FEM MODELING AND STRUCTURAL STATE ESTIMATOR DESIGN FOR A 10 MW OFFSHORE WIND TURBINE

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INTRODUCTION

Wind power has great potential to lessen our dependence on traditional resources like oil, gas and coal, with less negative impact on the environment. As a path to fight the climate changes the European Union is targeting that within 2020, 20 % of all energy consumption should come from renewable energy sources, where 12-14 % should come from wind energy [1] . The path to make offshore wind energy commercially competitive is long, with many challenges ahead to reach this goal. Wind turbines at offshore locations are subjected to varying environmental loads from the wind and waves making them vulnerable to fatigue damage. Locating wind turbines offshore makes them less accessible for maintenance and supervision. Reliable design and control systems are necessary to make them capable of operating with a minimum downtime over its life time. State of the art within wind turbine control design is with focus on maximum power output. This work suggests a structural state estimator which can be used as an input for designing a control system which in addition to control for maximum power output also minimize the structural impact on the turbine, with possibilities to reduce fatigue damage, and operational costs. The model is based on the DTU10-MW reference turbine fitted on a monopile structure. To test the estimator performance, the turbine will be exposed to realistic time varying wind and wave loading.

Figure 1: Sheringham Shoal Offshore Wind Park, Foto: Harald Pettersen/Statoil

STATE AND FORCE ESTIMATOR DESIGN

The state and force estimation is a dual problem, i.e. we want to estimate the states of the system, which are displacements, velocities, and estimate the environmental forces acting on the turbine. The proposed estimator was first designed by [2] and adapted for the FE turbine model. The estimator design is based on acceleration measurements at the turbine top and turbine foot. Since the forces acting on the turbine have to be considered unknown, an estimate of $\hat{\tau}_k$ is obtained. Using the force estimate, a state estimate $\hat{x}_{k|k}$ can be derived. The estimator design is consisting of a three step recursive filter, with similarities to the well known Kalman filter. The state estimator is described on discrete form, where the state transition matrix and input matrix given in (5) are discretized with ZOH-method and given by $\mathbf{\Phi}$ and $\mathbf{\Gamma}$.

The filter is initialized by the known initial state estimate and covariance matrix,

$$\hat{x}_0 = \mathbb{E}[x_0], \tag{7}$$
$$\mathbf{P}_0^x = \mathbb{E}[(\hat{x}_0 - x_0)(\hat{x}_0 - x_0)^T]. \tag{8}$$

The three step recursive filter are given by:

Input estimation:

$$\tilde{\mathbf{R}}_k = \mathbf{C}\mathbf{P}_{k|k-1}\mathbf{C}^T + \mathbf{R}, \tag{9}$$
$$\mathbf{M}_k = \left(\mathbf{J}^T\tilde{\mathbf{R}}_k\mathbf{J}\right)^{-1}\mathbf{J}^T\tilde{\mathbf{R}}_k^{-1}, \tag{10}$$
$$\hat{\tau}_k = \mathbf{M}_k\left(y_k - \mathbf{C}\hat{x}_{k|k-1}\right), \tag{11}$$
$$\mathbf{P}_k^\tau = \left(\mathbf{J}^T\tilde{\mathbf{R}}_k^{-1}\mathbf{J}\right)^{-1} \tag{12}$$
$$\tag{13}$$

Measurement update:

$$\mathbf{L}_k = \mathbf{P}_{k|k-1}^x\mathbf{C}^T\tilde{\mathbf{R}}_k^{-1} \tag{14}$$
$$\hat{x}_{k|k} = \hat{x}_{k|k-1} + \mathbf{L}_k\left(y_k - \mathbf{C}\hat{x}_{k|k-1} - \mathbf{J}\hat{\tau}_k\right) \tag{15}$$
$$\mathbf{P}_{k|k}^x = \mathbf{P}_{k|k-1}^x - \mathbf{L}_k\left(\tilde{\mathbf{R}}_k - \mathbf{J}\mathbf{P}_k^\tau\mathbf{J}^T\right)\mathbf{L}_k^T \tag{16}$$
$$\mathbf{P}_k^{x\tau} = \left(\mathbf{P}_k^{\tau x}\right)^T = -\mathbf{L}_k\mathbf{J}\mathbf{P}_k^\tau \tag{17}$$
$$\tag{18}$$

Time update:

$$\hat{x}_{k+1|k} = \mathbf{\Phi}\hat{x}_{k|k} + \mathbf{\Gamma}\hat{\tau}_k \tag{19}$$
$$\mathbf{P}_{k+1|k}^x = \begin{bmatrix}\mathbf{\Phi} & \mathbf{\Gamma}\end{bmatrix}\begin{bmatrix}\mathbf{P}_{k|k}^x & \mathbf{P}_k^{x\tau} \\ \mathbf{P}_k^{\tau x} & \mathbf{P}_k^\tau\end{bmatrix}\begin{bmatrix}\mathbf{\Phi}^T \\ \mathbf{\Gamma}^T\end{bmatrix} \tag{20}$$

METHOD

The proposed method is based on designing a low fidelity FEM model of the turbine structure which can be used as a state observer and input for a wind turbine control system. The control system can then based on structural state input perform take action to reduce structural response and decreasing fatigue damage. A structure like a large offshore wind turbine is mostly excited by its first and second $mode$ which means it is possible to reduce the model to modal form, which in turn reduces the computational time. The state estimator is based on a recursive three step filter where a force estimate based on measured accelerations is obtained. Using the force estimate, it is possible to deduct an estimate of the full system.

MATHEMATICAL MODEL

The underlying structural model is based on a FEM discretization using Euler Bernoulli beam elements with varying structural properties. Using the Hermitian cubic shape functions for interpolating the elemental behavior we can derive the necessary stiffness and inertia matrices for the elements. The shape functions are given in the vector $\mathbf{N}^e = \begin{bmatrix} N_{v1} & N_{\theta 1} & N_{v2} & N_{\theta 2}\end{bmatrix}$.The elemental stiffness matrix is derived based on the minimum potential energy theorem, where the resulting expression for the stiffness matrix can be written as

$$\mathbf{K}^e = \int_{l^e} EI\mathbf{B}^{eT}\mathbf{B}^e dx = \int_{-1}^{1} EI\mathbf{B}^{eT}\mathbf{B}^e\frac{1}{2}l^e d\xi, \tag{1}$$

where $\mathbf{B}^e$ is the double derivative wrt. x of $\mathbf{N}^e$. Due to the heavy compressive force from the turbine nacelle a geometric stiffness matrix is included to account for the reduced stiffness.

This can be given as

$$\mathbf{K}_\sigma^e = -Mg\int_0^{l^e}\left(\frac{d\mathbf{N}^e}{dx}\right)^T\frac{d\mathbf{N}^e}{dx}\frac{l^e}{2}dx, \tag{2}$$

where M is the total weight of the nacelle top, and g the gravitational acceleration. To implement the soil-structure interaction in the monopile section, a Winkler model, consisting of non-linear spring elements is connected to the element nodes located in soil level. The spring stiffness functions are obtained by using the pressure displacement $(P-y)$ method with numerical data for soil properties for a typical offshore wind turbine site. The elemental inertia matrix $\mathbf{M}^e$ is obtained by considering a kinetic energy perspective in transversal direction on a element. The resulting elemental inertia matrix is given as,

$$\mathbf{M}^e = A\int_0^{l^e}\rho(\mathbf{N}^e)^T\mathbf{N}^e\frac{1}{2}l^e d\xi, \tag{3}$$

where A is the cross sectional element area, and ρ is the elemental mass density. Included damping effects consists of structural damping and aerodynamic damping. The structural damping is implemented using *Rayleigh damping*, given as

$$\mathbf{D_d} = \alpha\mathbf{M} + \beta\mathbf{K} \tag{4}$$

where α and β are selected based on the systems natural frequencies and damping damping ratio ξ. The aerodynamic damping is taking into account when modeling the wind thrust force. For simulation and estimator purposes the $n-dimensional$ 2^{nd} order system can be represented on first order state space form given as

$$\begin{aligned}\dot{\mathbf{x}} &= \mathbf{A}\mathbf{x} + \mathbf{G}\tau(t) \\ \mathbf{y} &= \mathbf{C}\mathbf{x} + \mathbf{J}\tau(t) + v(t)\end{aligned} \tag{5}$$

Where the matrices are given by

$$\mathbf{A} = \begin{bmatrix}\mathbf{0}_{n\times n} & \mathbf{I}_{n\times n} \\ -\mathbf{M}^{-1}\mathbf{K} & -\mathbf{M}^{-1}\mathbf{D_d}\end{bmatrix} \quad \mathbf{G} = \begin{bmatrix}\mathbf{0}_{n\times q} \\ -\mathbf{M}^{-1}\mathbf{b}\end{bmatrix} \tag{6}$$

τ are the environmental disturbance forces, $v(t)$ is white measurement noise. $\mathbf{C}$ and $\mathbf{J}$ are the output and feedthorugh matrices, respectively.

RESULTS AND SIMULATIONS

Simulations of the model being subjected to various time varying disturbances from wind, waves and tower-blade interaction show that the estimator model is able to estimate the unknown forces and the state of the system in a good manner. Figure 2 and 3 show simulations of the turbine structure subjected to a turbulent wind field with mean wind speed of 14 [m/s] and a irregular sea state. The wind turbulence is realized using the Kaimal Spectrum with turbulence intensity 0.2, and the sea state is simulated from the JONSWAP spectrum with $H_{m0} = 1$[m] and $T_p = 5$ [s].

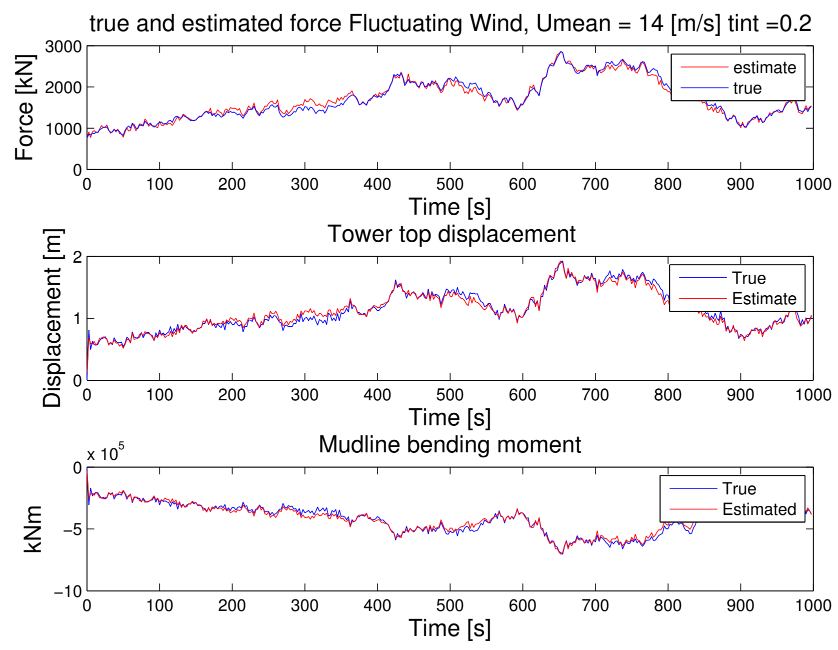

Figure 2: True and estimated forces, tower top displacement and mudline bending moment

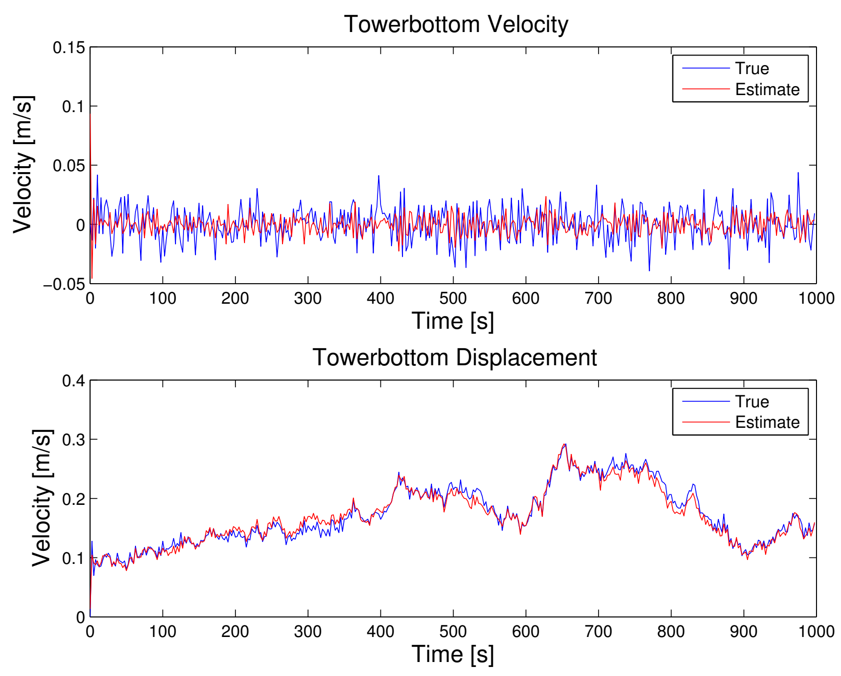

Figure 3: True and estimated tower foot transversal velocity and displacement

Figure 2 show that the state estimate is able to follow the true evolution of the system's tower top displacement. Due to the good estimation of state evolution, the estimator is also able to estimate the mudline bending moment with good precision. The wind thrust force evolution is also estimated with relatively good precision. Figure 3 show the evolution of the tower foot velocity and displacement. As the figure show, the state estimate of the displacement is showing promising results. The estimate of the tower foot velocity is performing satisfactory, it is however not able to follow the true state as good as with displacement estimates. This is believed to be due to the larger fluctuations in velocity with time, which makes it difficult for the estimate to follow the evolution with good precision. Overall the simulations show promising results in estimating both force and structural response.

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