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A Condition Monitoring Algorithm for Estimating Tower and Foundation Integrity

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Abstract

The analysis of tower and foundation integrity currently relies heavily on inspections (which may include destructive testing) or on the installation of additional sensors, such as strain gauges installed at the tower base. As the collection of SCADA data at high frequency (1Hz or above) becomes more popular, an attractive alternative becomes feasible – that of estimating the remaining fatigue life of the tower and foundation from proxies calculated remotely from available data. De-rating policies can then be employed for turbines that show lower than expected remaining life, whereas turbines with more than expected remaining life can be allowed to run beyond 20 years. The present work describes a method for estimating the remaining life of the tower and foundation, and how that can be used to inform wind farm operational policies using data that is readily available through SCADA.

Objectives

We develop a method for estimating the remaining fatigue life of a wind turbine tower, given only historical 10-minute wind data and 1Hz measurements of nacelle acceleration covering a limited representative period of time. The method allows owners and operators to adapt their operational strategy in order to maximise the value of a wind farm.

Fatigue Estimation Method

Nacelle inclination

Tower base bending moment is normally not measured on wind turbines due to the difficulty and cost of using strain gauges. In this work, we estimate the fatigue experienced by the tower base and foundation by exploiting the inclination signal calculated from the nacelle or tower-top accelerometers. Commonly these accelerometers are set up to measure fore-aft and side-side motion in the nacelle reference frame, respectively denoted $\ddot{x}$ and $\ddot{y}$. The inclination of the nacelle from vertical, θ, for low frequencies, is:

$$g \sin\theta = \sqrt{\ddot{x}^2 + \ddot{y}^2}$$

where g is acceleration due to gravity.

Cantilever model

We treat the turbine as a cantilever beam, fixed at the foundation, with a point force F due to mean rotor thrust, and an overturning moment M due to the vertical component of asymmetric loading. The asymmetry, mainly due to wind shear, varies over time with turbulence. In steady state, the tower base righting moment, Q, is:

$$Q = M + Fh$$

where h is the hub height. For small deflections, the nacelle inclination is:

$$\theta = \left(M + \frac{Fh}{2}\right)\frac{h}{EI} = (Q + M)\frac{h}{2EI}$$

where EI is a characteristic of the tower.

Provided the asymmetric loading is small compared to the tower base moment, nacelle inclination is approximately proportional to the moment, giving a simple, reliable estimate directly from SCADA data.

Simulation

A 3MW upwind turbine was simulated in Bladed over all DLC 1.2 fatigue cases. Each simulation is 600 seconds long and together they cover the entire power production envelope.

The fore-aft accelerometer signal was sampled at 1Hz then filtered to give an estimate of the tower base moment. Example results are given in Figure 2, shown with the true 1Hz base moment. Although the base moment signal is not estimated perfectly, the important characteristics are captured.

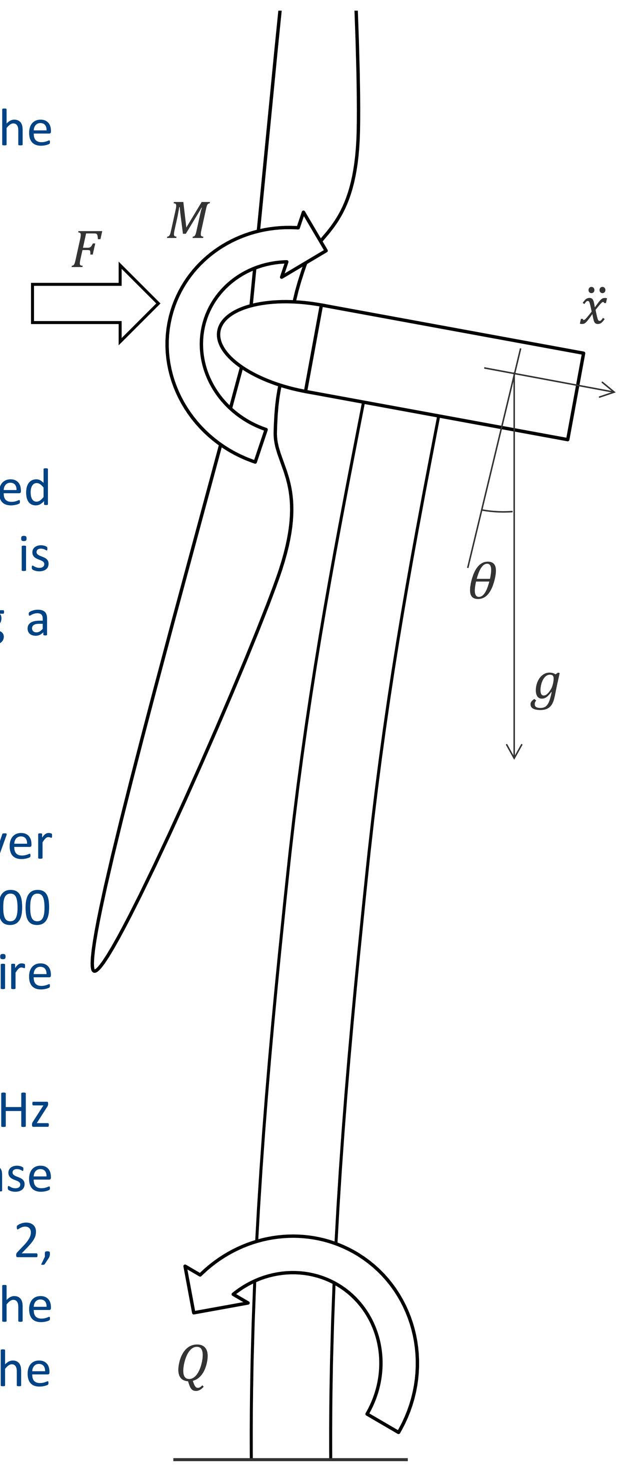

Figure 1: Wind turbine model showing forces and moments

Fatigue Estimation Results

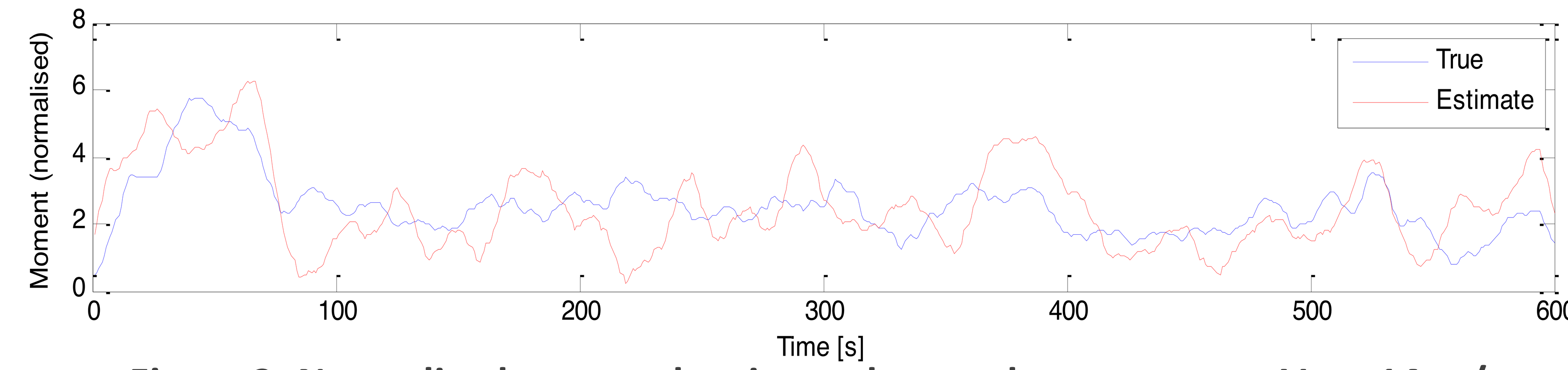

Figure 2: Normalised true and estimated tower base moment, V_{10} = 14 m/s

The estimated tower base moment is rainflow counted and fatigue is estimated for each 10-minute simulation assuming a material coefficient of 4. This is compared to the fatigue calculated from the base moment directly. The correlation of these results for 60 simulations over 10 different mean wind speeds is shown in Figure 3. Fatigue units are normalised and weighted by annual wind speed distribution.

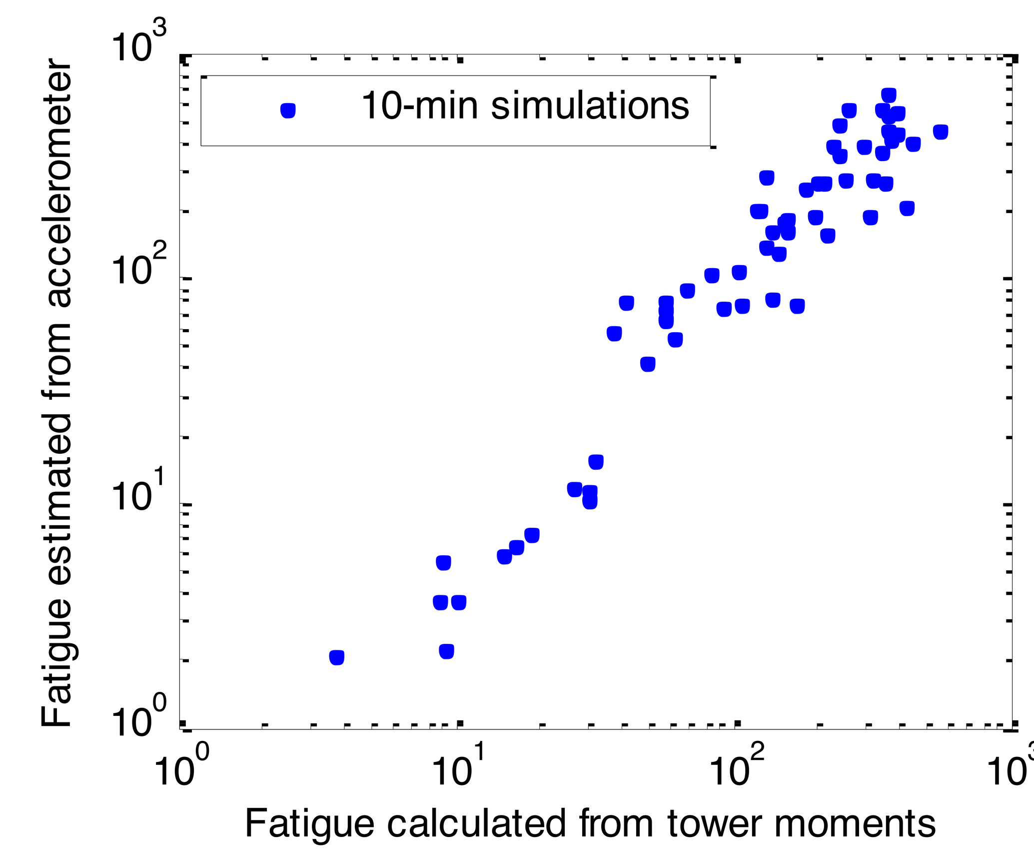

Figure 3: Performance of fatigue estimation method

Foundations

The tower base moment is resolved through the foundation, so the method given above can be adapted to estimate foundation loads. However, the nature of fatigue accumulation in foundation components is more complex than in steel towers, so foundation fatigue life estimates require more research. The authors have previously shown that 1Hz data can be used to assess foundation integrity using spectral methods.

Estimating Remaining Life

From the commissioning of the turbine at age a_0 the SCADA system records the average wind speed and turbulence intensity in 10-minute intervals, denoted V_{10} and I_{10}. A measurement campaign is conducted from turbine age a_1 to a_2 wherein additionally the 1Hz base moment and corresponding 10-minute fatigue are estimated. Figure 4 gives an illustration of the data such a campaign might yield. Fatigue is represented as damage equivalent load.

A data model of estimated tower fatigue against wind conditions is created. Historical wind conditions are put through the model to estimate the fatigue life from a_0 to a_1. Estimated future wind conditions are put through the map to predict fatigue accumulation from a_2 to end of life. Each turbine requires its own model, especially in complex terrain. Due to variation in wind direction, an extra dimension in the model is recommended to account for nacelle heading. Side-side tower motion is treated with a similar method.

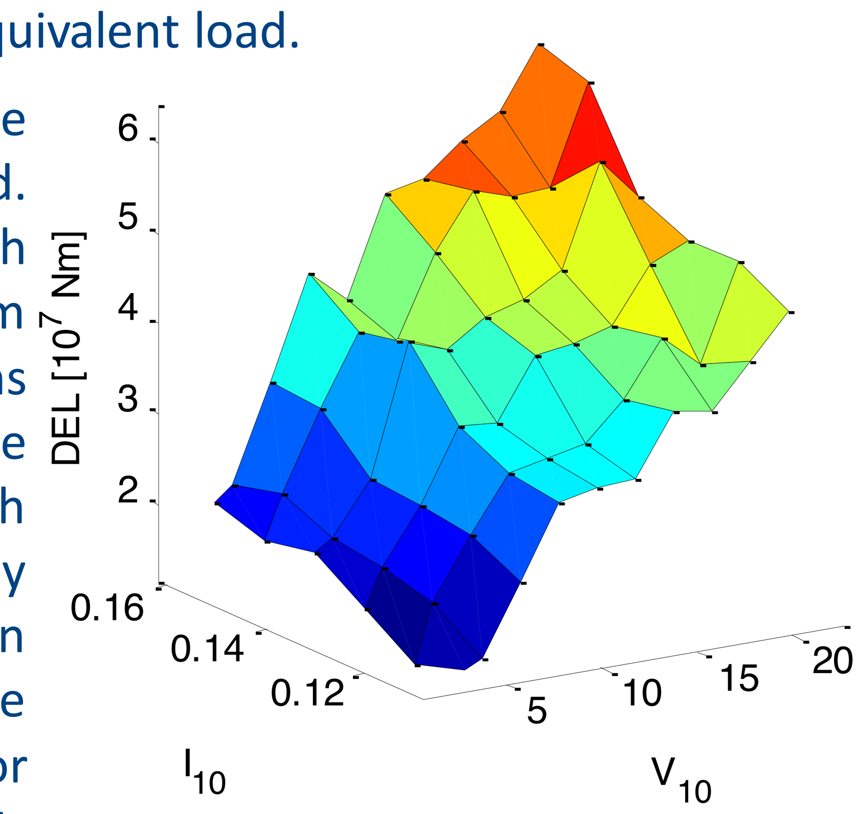

Figure 4: Illustrative map from wind conditions to tower fatigue

Conclusions

Based on a simple relationship between nacelle inclination and tower base moment, a load estimate can be generated using signals available in 1Hz SCADA data sets. The load estimate is rainflow counted for each 10-minute period to give a fatigue estimate; the relationship of this to the wind conditions is mapped. This is then extrapolated to estimate the turbine's remaining life. The method is well suited to integration into existing lifetime extension services. Commercial benefits of this knowledge to owner/operators are described in [1].

References

1. M.L. Wymore, J.E. Van Dam, H. Ceylan, D. Qiao, "A survey of health monitoring systems for wind turbines", *Renewable and Sustainable Energy Reviews 52* (2015), pp 976-990