0. Title

Anomaly detection of a horizontal wind turbine using an Extended Kalman Filter

1. Introduction

Loads that have a disproportionate impact on the components and structure of a wind turbine can be induced by anomalies in the wind-field. For example, large unbalanced rotor loads could arise from blades sweeping through low level jets. The work presented in this abstract proposes a novel anomaly detection scheme. It would aid in the early detection of anomalous conditions, such as mass imbalance, extreme wind shear and gust, in order to allow the wind turbine controllers to take appropriate diagnostic action to cope with such conditions.

2. Approach

An Extended Kalman Filter (EKF) is designed primarily based on a 3D effective wind speed model [1] and a nonlinear 3-bladed rotor model.

To enable the use of an EKF, any representation of the wind field needs to be in the form of a lumped parameter ordinary differential equation model. A 3D wind speed model, that meets this requirement, has been developed, see Figure 1. It outputs "effective wind speeds" for each blade and the rotor such that the rotor thrust, torque and the blade in-plane and out-of-plane blade root bending moments (BRBMs) are represented reasonably accurately for frequencies up to 1P, i.e., the auto and cross-spectral density functions for the forces and torques are reasonably accurate up to and including the 1P spectral peak due to rotational sampling [2]. To further improve detection of anomalies, this wind-field model could, if necessary, be extended up to 3P.

A nonlinear 3-bladed rotor model, suitable for use with the 3D wind speed model, employs standard aerodynamic coefficient models for rotor and in-plane and out-of plane BRBMs [1]. The coefficients are functions of wind speed that includes the effect of rotational sampling (passed on from the 3D wind speed model), tip-speed ratio and pitch angle. They are derived using DNV-GL Bladed. The 3-bladed rotor model also takes into account the gravitational loading on the blades.

The EKF is designed to track measurements of aerodynamic torque (at the hub) and in-plane and out-of-plane BRBM of each blade and thus to provide estimates of the states of the 3D wind and the gravitational loading on the blades. Monitoring of the state estimates subsequently allows detection of various anomalous wind conditions, e.g., extreme wind shear and gust, dynamic inflow, etc. along with structural anomalies, e.g., mass imbalance, aerodynamic imbalance, yaw misalignment, etc..

3. Main body of abstract

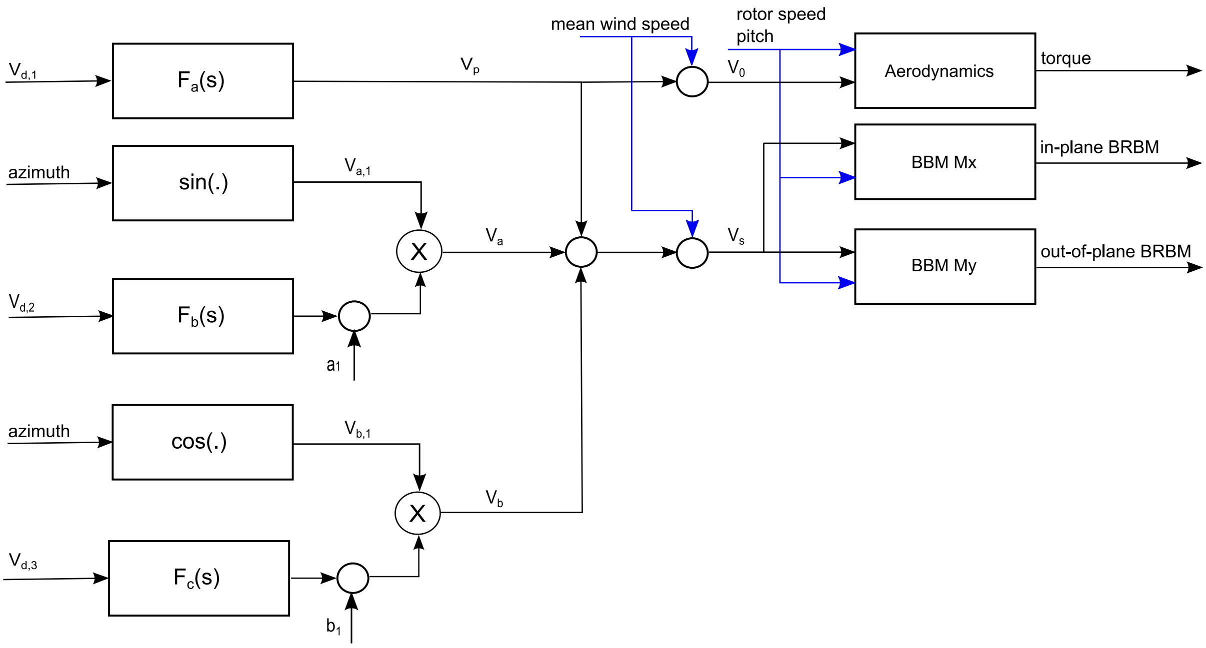

Figure 1: 3D wind speed model and the model of one of the three blades.

Anomaly monitoring can be classified into detection, diagnosis and isolation. The work presented here focuses on detection. An EKF is designed based on a 3D wind field model [1] and a nonlinear 3-bladed rotor model.

As the wind speed varies across the rotor, a blade element will experience different wind speeds as it rotates. The difference in wind speed across the rotor is caused by deterministic components, including wind shear, tower shadow and blade imbalance, and stochastic components, including turbulence. The 3D wind speed model separates the effects of deterministic and stochastic components on the blades as depicted in Figure 1, in which V_p, $V_{a,1}$ and $V_{b,1}$ represent stochastic components, a_1 and b_1 deterministic components, $V_{d,i}$ (for i=1,2,3) point wind speeds, F_a, F_b and F_c dynamic filters and V_s the aggregated wind speed, i.e., the effective wind speed experienced by the blade.

The aerodynamic torque and in-plane and out-of-plane BRBM models depicted in Figure 1 are nonlinearly related to wind speed, rotor speed and pitch angle through the torque and in-plane and out-of-plane BRBM. The effect of the gravitational loading on the blades is also incorporated into the model.

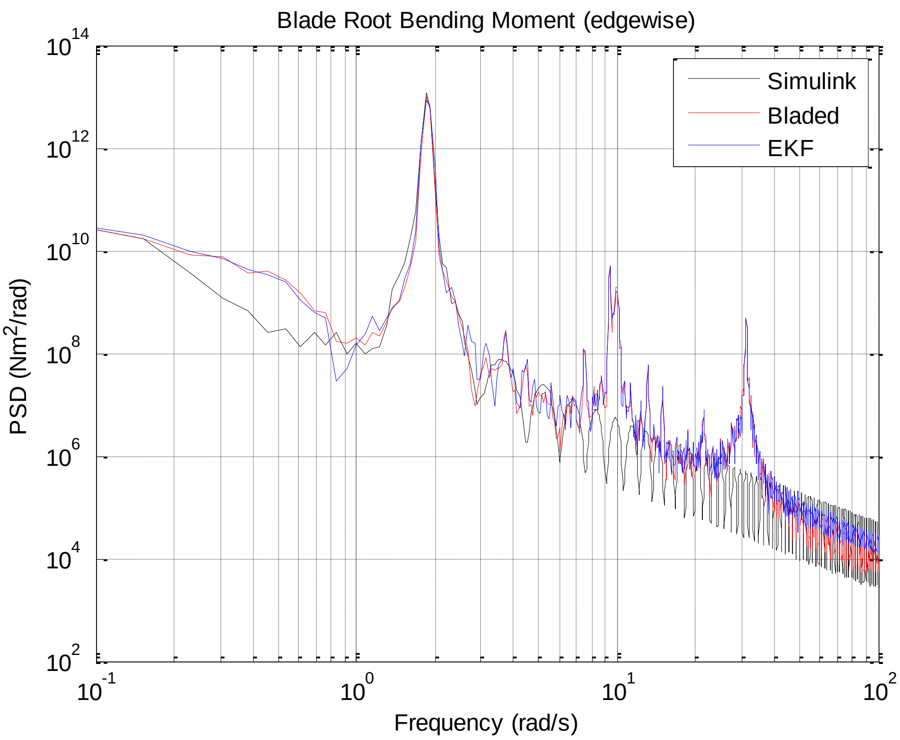

Figure 2: Power Spectra, estimation of RBM Mx by the EKF compared with Bladed and Simulink models.

The combined model is developed in Matlab/Simulink and validated against the high-fidelity aero-elastic Bladed model. For example, Figure 2 depicts power spectral density function for out-of-plane BRBM from the Matlab/Simulink model in comparison to that from the Bladed model. The power spectra demonstrate similar characteristics at lower frequencies, in particular both displaying 1P (the peak at 1.8 rad/s). The Matlab/Simulink model excludes high frequency components. Hence, the main difference is at high frequencies, at which blade flap dynamics is observed. This combined model is the model included in the EFK. To further improve detection of anomalies, this model could, if necessary, be extended up to 3P.

An Extended Kalman Filter (EKF) is an unknown input observer and, here, consists of 39 states, which include stochastic and deterministic wind components, gravitational terms, etc. The EFK tracks measurements of aerodynamic torque and in-plane and out-of-plane BRBM from the Bladed model (which is used to simulate the turbine), thereby estimating the states. An example of the EKF tracking measurements of in-plane BRBM is demonstrated in Figure 3. Realistically, the measurement is contaminated by noise; that is, the noisy measurement (green) as opposed to the original (red) signal is accepted by the EFK. Nonetheless, the estimate of the EKF (black) is almost noise-free as demonstrated in the figure. This is due to the computation of the measurement noise covariance online. Examples of the states, i.e., combined stochastic and deterministic wind components, $V_p(t)$, $V_{a1}(t)$ and $V_{b1}(t)$ (see Figure 1) are depicted in Figure 4 (left sub-figure). These wind components constitute the aggregated effective wind speed experienced by one of the blades as depicted in the figure (right sub-figure).

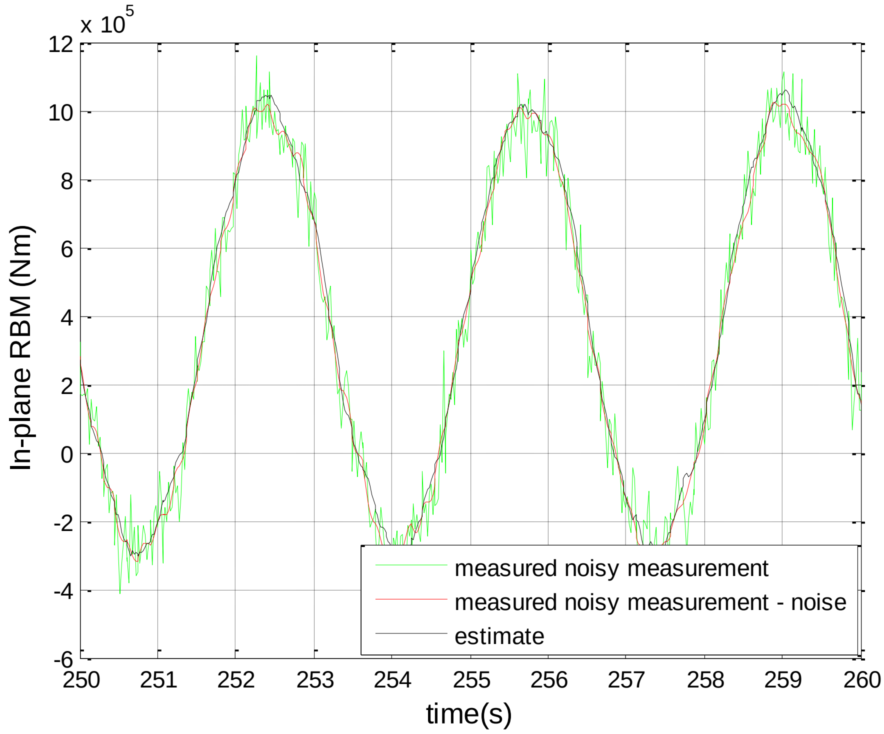

Figure 3: EKF tracking noisy measurements of in-plane BRBM.

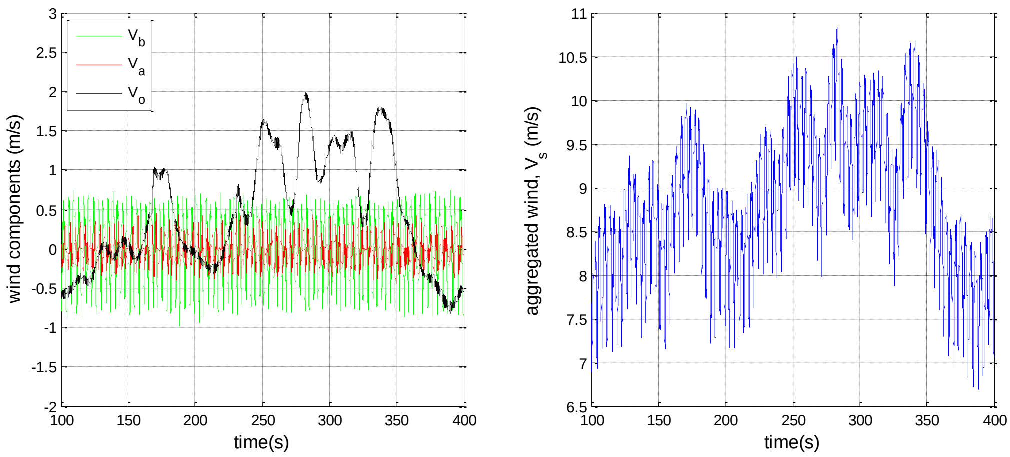

Figure 4: left: wind components, $V_o(t)$, $V_a(t)$ and $V_b(t)$; right: sum of the three components, i.e., $V_s(t)$.

The observed states subsequently enable detection of anomalies. For instance, the oscillation observed on out-of-plane BRBM is dominated by wind shear, while that observed on in-plane BRBM is dominated by the gravitational loading. Since gravity is at its maximum value at the blade horizontal position while wind shear causes the wind speed to be at its maximum value at the blade vertical position the phase difference, θ_d, between the in-plane and out-of-plane BRBM measurements, as depicted in Figure 5, should be roughly 90°. Otherwise, occurrence of an anomaly, potentially wind shear, wind veer, yaw misalignment, etc., could be suspected. The effect of wind shear on a_1 or b_1 is demonstrated in Figure 6. As the strength of wind shear increases from the left to right sub-figures, the magnitude of b_1 increases. Note that a_1 would be 0, such that $\theta_d = tan^{-1}(b_1/a_1)$ equals 90° (i.e., $a_1 \approx 0$), if there were no wind shear, wind veer, nacelle tilting, yaw misalignment, etc..

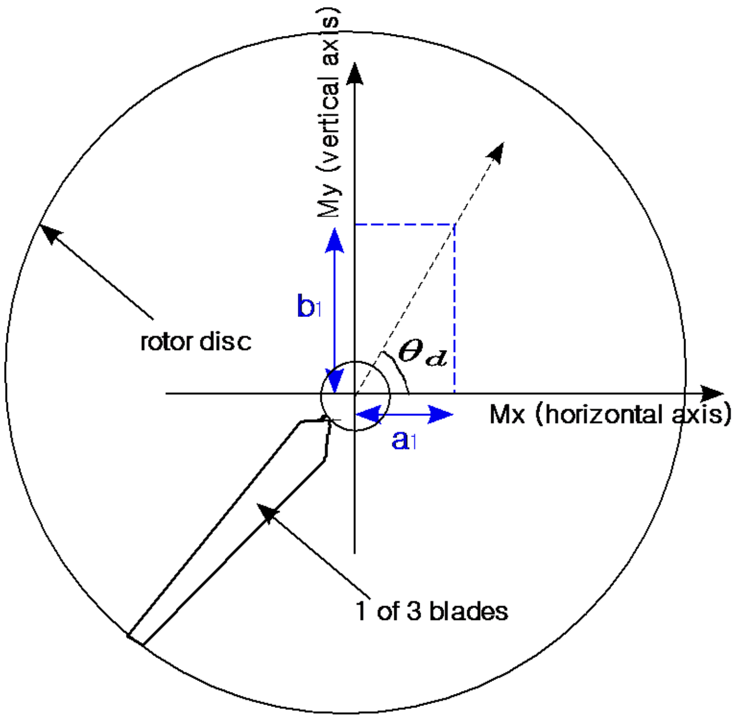

Figure 5: a_1 and b_1; variations in the horizontal and vertical axes.

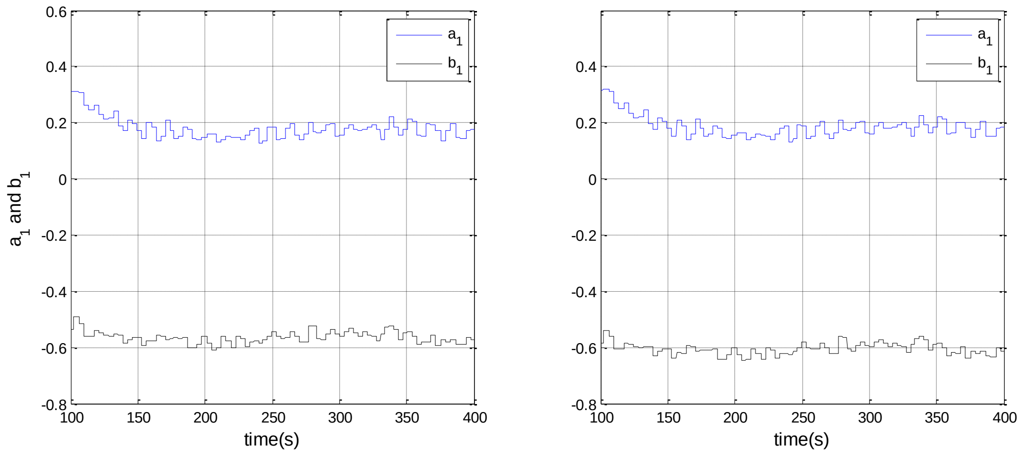

Figure 6: Wind shear detection using a_1 and b_1.

Moreover, as depicted in Figure 7, the EKF is also capable of detecting an increase in mass of blade 3 where it is increased from 65000 to 70000 kg. Post-processing following the detection of anomalies, i.e., diagnosis and isolation as mentioned above, is not discussed here.

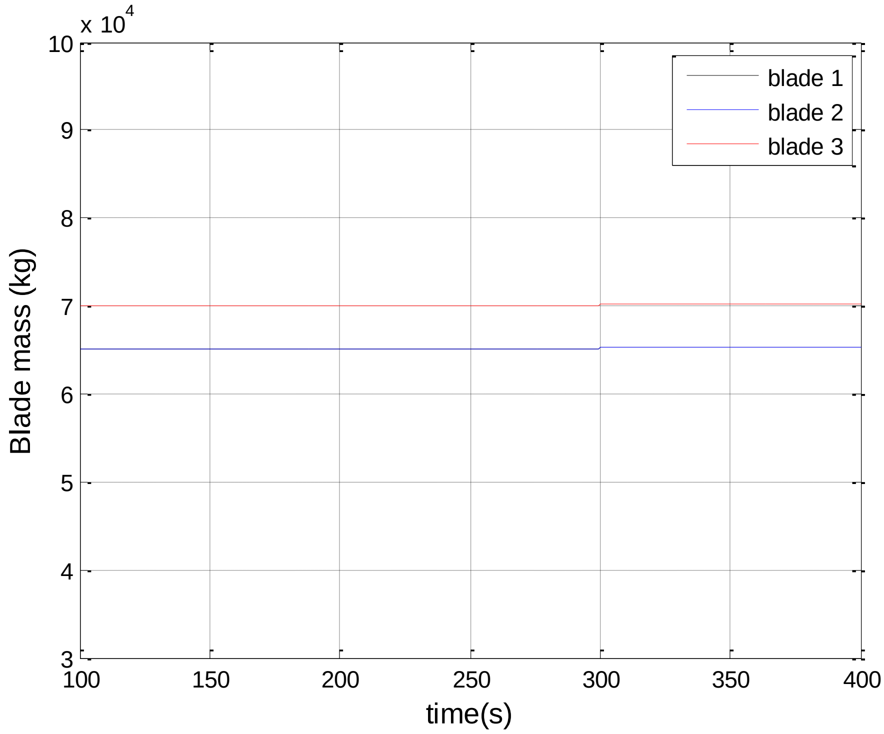

Figure 7: Mass imbalance.

4. Conclusions

An EKF is designed and implemented based on a 3D wind model, which creates a map of the wind field at the rotor disc using a lumped parameter model, and a 3-bladed rotor model. The wind field map enables deterministic and stochastic components to be estimated, and an EKF-based anomaly detector is then applied to this wind field map. The EKF accepts measurements, i.e. aerodynamic torque and in-plane and out-of-plane BRBM, from the Bladed model of a wind turbine. The simulation results demonstrate that the EKF closely tracks the measurements and that the estimated states could successfully be exploited for detecting various anomalies, i.e., wind shear, mass imbalance and potential yaw misalignment.

To date, the model used in the EKF is accurate up to 1P, but it will be extended up to 3P to improve detection of further anomalous scenarios, including gust and tower shadow. In future, control counteraction will also be applied, which may be based on some version of individual pitch control or on directly applied feedback loops.

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5. Learning objectives

Anomalies could have a severely adverse effect on the operation of a wind turbine. A novel anomaly detector, to allow the turbine controller to cope with various anomalous situations, is presented and its performance investigated in Matlab/Simulink, using data obtained from a high fidelity aero-elastic DNV-GL Bladed model, which simulates the wind turbine in this work.

6. References

[1] M. L. G. Santos, “Aerodynamic and wind field models for wind turbine control,” Ph.D. Thesis, University of Strathclyde, Glasgow, 2015.

[2] P. Brøndsted and R. Nijssen, “Advances in Wind Turbine Blade Design and Materials,” Elsevier, 2013.