Experimental validation of an observer for the deformation state of wind turbine structures based on inertial measurements

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EXTENDED ABSTRACT

1 Introduction

As classified by the certification e.g. from DNVGL [1], wind turbine structures are normally designed for a reference lifetime of 20 to 25 years based on the specific erection sites and conservative load assumptions. As a consequence, the actual fatigue loads tend to be lower than originally assumed leaving structural reserves for an economical extended operation of the wind turbines beyond the approved service life. With the aim to exploit these reserves safely, continuous recording of actual fatigue loads by means of an adequate monitoring system is needed. An intuitive approach is measuring strain directly at critical spots of the structures. However, locations with high strain concentration are often not accessible and suitable for strain gauge application, and strain measurements tend to require high metrological effort. Therefore, a concept of model-based estimation of fatigue loads is proposed that relies on inertial sensor measurements. The underlying process chain consists of three steps: (1) Estimation of the elastic deformation fields of the main wind turbine substructures such as tower and blade by a state observer exploiting inertial measurements with a minimal number of Inertial Measurement Units (IMUs); (2) Derivation of stresses at critical fatigue spots using finite element (FE) structural models; (3) Online fatigue calculation based on damage models [2]. This approach allows for an individual estimation of the deformation fields in tower and blade substructures. For rotor blades, the kinematic influence of the nonlinear rigid-body motion of the rotor on the measured quantities needs to be considered, whereas the ground-fixed tower structure can be regarded as a special case of a non-rotating blade. In this contribution, some experimental results from a small-scale structural test rig of a wind turbine structure are presented.

2 Kinematic measurement equations of the state observer for blade deformations

In order to take the dynamic effects of the nonlinear rigid body motion of the rotor into account, the substructure FE model of the blade is formulated in a Floating Frame of Reference (FFR) system to separate the overall blade motions into the elastic deformations and the rigid body motions [3, 4, 5]. The Nodal-Based Floating Frame of Reference (NFFR) method is specially used in this case to solve the volume integrals in dynamic equilibrium conditions [6]. Assuming small and linear-elastic displacements and rotations of the FE nodes with respect to the undeformed configuration of the blade and placing the reference coordinate system on one node of the FE model, the elastic displacements and rotations of the remaining FE nodes with respect to the reference frame can be described by the vectors $\boldsymbol{u}_{\mathrm{e}}^{i}$ and $\boldsymbol{\varphi}_{\mathrm{e}}^{i}$ with $i = 2, ..., n$, which can be written as a $6(n-1)$-vector $\boldsymbol{q}(t) = [\boldsymbol{u}_{\mathrm{e}}^{2}(t), ..., \boldsymbol{u}_{\mathrm{e}}^{n}(t), \boldsymbol{\varphi}_{\mathrm{e}}^{2}(t), ..., \boldsymbol{\varphi}_{\mathrm{e}}^{n}(t)]^{\mathrm{T}}$. They can also be approximated as a product of a $(6(n-1), n_s)$-reduction matrix $\boldsymbol{V}$ and $n_s \ll n$ elastic coordinates $\boldsymbol{s}(t)$, thus $\boldsymbol{q}(t) = \boldsymbol{V}\boldsymbol{s}(t)$. The strain field $\boldsymbol{\varepsilon}(\boldsymbol{r}, t)$ can then be reconstructed under the assumption of linear-elastic behavior using the relation between the n_s elastic coordinates and the strains at all the n nodes by means of a (n, n_s)-matrix of reduced strain modes $\boldsymbol{\Phi}_{V,\varepsilon}$ as $\boldsymbol{\varepsilon}(\boldsymbol{r}, t) = \boldsymbol{\Phi}_{V,\varepsilon}(\boldsymbol{r})\,\boldsymbol{s}(t)$ [7]. Considering relative kinematics between the IMUs, kinematic measurement equations for the elastic coordinates can be derived [8],

$$\boldsymbol{N}_r \boldsymbol{V} \ddot{\boldsymbol{s}} + \boldsymbol{N}_v \boldsymbol{V} \dot{\boldsymbol{s}} + \boldsymbol{N}_a \boldsymbol{V} \boldsymbol{s} = \boldsymbol{v} \tag{1}$$

with the matrices (notation: $\tilde{\boldsymbol{a}}\,\boldsymbol{b} = -\tilde{\boldsymbol{b}}\,\boldsymbol{a} \equiv \boldsymbol{a} \times \boldsymbol{b}$)

$$\boldsymbol{N}_r = \begin{bmatrix} \boldsymbol{S}_u^j \\ \boldsymbol{0} \end{bmatrix}, \quad \boldsymbol{N}_v = \begin{bmatrix} 2\,{}^{\mathrm{R}}\tilde{\boldsymbol{\omega}}_{\mathrm{R0}}\,\boldsymbol{S}_u^j \\ \boldsymbol{S}_\varphi^j \end{bmatrix}, \quad \boldsymbol{N}_a = \begin{bmatrix} \left({}^{\mathrm{R}}\tilde{\boldsymbol{\omega}}_{\mathrm{R0}}{}^{\mathrm{R}}\tilde{\boldsymbol{\omega}}_{\mathrm{R0}} + {}^{\mathrm{R}}\tilde{\boldsymbol{\alpha}}_{\mathrm{R0}}\right)\boldsymbol{S}_u^j + {}^{\mathrm{S}}\tilde{\boldsymbol{a}}_{\mathrm{S0}}\,\boldsymbol{S}_\varphi^j \\ {}^{\mathrm{S}}\tilde{\boldsymbol{\omega}}_{\mathrm{S0}}\,\boldsymbol{S}_\varphi^j \end{bmatrix} \tag{2}$$

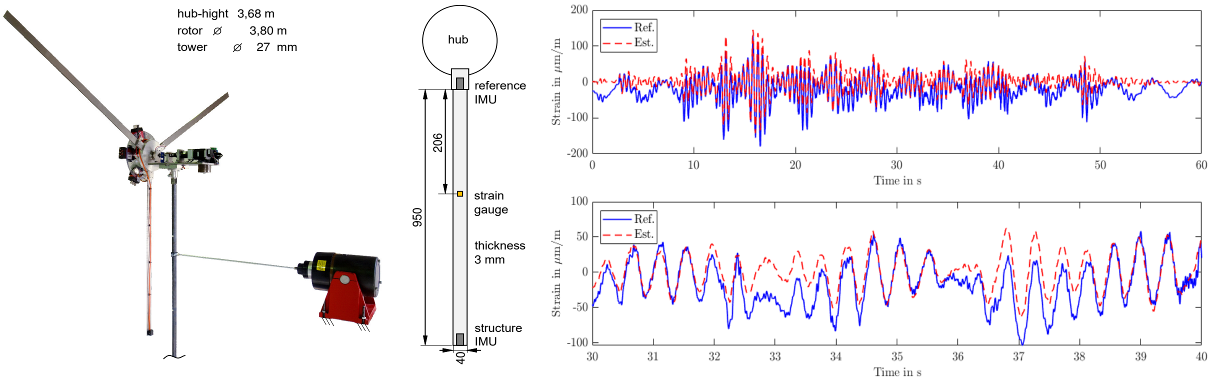
and the vector

$$\boldsymbol{v} = \begin{bmatrix} {}^{\mathrm{S}}\boldsymbol{a}_{\mathrm{S0}} - \left({}^{\mathrm{R}}\boldsymbol{a}_{\mathrm{R0}} + \left({}^{\mathrm{R}}\tilde{\boldsymbol{\omega}}_{\mathrm{R0}}{}^{\mathrm{R}}\tilde{\boldsymbol{\omega}}_{\mathrm{R0}} + {}^{\mathrm{R}}\tilde{\boldsymbol{\alpha}}_{\mathrm{R0}}\right){}^{\mathrm{R}}\boldsymbol{r}_{\bar{\mathrm{N}}\mathrm{R}}^{j}\right) \\ {}^{\mathrm{S}}\boldsymbol{\omega}_{\mathrm{S0}} - {}^{\mathrm{R}}\boldsymbol{\omega}_{\mathrm{R0}} \end{bmatrix}. \tag{3}$$

Here, $\boldsymbol{S}_u^j$ and $\boldsymbol{S}_\varphi^j$ are Boolean assignment matrices according to ${}^{\mathrm{R}}\boldsymbol{u}_{\mathrm{e}}^{j}(t) = \boldsymbol{S}_u^j\,\boldsymbol{q}(t)$, $\boldsymbol{\varphi}_{\mathrm{e}}^{j}(t) = \boldsymbol{S}_\varphi^j\,\boldsymbol{q}(t)$, while ${}^{\mathrm{R}}\boldsymbol{\omega}_{\mathrm{R0}}$, ${}^{\mathrm{S}}\boldsymbol{\omega}_{S0}$ and ${}^{\mathrm{R}}\boldsymbol{a}_{R0}$, ${}^{\mathrm{S}}\boldsymbol{a}_{S0}$ are the angular velocities and translational accelerations, respectively, measured by the IMUs. The superscripts S and R refer to the measurement coordinate systems of the structure and the reference IMUs, respectively. Under the assumption that the structural vibrations occur around a quasi-stationary configuration which changes very slowly in relation to the frequencies of the observed vibrations, the elastic coordinates $\boldsymbol{s}(t)$ are divided into a slowly varying, low-frequency (LF) component $\grave{\boldsymbol{s}}(t)$ and a high-frequency (HF) component $\acute{\boldsymbol{s}}(t)$: $\boldsymbol{s}(t) = \grave{\boldsymbol{s}}(t) + \acute{\boldsymbol{s}}(t)$. The observer model for reconstruction of the HF components of the elastic coordinates $\acute{\boldsymbol{s}}(t)$ is derived from the kinematic model (1) by calculating the matrices $\boldsymbol{N}_v$ and $\boldsymbol{N}_a$ as well as the vector $\boldsymbol{v}$ with the high-pass filtered components of the inertial measurements $\boldsymbol{N}_r V \ddot{\acute{\boldsymbol{s}}} + \acute{\boldsymbol{N}}_v V \dot{\acute{\boldsymbol{s}}} + \acute{\boldsymbol{N}}_a V \acute{\boldsymbol{s}} = \acute{\boldsymbol{v}} + \boldsymbol{w}_S$, with a mean-free normally distributed noise $\boldsymbol{w}_S$ approximates the system noise and uncertainties in the kinematic structure model. The system model is aided using the estimated values $\grave{\boldsymbol{s}}(t)$ by neglecting the terms with time derivatives of $\grave{\boldsymbol{s}}$ in (1), $\grave{\boldsymbol{N}}_a \boldsymbol{V} \grave{\boldsymbol{s}} = \grave{\boldsymbol{v}}$.

3 Experimental results

The functionality of the state observer has been experimentally validated using a structural test rig on laboratory scale as shown in Figure 1 (a), which was originally designed to test methods for vibration analyses in the low frequency range of a wind turbine [9]. As the test rig is not designed to operate under wind load, the tower and the blades are not aerodynamically shaped but represented by geometrically simple flexible beam structures. The rotor is driven by a stepper motor with up to 25 rpm to take the rotation into account. Results of deformation estimation for a load case are shown in Figure 1 (b). The first two out-of-plane eigenmodes of the blade are selected to build up the matrix $\boldsymbol{V}$. In this load case a stochastic excitation was applied by the shaker on the test rig with a rotor speed of 15 rpm. The excitation started at $t = 2\,\mathrm{s}$. The comparison between the time series of the estimated strain signal (red/dashed) and the reference strain signal (blue/solid) directly measured by the strain gauges shows a relative good strain estimation.



(a) (b)

Figure 1: (a) Laboratory structural test rig. (b) Experimental results of stochastic excitation, rotor speed 15 rpm

Acknowledgment This research is part of the DynAWind^2 project funded by the German Federal Ministry for Economic Affairs and Climate Action under grant number 0325228E/F/G.

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