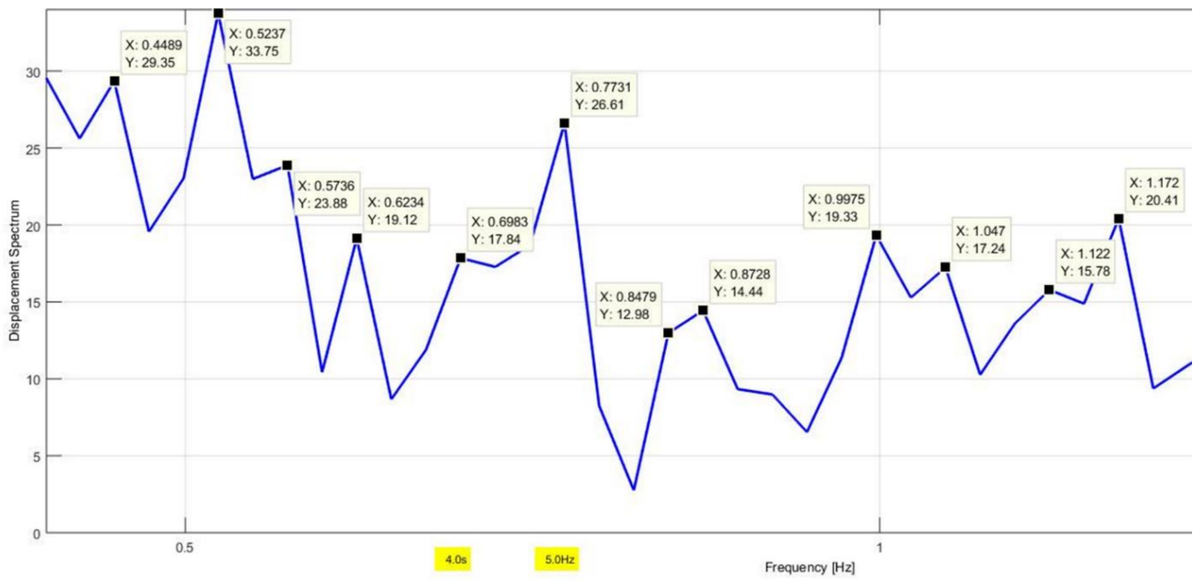

Figure 5: Resonant frequencies for WT1

4.3 Numerical model validation (Hypothesis testing)

The final aspect of the SHM framework is the hypothesis testing or numerical model development to assess the validity of the results obtained in the aforementioned steps 1 and 2. Subsequently, the displacements and modal frequencies were modelled using DNV GL **Bladed®** wind turbine numerical simulation tool to simulate the design and well as operating boundaries of the blades and towers. Such an analysis does provide for aeroelasticity calculations, however, it is only during operation of the wind turbines – that the validation of such numerical calculations can be achieved. To this end, the GBR is able to provide validation of the operating CP's.

The results of the numerical simulation was the provision of exact blade resonant frequency of 0.48 Hz as well as a range at ±5% Hz error band as shown in the Campbell diagram (Figure 6). To avoid resonance, the blade's first (1P) and second (3P) flapwise modes are numerically identified from the **DNV GL Bladed®** wind turbine simulation tool as ranging between 0.43 – 0.47 and 0.83 – 0.91 Hz. This bands are the optimal operating points for the WT.

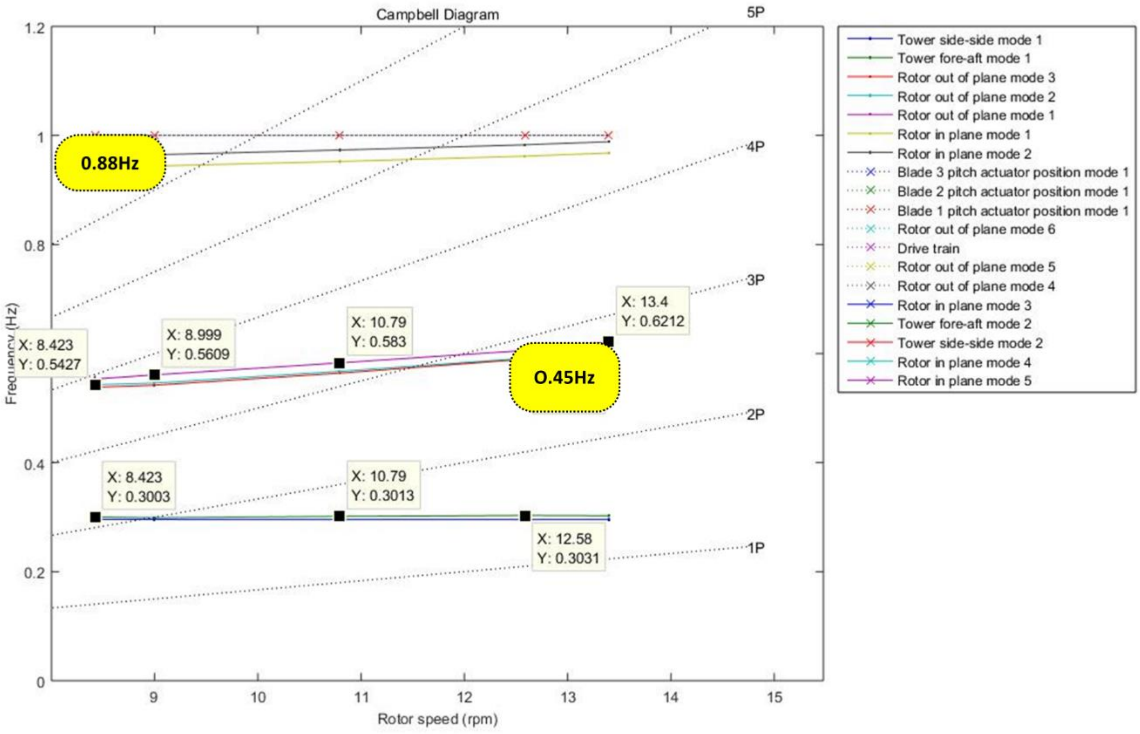

Figure 6: Campbell diagram for resonant frequencies

5 DISCUSSION AND CONCLUSION

Therefore, a comparison is made between the GBR condition parameters extracted from measurements and tested with the simulations (Table 1).

Table 1: SHM between GBR and Numerical simulation

Condition parameters	**GBR measurement (±5%)**	**Design / Simulation (±5%)**
Blade deflection	5.03 ±5% meters	Should not exceed 10.5 ±5% meters
Blade resonant frequencies (1P)	0.4489 Hz	0.45±5%Hz
Blade resonant frequencies (3P)	0.8728 HZ	0.88±5%Hz

The GBR resonant natural frequencies are identified at 0.45 ±5%Hz and 0.88±5%Hz are within the range of the Bladed® design frequency of the turbine of 0.45±5%Hz and 0.88±5%Hz. The measured GBR frequencies are rounded off to 2 significant figures

In conclusion, structural health monitoring (SHM) of typical and atypical unbalanced parameters in rotating in-field wind turbines enables assessing of vibrations and hence better structural understanding. The use of a GBR for SHM of wind turbines unbalanced parameters is a potential growing field with that enables a novel, fast, simplified and more precise understanding of rotating systems in hydropower stations and wind turbines.

The paper has presented a novel technique that can be applied to monitor the blades of wind turbines. The technique consists of monitoring the deflection of the rotor blades by estimating the unbalanced parameters (natural frequency and deflection) to provide an understanding of the structural integrity of the system. Furthermore, this technique is contactless and uses a ground-based radar (GBR) system that acquires the unbalanced parameters in under 5 minutes. The parameters can then be assessed to know if the system is at risk of fatigue damage by comparing with numerical simulations including Campbell diagrams.

SUGGESTION FOR FUTURE RESEARCH

The determination of blade deflection for rotating blades is still an area that the authors are working on, however, from results obtained so far, the GBR demonstrates a competency to determine the radial deflection and natural frequency of the blade and tower.

1. For modal analysis, further work is required to fine-tune the output-only modal analysis to stochastic processes of the type experienced by a rotating wind turbine in an atmospheric turbulence field and the simultaneous periodic deterministic excitation originating from mean wind shear and tower shadow.

2. An investigation into whether or not it is possible to extract supplemental information of value for modal damping characteristics [49] during wind turbine operation will also need consideration.

In conclusion, GBR can be applied for remote condition monitoring for on-shore wind turbines blades and mast. However, more experiential studies will need to be undertaken to determine the veracity of GBR applications for wind turbines in offshore situations where vertical subsidence of the sea surface plays a role.

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