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Modal-based damage localization on wind turbine blades under environmental variability

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Abstract

With wind power establishing itself as a widely effective form of renewable energy source, a diverse range of maintenance schemes is being investigated towards life-time extension of existing wind farms. Among the numerous structural and mechanical parts of a Wind Turbine (WT), blades are the most critical and costly components. Exposed to a number of degradation mechanisms, such as cracks and fatigue, they may be well rendered structurally ineffective and unsafe. Detecting and localizing thus the existence of damage on WT blades is a crucial and essential task for planning optimal maintenance and assuring operational reliability of WTs.

One of the main challenges for deploying Structural Health Monitoring (SHM) methodologies on in-service WT blades lies in the operational and environmental variability. It is widely reported that fluctuations in ambient temperature exert a strong impact on the vibration features of WTs, insinuating the damage induced structural changes may often be masked by changes due to temperature influences. With WTs operating in highly-varying climate conditions, it becomes thus imperative that temperature effects be properly taken into account within the context of damage detection and localisation.

In this contribution, the most common vibration-based criteria for damage localization are examined and compared through a numerical application on a small-scale WT blade. The study is built around a 3-dimensional finite element model of the blade, which comprises an exterior laminate composite surface, modelled with shell elements, and interior foam represented by solid elements. The efficacy of localization is evaluated under varying environmental conditions and a critical assessment on the accessibility of sensing information and the severity of damage is presented.

1. Introduction

With wind energy constituting a well established and mature renewable energy source, Wind Turbine (WT) structures experience a prominently rapid growth in size with the aim of maximizing energy production and reducing the levelized cost of energy. Such a tendency has unavoidably given rise to higher economic risks which subsequently call for stricter and more sophisticated management and maintenance strategies. Within this context, Structural Health Monitoring (SHM) emerges as a promising field, able to provide a more systematic operational management of WTs and assure structural integrity. With blades constituting the most important and expensive
component of a WT system, the presence of a damage detection and localization strategy for such components becomes thus paramount.

Among the various vibration-based SHM methods, a common class of approaches for damage detection and localization comprises features derived from basic modal properties [1]. A number of studies has been carried out already in that respect, although modal properties are reported to be noticeably sensitive to environmental effects [2, 3]. Indicatively, Pandey et al. [4] demonstrated in an early stage the usefulness of mode shape curvatures for detection and localization of damage through a simple numerical application. A critical assessment of modal curvature as a means for damage localization is conducted by Dessi and Camerlengo [5], which essentially constitutes a comparative study of several criteria associated with mode shape curvature. In a recent contribution, Shokrani et al. [6] proposed a novel approach for localizing damage under varying environmental conditions using modal curvature of systems featuring linear or weakly nonlinear behavior.

In the same context, modal flexibility and modal strain energy have been also utilized in a number of contributions for damage localization. The latter has not only been studied from a numerical point of view in beam-like [7] and plate-like [8] structures but also from an experimental perspective where Worden et al. [9] validated the efficacy of strain energy on a real stiffened panel. On the other hand, modal flexibility has been also used as effective damage indicator [10] which has been tested by Reynders and De Roeck [11] on numerical and experimental case studies for both localization and quantification.

In this contribution, mode shape curvature, modal strain energy and modal flexibility are examined for damage localization on WT blades under varying environmental conditions, as the most common modal-based features. The study is based on the Finite Element (FE) model of a small-scale blade which is subjected to a series of damage scenarios and a wide range of temperature conditions. The effectiveness of each approach is evaluated in terms of the number of available measurement points, the required vibration modes and the sensitivity to environmental variability.

2. Damage localization criteria

To this end, the present study examines the effectiveness of mode shape curvature, modal strain energy and flexibility matrix in localizing damage on structures exhibiting bending behaviour, such as WT blades.

2.1 Mode shape curvature

Mode shape curvature is often utilized as an alternative modal feature with significantly higher sensitivity to local damage in comparison to mode shapes. Obtained through the spatial derivation of mode shapes, curvatures have the property of magnifying the sign of discontinuities introduced in the mode shapes due to local damage. For a beam-like structure, such as WT blades, the mode shape curvature for each mode \( j \) in \( y \) and \( z \), or flapwise and edgewise directions respectively, can be approximated from the second order central difference approximation according to
\[ \psi_{jy}(k) = \frac{\Phi_{jy}(k + 1) - 2\Phi_{jy}(k) + \Phi_{jy}(k - 1)}{\Delta x^2} \]

\[ \psi_{jx}(k) = \frac{\Phi_{jx}(k + 1) - 2\Phi_{jx}(k) + \Phi_{jx}(k - 1)}{\Delta x^2} \]

where \( \Delta x \) indicates the longitudinal distance of equally spaced measurement points. For
the curvature at the ends of the structure, backward and forward operators are
employed. Finally, what can serve as indication of damage in a particular location is the
absolute value of change in mode shape curvature.

### 2.2 Modal strain energy

The second feature to be examined is modal strain energy which, as designated by
the name, refers to the strain energy stored in a system subjected to the deformation of a
certain mode shape pattern. This criterion is based on the principle that the distribution
of strain energy stored in the system will be prominently changed in the damaged areas,
due to reduction in the capacity of energy absorption. The latter insinuates that damage
is accompanied by a stiffness reduction, which constitutes a valid assumption for the
vast majority of structural cases. Closely related to the mode shape curvature, the modal
strain energy of a three-dimensional beam-like structure, such as WT blades, deformed
in \( y \), i.e. flapwise, direction is derived from the stored strain energy

\[ S_y = \frac{1}{2} \int_0^L EI_y \left( \frac{\partial^2 \psi}{\partial x^2} \right)^2 dx \]

where \( x \) is the coordinate along the length \( L \) of the structure, while \( EI_y \) and \( \psi \) denote the
flexural rigidity and transverse displacements in \( y \) direction, respectively.

The expression of strain energy, as well as the derivations below, may be equally
established for deformation in \( z \), i.e. edgewise, direction however for the sake of brevity
they are only shown for vibration modes in \( y \) direction. The part of strain energy
associated with a mode shape \( \varphi_j \) is expressed by

\[ S_{y,j} = \frac{1}{2} \int_0^L EI_y \left( \frac{\partial^2 \varphi_j}{\partial x^2} \right)^2 dx \]

Assuming now that the system may be divided into a number of longitudinal regions \( N \),
the modal strain energy stored in a region \( k \) and associated with the \( j \)th mode shape is
given by

\[ S_{y,jk} = \frac{1}{2} \int_{L_{k+1}}^{L} \left( EI_y \right)_k \left( \frac{\partial^2 \varphi_j}{\partial x^2} \right)^2 dx \]

which may be used to define the fractional energy
\[ F_{jk} = \frac{S_{x,jk}}{S_{y,j}}, \quad \text{with} \quad \sum_{k=1}^{N_k} F_{jk} = 1 \]

Likewise, the above expressions can be written for a damaged state of the system as soon as the corresponding flexural rigidity and mode shapes are available. Under the assumption that damage is mainly located in a single area and flexural rigidity is constant over the length of the system in both damaged and undamaged conditions, one can obtain an estimate of the change in flexural rigidity within a region \( k \) as

\[
\frac{f_{jk,d}}{f_{jk,h}} = \frac{\int_0^{L_k} \left( \frac{\partial^2 \varphi_{j,d}}{\partial x^2} \right)^2 \, dx}{\int_0^{L_k} \left( \frac{\partial^2 \varphi_{j,h}}{\partial x^2} \right)^2 \, dx}
\]

where subscripts \( h \) and \( d \) denote the healthy and damaged states respectively. The above ratio is expressed in terms of a single vibration mode and therefore, in order to include all measured modes, the damage index for region \( k \) may be obtained through the summation over all available modes, according to

\[
d_k = \frac{\sum_{j=1}^{m} f_{jk,d}}{\sum_{j=1}^{m} f_{jk,h}}
\]

Subsequently, it can be assumed, as introduced by Farrar and Worden [1], that damage indices \( d_k \) of all regions \( k \) are normally distributed, and an evidence of damage location can be obtained from the normalized index

\[
D_k = \frac{d_k - \bar{d}_k}{\sigma_k}
\]

where \( \bar{d}_k \) and \( \sigma_k \) designate the mean and standard deviation of the all damage indices \( d_k \) along the length of the structure.

2.3 Modal flexibility

Once modal parameters are available, the flexibility matrix of a system may be approximated by

\[
\mathbf{F} \approx \mathbf{\Phi} \mathbf{\Omega}^{-1} \mathbf{\Phi}^T \approx \sum_{j=1}^{m} \frac{1}{\omega_j^3} \mathbf{\Phi}_j \mathbf{\Phi}_j^T
\]

where \( \mathbf{\Phi} \in \mathbb{R}^{mxm} \) are the mass normalized mode shapes and \( \mathbf{\Omega} \in \mathbb{R}^{mxm} \) is a diagonal matrix containing the square of natural frequencies \( \omega_j \) for \( j = 1, 2, \ldots, m \). The important step in obtaining an accurate representation of the flexibility matrix consists in identifying a sufficient number \( m \) of vibration modes. Subsequently, the flexibility matrix of the system in two different states “a” and “b” can be used to define a damage index from their difference as follows

\[
\Delta \mathbf{F} = \mathbf{F}_a - \mathbf{F}_b
\]
where $\Delta F_{ij} \in \mathbb{R}^{s \times s}$ denotes the change in flexibility matrix. Such a metric does not only provide an indication of damage, but it also entails information associated with the extent and the location thereof. To determine the latter, the maximum change of the entries of flexibility matrix in $j$th column can be calculated

$$\max \Delta F_j = \max |\Delta f_{ij}|, \ i = 1, 2, \ldots, m$$

where $\Delta f_{ij}$ denotes the entries of matrix $\Delta F$. Finally, the column of the flexibility matrix characterized by the biggest change indicates the sought for vicinity of damage.

### 3. Case Study

The present study is based on the blade of a Windspot 3.5 kW WT model [12], which is manufactured by Sonkyo Energy and illustrated in Figure 1. The 1.75m long blade with a total mass of approximately 5.0kg is constructed as a three-layered sandwich component and modelled using the FE method. The outer surface of the structure is made of a 0.93 mm thick double-layered composite material, which consists of (i) a plain-weave fabric and (ii) a chopped strand mat (CSM) of E-glass fibres. The two layers are stitched together with a sew thread to form the product coded as WR500M300, also referred to as combi mat, which is numerically represented by shell elements. The inner part of the blade is composed of a low-stiffness core of polyurethane (PU) foam which is modelled with solid elements.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Location</th>
<th>Reduction</th>
<th>Case</th>
<th>Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>0.3L</td>
<td>20%</td>
<td>I_a</td>
<td>From -15°C to +40°C</td>
</tr>
<tr>
<td></td>
<td></td>
<td>50%</td>
<td>I_b</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>70%</td>
<td>I_c</td>
<td></td>
</tr>
<tr>
<td>II</td>
<td>0.7L</td>
<td>20%</td>
<td>II_a</td>
<td>From -15°C to +40°C</td>
</tr>
<tr>
<td></td>
<td></td>
<td>50%</td>
<td>II_b</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>70%</td>
<td>II_c</td>
<td></td>
</tr>
</tbody>
</table>

To examine the performance of the mode-based criteria for damage localization, the blade is numerically subjected to a series of damage scenarios under varying environmental, i.e. temperature, conditions. These range from -15 to +40°C using a step of 5°C with the aim of tracking the effect of temperature-dependent material properties in both low [13] and high [14] regimes. The considered damage scenarios are focused on cracks with varying degree of severity whose location is determined on the basis of existing experimental [15] and simulation-based [16] contributions pertaining to damage on WT blades and positions where defects are most likely to emerge [17]. In this sense, two distinct locations at 0.3L and 0.7L distance from the blade root, where $L$ indicates the length of the blade, were selected, as shown in Figure 1. Both cracks initiate from the trailing edge and extend to a distance of 5cm in the transverse direction while the effect of each of them was tested for the cases of 20%, 50% and 70% stiffness reduction over the entire temperature interval.
4. Results

The effectiveness of the above-mentioned modal criteria for damage localisation is assessed below under varying temperature conditions in terms of damage level and information availability. The former is materialized through the regulation of stiffness reduction at the cracked area, as reported in Table 1, while the latter is investigated by assuming different levels of modal information to be accessible. In this sense, the vibration modes of the blade are initially assumed to be known at a dense grid, which comprises four fibers running along the longitudinal direction, as shown in Figure 1. Subsequently, the grid is rarefied up to the extend where only a few measurement points along each fiber are available, with the aim of illustrating the operational limits of the said criteria. The effect of temperature variability is indicatively presented through the natural frequencies of the first four vibration modes which are reported in Table 2. The frequencies show a noticeable variation within the considered temperature range and as expected, environmental changes are more influential on high-order modes.

Table 2. The first two flapwise and edgewise natural frequencies.

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>1st Flapwise</th>
<th>1st Edgewise</th>
<th>2nd Flapwise</th>
<th>2nd Edgewise</th>
</tr>
</thead>
<tbody>
<tr>
<td>-15</td>
<td>14.34</td>
<td>38.46</td>
<td>67.77</td>
<td>159.26</td>
</tr>
<tr>
<td>-10</td>
<td>14.24</td>
<td>38.21</td>
<td>67.31</td>
<td>158.22</td>
</tr>
<tr>
<td>-5</td>
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<td>37.95</td>
<td>66.85</td>
<td>157.18</td>
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</tr>
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<td>65.92</td>
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</tr>
<tr>
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</tr>
<tr>
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<td>36.91</td>
<td>64.99</td>
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</tr>
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<td>36.64</td>
<td>64.52</td>
<td>151.91</td>
</tr>
<tr>
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<td>30</td>
<td>13.44</td>
<td>36.11</td>
<td>63.56</td>
<td>149.75</td>
</tr>
<tr>
<td>35</td>
<td>13.34</td>
<td>35.83</td>
<td>63.08</td>
<td>148.66</td>
</tr>
<tr>
<td>40</td>
<td>13.23</td>
<td>35.56</td>
<td>62.59</td>
<td>147.55</td>
</tr>
</tbody>
</table>
4.1 Mode shape curvature

Under the assumption that the vibration modes of the blade are initially identified over the entire grid of measurement points, as illustrated in Figure 1, the curvature of the first vibration mode for model Ia is calculated on the basis of Eq. (1). The result is depicted in Figure 2 where it is shown that the damaged area can be accurately determined from all four fibers. It should be further noticed that although the indicator is calculated using as baseline the model at 25 °C, crack location is still identifiable over the entire temperature interval.

Figure 2. Normalized absolute difference in the mode shape curvature obtained from the first flapwise vibration mode of case Ia. The model at 25 °C is used as the baseline and information from the entire measurement grid is employed.

Figure 3. Normalized absolute difference in the mode shape curvature obtained from the first flapwise vibration mode of case Ia. The model at 25 °C is used as the baseline and information from seven equally spaced measurement points along the fibers is employed.
Although it is prominent that damage localization on the basis of mode shape curvatures may be reliable and accurate only when a dense grid of measurement points is available, it should be remarked that curvatures present a significant advantage against modal strain energy and modal flexibility. This consists in the fact that the efficacy is not strongly dependent on the number of identified modes. Instead, the position can be identified from a single vibration mode, as soon as damage leaves a prominent signature thereto. This is clearly demonstrated in Figure 2, where crack position is identified on the basis of the first flapwise mode alone, but also in Figures 3 and 4 where additionally, only seven measurement points are taken into account. In practice, only the first few eigenmodes of an operating WT blade can be identified and therefore such a feature proves to be rather advantageous. Moreover, it is seen through Figure 4 that the choice of reference configuration plays a rather important role since it can render damage unidentifiable under certain environmental conditions.

Figure 4. Normalized absolute difference in the mode shape curvature obtained from the first flapwise vibration mode of case 1. The model at 5 °C is used as the baseline and information from seven equally spaced measurement points along the fibers is employed.

4.2 Modal strain energy

Likewise, the results using modal strain energy are firstly documented for a fully measured grid and thereafter for a reduced set of 7 sensors along each fiber. Figure 5 shows the damage indicator, as derived in Section 2.2, from changes in modal strain energy when all 10 vibration modes are utilized. In contrast with the mode shape curvature which was proven to perform sufficiently well over the entire temperature range, modal strain energy is shown to successfully predict the damage vicinity only for temperatures close to the reference configuration, which is chosen to be the one at 15 °C. A similar performance is observed when only 7 measurement points on each fiber are utilized, as shown in Figure 7. It should be noticed that apart from the interpolation required when a limited number of sensory information is available, modal strain energy imposes the additional assumption of constant rigidity over the length of the structure for both undamaged and damaged condition, which is essentially violated.
Figure 5. The damage index from changes in modal strain energy using the first ten mode shapes for case I. The model at 15 °C is used as the baseline and information from the entire measurement grid is employed.

Figure 6. The damage index from changes in modal strain energy using the first ten mode shapes for case I. The model at 15 °C is used as the baseline and information from seven equally spaced measurement points along the fibers is employed.

4.2 Modal flexibility

The last criterion to be assessed is modal flexibility which is calculated on the basis of natural frequencies and modes shapes alone. As previously, the vibration modes are in first place assumed to be identified over the entire measurement grid, which consists of all degrees of freedom along the four fibers. Figure 7 demonstrates the maximum of
absolute change in flexibility due to damage scenario $I_c$, where the undamaged model at 15 °C is utilized as the reference configuration. Again, it is seen that the crack location is well detected for temperatures close to the baseline, while it is hardly distinguishable at temperature values greater than 15 °C.

Figure 7. Absolute difference of flexibility change due to scenario $I_a$ when the first ten vibration modes are considered. The model at 15 °C is used as the baseline and information from the entire measurement grid is employed.

Figure 8. Absolute difference of flexibility change due to scenario $I_a$ when the first ten vibration modes are considered. The model at 15 °C is used as the baseline and information from seven equally spaced measurement points along each fiber is employed.
Similarly, Figure 8 depicts the maximum of absolute change in flexibility when a considerably sparser grid of 7 sensors along each fiber is employed. The same event is observed also in this case, where the location of damage is well determined for temperatures close to the reference one, i.e. 15 °C, while it becomes unnoticeable towards the two extremities. Moreover, it should be underlined that due to spatial incompleteness, the exact location of crack cannot be precisely pointed out however, the indicator is only capable of identifying the vicinity to sensor locations.

5. Conclusions

A critical assessment of the most common modal-based features for damage localization was presented. The study was based on a three-dimensional finite element model of a small scale wind turbine which was numerically subjected to the most likely to occur, according to existing reports, damage scenarios under varying environmental, i.e. temperature, conditions. The performance of each indicator was evaluated in terms of the available sensor information, the underlying assumptions and the ability to localize damage over the considered temperature range.

All three criteria prove to successfully pinpoint damage when the system is redundantly monitored. However, as broadly reported already, such features are shown to strongly underperform when sparsely instrumented. Such a behaviour is typically treated by curve-fitting so as to infer the intermediate missing information, which inevitably smooths out the sought for local changes and subsequently renders damage unidentifiable. The number of identified modes plays also a significant role in the performance of these indicators, and in particular for strain energy and flexibility; on the contrary, curvatures are seen to perform noticeably better in that respect. The number of contributing modes in the response of a system is exclusively dependent on the properties thereof and the nature of excitation, but in practice only a few vibration modes are identifiable which constitutes a significant limitation in the applicability of such criteria. Finally, it is shown that the choice of reference configuration constitutes an additional sensitive point of modal-based criteria. Although for curvatures this baseline can be properly chosen to render damage localizable, this is not the case for strain energy and flexibility which prove to be efficient only in the environmental vicinity of the reference state.

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