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A substructure approach for fatigue assessment on wind turbine support structures using output-only measurements

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Abstract

Fatigue constitutes a major and highly-uncertain safety-related factor for wind turbines. In order to ensure a reliable fatigue assessment of such structures, it is essential that stress predictions be based on the actual structural behaviour. The response identification of operational wind turbines in a global framework constitutes a challenging problem due to the uncertainties associated with the variability of the wind loading and the dynamics of the rotor. In reducing these uncertainties, this study proposes a substructuring approach, which abolishes the need for modelling the intricate and time-varying dynamics of the rotor. Instead, response prediction is performed on a substructure model of the tower and the effect of wind loads and servo dynamics is accounted for via the estimated interface forces at the top of the support structure. The application is based on synthetic vibration data generated via the FAST software and an output-only Bayesian filter employing the structural model of the support structure. The effectiveness of the proposed approach is presented in terms of fatigue damage estimates at different locations on the tower.

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Keywords: Wind turbine; Dynamic substructuring; Input-state estimation; Response identification; Fatigue damage;

1. Introduction

Response prediction on the basis of output-only measurements has received significant attention in recent years, with emphasis on methodologies for online applications. A number of algorithms [1–3] has been proposed to date for the simultaneous estimation of the unknown inputs and states of linear systems. These estimates may be exploited for numerous objectives, such as damage identification, structural control and fatigue assessment among others. From this perspective, Papadimitriou et al. [4] implemented a vibration-based methodology to address the fatigue estimation problem while in a more recent work, Dertimanis et al. [5] proposed an input-state-parameter estimation framework for output-only predictions of fatigue damage.

As far as wind turbine support structures are concerned, the utilization of model-based response identification methods in a global framework becomes a challenging and computationally prohibitive task. This is due to the inherently stochastic nature of wind turbines, which originates from a number of uncertain environmental, operational and structural factors that are mainly related to the aerodynamics. In overcoming this hurdle, this contribution proposes a substructure approach, which circumvents the modelling of intricate and time-varying dynamics.

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Instead, the wind turbine is decomposed into two subsystems, namely the support structure and the rotor-nacelle assembly along with the blades. The response identification of the tower can be then viewed as an input-state estimation problem with the interface forces acting as the unknown excitation. The joint input-state estimator of Gillijns and De Moor [1] is exploited to this end relying artificial measurements obtained from a limited number of acceleration and inclination measurements. The performance of the approach is presented through the compatibility and equilibrium conditions at the interface and the accuracy of fatigue estimates at different tower locations.

2. Substructural formulation

Consider a linear Finite Element (FE) model defined on a domain \( \Omega \) and its continuous-time second-order differential equations describing the dynamic response

\[
M \ddot{u}(t) + C \dot{u}(t) + K u(t) = f(t)
\]

with initial conditions \( u(0) = u_0 \) and \( \dot{u}(0) = \dot{u}_0 \), where \( u(t) \in \mathbb{R}^n \) is the displacement vector, \( M, C, K \in \mathbb{R}^{n \times n} \) are the mass, damping and stiffness matrices and \( f(t) \in \mathbb{R}^m \) is the excitation vector.

Let us further consider that the finite element domain \( \Omega \) described by Eq. (1) is divided into a number of non-overlapping subdomains \( \Omega^{(s)} \), for \( s = 1, 2, \ldots, N_s \), so that each node of the FE model belongs to exactly one substructure except for those on the interfaces. Upon omitting the explicit time-dependency, the dynamic response of each substructure in the domain \( \Omega^{(s)} \) is determined by the local equations

\[
M^{(s)} \ddot{u}^{(s)} + C^{(s)} \dot{u}^{(s)} + K^{(s)} u^{(s)} = f^{(s)} + \mathbf{g}^{(s)}, \quad s = 1, \ldots, N_s
\]

which can be partitioned as

\[
\begin{bmatrix}
M^{(s)}_{ii} & M^{(s)}_{ib} \\
M^{(s)}_{bi} & M^{(s)}_{bb}
\end{bmatrix}
\begin{bmatrix}
\dot{u}^{(s)}_i \\
\dot{u}^{(s)}_b
\end{bmatrix} +
\begin{bmatrix}
C^{(s)}_{ii} & C^{(s)}_{ib} \\
C^{(s)}_{bi} & C^{(s)}_{bb}
\end{bmatrix}
\begin{bmatrix}
\ddot{u}^{(s)}_i \\
\ddot{u}^{(s)}_b
\end{bmatrix} +
\begin{bmatrix}
K^{(s)}_{ii} & K^{(s)}_{ib} \\
K^{(s)}_{bi} & K^{(s)}_{bb}
\end{bmatrix}
\begin{bmatrix}
u^{(s)}_i \\
u^{(s)}_b
\end{bmatrix} =
\begin{bmatrix}
f^{(s)}_i \\
\mathbf{g}^{(s)}_b
\end{bmatrix}
\]

where the superscript\(^{(s)}\) denotes the quantities referring to the subdomain \( \Omega^{(s)} \), \( \mathbf{g}^{(s)} \in \mathbb{R}^{n^{(s)}} \) indicates the vector of internal forces at the interfaces, \( n^{(s)} \) is the number of degrees of freedom of the \( s \)-th substructure and the subscripts \( i \) and \( b \) refer to the internal \( u^{(s)}_i \in \mathbb{R}^{n^{(i)}} \) and boundary \( u^{(s)}_b \in \mathbb{R}^{n^{(b)}} \) degrees of freedom, respectively. Assuming now that a substructure is not externally excited or the external forces \( f^{(s)} \) are negligible, its dynamics are exclusively driven by the interface forces and the governing equations of motion can be written as

\[
M^{(s)} \ddot{u}^{(s)} + C^{(s)} \dot{u}^{(s)} + K^{(s)} u^{(s)} = S^{(s)}_g \mathbf{g}^{(s)}_b
\]

where \( S^{(s)}_g \in \mathbb{R}^{n^{(s)} \times n^{(b)}} \) is the input selection matrix.

In order to ensure equivalence between the two formulations, the assembled system of substructures described by Eq. (2) should additionally satisfy the compatibility and equilibrium conditions. According to the former, any pair of connected degrees of freedom at the interface should have identical displacement while the latter requires that interface forces on connected degrees of freedom sum to zero. These can be written in compact form as

\[
\begin{align}
\mathbf{B} \ddot{\mathbf{u}} &= \mathbf{0} \\
\mathbf{L}^T \hat{\mathbf{g}} &= \mathbf{0}
\end{align}
\]

where \( \hat{\mathbf{u}} = \text{vec}\left(\begin{bmatrix} u^{(1)} & u^{(2)} & \ldots & u^{(N_s)} \end{bmatrix}\right) \) and \( \hat{\mathbf{g}} = \text{vec}\left(\begin{bmatrix} g^{(1)} & g^{(2)} & \ldots & g^{(N_s)} \end{bmatrix}\right) \), with \( \text{vec}(\bullet) \) indicating the operator that stacks the columns of a matrix on top of each other in a single column, and the operators \( \mathbf{B} \) and \( \mathbf{L} \) are Boolean matrices, with the one representing the null space of the other, associating the interface degrees of freedom of the substructures.

3. Input-state estimation

By introducing the state vector \( \mathbf{x} = \text{vec}\left(\begin{bmatrix} u^{(1)} & \dot{u}^{(1)} \end{bmatrix}\right) \in \mathbb{R}^{2n^{(s)}} \), the governing equations of motion of a substructure, given by Eq. (4) and subjected to the compatibility and equilibrium constraints expressed by Eqs. (5), can be
transformed into a state-space representation

\[
\begin{align*}
\dot{x} &= A_p x + B_p p \\
y &= G_p x + J_p p
\end{align*}
\]

where for simplicity, \( p \) indicates the interface forces. The matrices of the state equation, i.e. Eq. (6a), are given by

\[
A_p = \begin{bmatrix} 0 & I \\ -\left( M^{(s)} \right)^{-1} K^{(s)} & -\left( M^{(s)} \right)^{-1} C^{(s)} \end{bmatrix}, \quad B_p = \begin{bmatrix} 0 \\ \left( M^{(s)} \right)^{-1} S_g^{(s)} \end{bmatrix}
\]

and the output influence and direct transmission matrices are defined as

\[
G_p = \begin{bmatrix} S_y^{(s)} d & 0 \\ 0 & S_y^{(s)} v \\ S_y^{(s)} (M^{(s)})^{-1} K^{(s)} & S_y^{(s)} (M^{(s)})^{-1} C^{(s)} \end{bmatrix}, \quad J_p = \begin{bmatrix} 0 \\ 0 \\ S_y^{(s)} (M^{(s)})^{-1} S_g^{(s)} \end{bmatrix}
\]

where \( S_y^{(s)} d, S_y^{(s)} v \in \mathbb{R}^n \) and \( S_y^{(s)} a \in \mathbb{R}^n \) are the selection matrices for displacement, velocity and acceleration respectively.

By temporal discretization of the state-space model of Eqs. (6) with a sampling rate of \( 1/\Delta t \), and upon supplementing it with the random variables \( w_k \) and \( v_k \), representing the modelling and measurement errors respectively, the discrete-time stochastic state-space model is obtained as

\[
\begin{align*}
x_{k+1} &= A x_k + B p_k + w_k \\
y_k &= G x_k + J p_k + v_k
\end{align*}
\]

where both \( w_k \in \mathbb{R}^{2n} \) and \( v_k \in \mathbb{R}^n \) are zero-mean Gaussian processes with known covariance matrices \( Q = \mathbb{E}[w_k w_k^T] \) and \( R = \mathbb{E}[v_k v_k^T] \). The discrete-time system matrices are accordingly given by: \( A = e^{A \Delta t} \), \( B = [A - I] A_c^{-1} B_c \), \( G = G_c \) and \( J = J_c \).

In the absence of prior knowledge with respect to the driving forces, the aim is to estimate the input \( p_k \) and the state \( x_k \) of the substructure, relying on the model of Eq. (9a) and the noisy measurements \( y_k \) of Eq. (9b). To this end, the unbiased minimum-variance input state estimator [1] is employed, which needs to be initialized with an estimate of the state \( x_0 = \mathbb{E}[x_0] \) and its error covariance matrix \( P_0^x = \mathbb{E}[(x_0 - \hat{x}_0)(x_0 - \hat{x}_0)^T] \). Subsequently, the input and state estimation is performed in three steps:

**Input prediction**

\[
\begin{align*}
\hat{R}_k &= G P_k^x G^T + R \\
M_k &= (J^T \hat{R}_k^{-1} J)^T \hat{R}_k^{-1} \\
\hat{p}_k &= M_k (y_k - G \hat{x}_k) \\
P_k^p &= (J^T \hat{R}_k^{-1} J)^{-1}
\end{align*}
\]

**Measurement update**

\[
\begin{align*}
L_k &= P_k^x G^T \hat{R}_k^{-1} \\
\hat{x}_k &= \hat{x}_k^+ + L_k (y_k - G \hat{x}_k^+ - J \hat{p}_k) \\
P_k^x &= P_k^x + L_k \left( \hat{R}_k - JP_k^p J^T \right) L_k^T \\
P_k^{sp} &= (P_k^{sp})^T = -L_k J P_k^p
\end{align*}
\]

**Time update**

\[
\begin{align*}
\hat{x}_{k+1} &= A \hat{x}_k + B \hat{p}_k \\
P_k^{x+1} &= \begin{bmatrix} A & B \end{bmatrix} \begin{bmatrix} P_k^x & P_k^{sp} \\ P_k^{px} & P_k^p \end{bmatrix} \begin{bmatrix} A^T \\ B^T \end{bmatrix} + Q
\end{align*}
\]
4. Fatigue damage

For the evaluation of fatigue damage in steel structures, the linear accumulation rule, also known as Palmgren-Miner rule [6,7], is commonly used. According to this law, damage at a structural point is defined as the ratio of the number of operational cycles to the number of failure cycles at a given stress level. For varying stress-level conditions, this is expressed by

\[ D = \sum_{j=1}^{k} D_j = \sum_{j=1}^{k} \frac{n(\Delta \sigma_j)}{N_j(\Delta \sigma_j)} \]  

(13)

where \( n(\Delta \sigma_j) \) is the number of cycles at the stress level \( \Delta \sigma_j \), \( N_j(\Delta \sigma_j) \) is the number of cycles to failure at the same stress level and \( k \) is the number of stress levels contained in the examined time history. Provided that stress time histories are available through measurements or, as in this study, inferred through the state estimates, the cycles \( n \) at stress amplitude \( \Delta \sigma_j \) may be obtained through counting algorithms, with rainflow counting method constituting the common practice. The number of cycles \( N_j \) to failure is provided by the experimentally obtained \( S - N \) curve model \( N_j \Delta \sigma^m = A \) where \( A \) is a fatigue strength constant and \( m \) denotes the slope of the curve, with both being material-dependent parameters. Combining now Palmgren-Miner rule and the \( S - N \) curve model [8], the damage accumulation can be related to the number of stress cycles by the expression

\[ D = \sum_{j=1}^{k} C(\Delta \sigma_j)^m n(\Delta \sigma_j) \]  

(14)

where \( C \) denotes the reciprocal of the fatigue strength constant.

5. Application

In what follows, the effectiveness of the proposed framework is illustrated through an application to the NREL 5.0 MW land-based wind turbine (Fig. 1) under operational conditions. For a detailed description of the structural properties, the reader is referred to Jonkman et al. [9]. The examined wind turbine is modelled using the FAST v8 software platform and a set of 20 aero-servo-elastic simulations, each with a duration of 600s, is performed for the generation of synthetic vibration data. The mean wind speed of each simulation is sampled from a Weibull distribution with mean equal to 10 m/s and the corresponding turbulence is derived from a conditional, on the sampled mean wind speed, lognormal distribution.

The large degree of uncertainty that characterizes the evolution of the dynamic behaviour of an operating wind turbine, constitutes a limiting factor for the response identification in a global framework. In reducing this uncertainty, which is mainly associated with the aerodynamic loads and a number of factors related to the rotor and the mechanical components at the level of the nacelle, the identification process is implemented in a substructural approach which

![Diagram](image-url)

Fig. 1. Overview of the sensor locations, the substructural model and the estimated interface forces
does not require the modelling of intricate and time-varying dynamics. To this end, the structural model of the tower is integrated in the formulation presented in Section 2 and the effect of the dynamics occurring above the tower is taken into account through the estimated interface quantities. Moreover, taking into account that the wind loads acting on the tower, i.e. drag forces, only bear a minor contribution to the global dynamics of a wind turbine, it can be reasonably assumed that the tower vibration is driven by the interface forces at the level of the nacelle.

In order for the proposed methodology to be implementable within a long-term monitoring strategy, that can be extended to the life-cycle of the structure, the employed monitoring devices should be sufficiently durable while providing highly accurate sensory information. Apart from accelerometers, which are widely used for permanent monitoring, this study proposes the supplementary use of inclinometers for the measurement of angle of rotation. In consideration of the invertibility and stability conditions [10], the number of sensors to be deployed is dictated by the number of identified forces. Therefore, two acceleration and two tilt measurements in each direction of the tower are used, with the sensor configuration depicted in Figs. 1(a) and 1(b). The response time histories at these sensor locations, obtained from FAST, are corrupted with 3% white Gaussian noise and combined with the substructural model, illustrated in Fig. 1(c), for jointly estimating the interface forces and the response of the tower. The latter is used to retrieve the stress response at critical locations and subsequently estimate the accumulated fatigue damage.

The assessment of the proposed approach is performed in terms of the compatibility and equilibrium conditions at the interface of the tower with the nacelle, as well as through the accuracy of the estimated fatigue damage. Figure 2 illustrates the time histories of the estimated kinematic quantities at the interface along with the real values. Accordingly, the estimated interface forces are presented and compared with the true time histories in Fig. 3. Although the dynamics of the turbine are not included in the identification process, a high degree of accuracy is achieved for the response estimates. This can be further verified through the damage estimates, presented in Fig. 4 and Table 1, at
different locations on the tower, illustrated in Fig. 1(c), where it is seen that the predicted values show high agreement with the real ones, corresponding to a mean error of less than 2%.

Table 1. Percentage difference between actual and estimated fatigue damage

<table>
<thead>
<tr>
<th>Cross section</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elevation h [m]</td>
<td>5</td>
<td>10</td>
<td>15</td>
<td>20</td>
<td>25</td>
<td>30</td>
<td>35</td>
<td>40</td>
</tr>
<tr>
<td>Error [%]</td>
<td>2.15</td>
<td>1.98</td>
<td>2.09</td>
<td>2.02</td>
<td>1.87</td>
<td>1.94</td>
<td>1.81</td>
<td>1.91</td>
</tr>
</tbody>
</table>

6. Conclusions

A substructuring scheme for response identification of wind turbine support structures has been proposed in this study. The approach was based on the assumption that the dynamics of the support structure are driven by the interface forces at the tower top, which can account for the complex and highly-varying aero and servo dynamics when properly estimated. It was shown that the dynamic response at unmeasured locations of wind turbine support structures may be accurately estimated, based on a limited number of acceleration and tilt measurements. The effectiveness of the estimates is assessed in terms of fatigue damage accumulation at critical locations on the tower which is also identified with a high degree of accuracy.

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