Vibration-Based Damage Identification in Wind Turbine Blades

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Introduction

Due to the existing trend of placing wind turbines in impassable terrain, for example, offshore, these structures constitute prime candidates for being subjected to structural health monitoring (SHM). The wind turbine blades have in particular been paid research attention [1] as these compose one of the most common and critical components to fail in the turbines [2]. The standard structural integrity assessment of blades is based on visual inspection, which requires the turbine in question to be stopped while inspections are conducted. This procedure is extremely costly and tedious, hence emphasizing the benefits of developing and integrating a reliable, remote monitoring method for detecting, localizing, and assessing potential structural deterioration.

Experimental work

Experiments were conducted with a Vestas V27 wind turbine, situated at DTU Wind Energy in Roskilde, Denmark. Fig. 1 depicts the experimental setup in which one blade was instrumented. The turbine was analyzed in four states; namely, the healthy state and three damaged ones with, respectively, a 15 cm, 30 cm, and 45 cm trailing edge crack in the instrumented blade. The experiments were conducted from October 2014 to January 2015 to capture the effects of environmental variability.

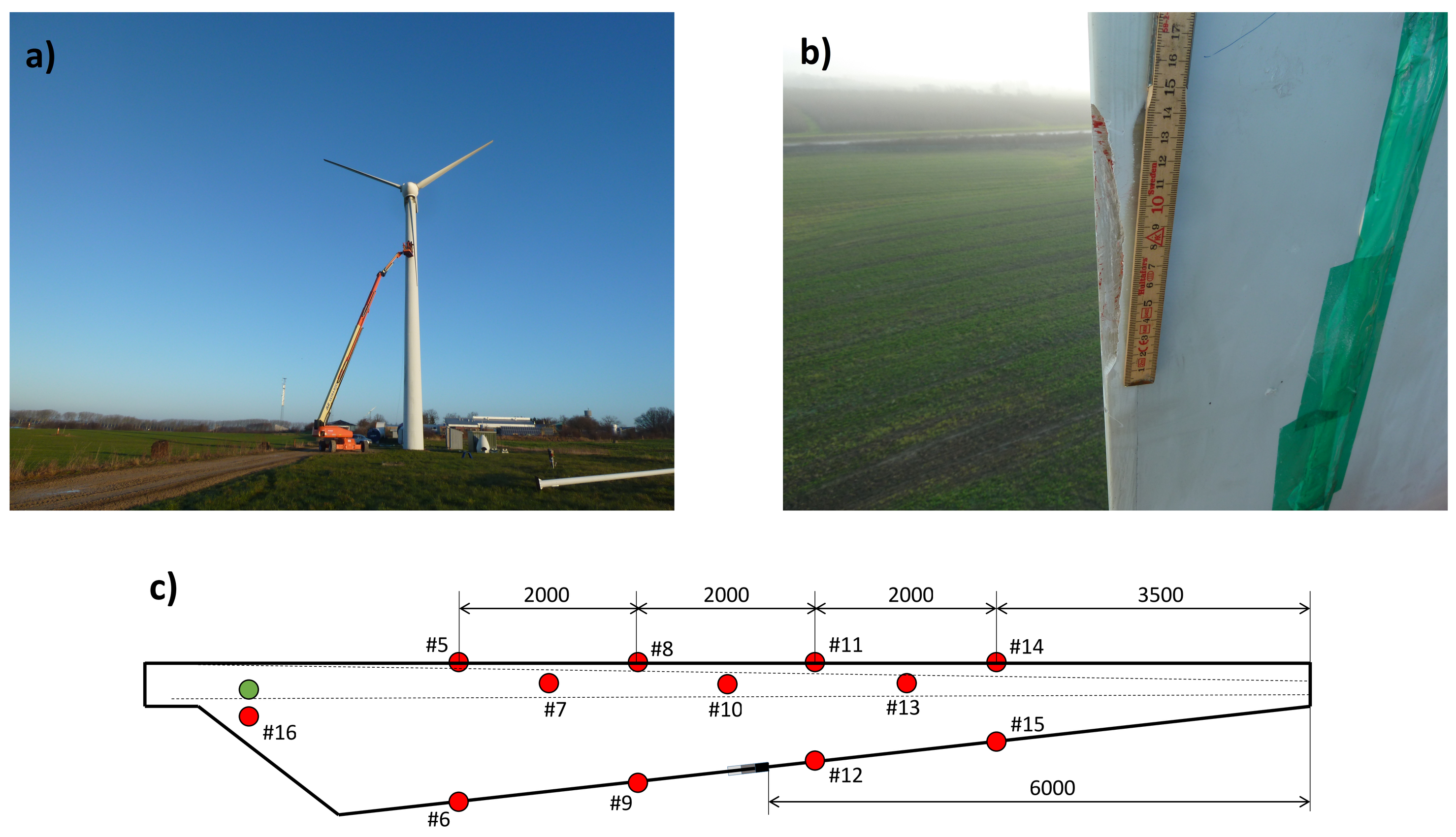

Fig. 1: a) Equipped Vestas V27 turbine. b) 15 cm crack. c) Sketch of instrumented blade with actuator (green dot), accelerometer (red dots), and damage (hatched boxes) locations.

Damage identification approach

We propose a damage identification approach, where damage detection is conducted during turbine operation on the basis of measured vibrations governed by actuator excitation. If a damage is detected, the turbine is stopped to perform localization and assessment - again, based on actuator-induced vibrations.

- **Damage detection:**
  Structural anomalies are detected through outlier analysis, where the discordance between a feature from the healthy state and the current one is evaluated to classify the structure in question as healthy or damaged.

  Discordance measure: $D^2 = (\mathbf{y} - \overline{\mathbf{x}})\Sigma^{-1}(\mathbf{y} - \overline{\mathbf{x}})^T$,

  with **y** being the feature vector (containing, for example, stacked acceleration histories) from the current state, while $\overline{\mathbf{x}}$ and Σ are, respectively, the vector mean and covariance of the matrix containing the numerous healthy-state realizations of the concerned feature.

  Hypothesis testing with threshold ϑ : $\begin{cases} H_0 : D^2 \leq \vartheta \rightarrow \text{Healthy}, \\ H_1 : D^2 > \vartheta \rightarrow \text{Damaged}. \end{cases}$

- **Combined damage localization and assessment:**
  Damage localization and assessment are performed through statistical evaluation of changes in a surrogate of the transfer function matrix (TFM); changes that arise due to damage plus operational and environmental variability. The method is an extension of the SDDLV method proposed in [3].

  TFM change: $\Delta G = \tilde{C}_c\tilde{A}_c^{-b}(sI - \tilde{A}_c)^{-1}\tilde{B}_c - C_cA_c^{-b}(sI - A_c)^{-1}B_c$,

  where s is the Laplace variable, $b = 0, 1, 2$ (depending on whether we measure displacements, velocities, or accelerations), I is the identity matrix, and ~ is used to denote the damaged-state editions of the state-space realizations, A_c, B_c, C_c.

Damage identification approach - cont.

We derive a surrogate change, $\Delta R^T \propto \Delta G$, of which the quasi-null vectors constitute load vectors that yield stresses approaching zero in the damaged area(s), when applied to a mechanical model of the undamaged system.

Selecting load vectors: $\Delta R^T = \begin{bmatrix} U_1 & U_2 \end{bmatrix} \begin{bmatrix} \sigma_1 & 0 \\ 0 & \sigma_2 \end{bmatrix} \begin{bmatrix} V_1 & V_2 \end{bmatrix}^H$,

where $\sigma_2 \approx 0$, thus $V_2 \subseteq V = [\mathbf{v}_1, \mathbf{v}_2, \ldots, \mathbf{v}_l]$ constitute quasi-null vectors with potential as load vectors. In particular, the vector in V_2 associated with the lowest singular value, that is, $\mathbf{v}_l$, is chosen as load vector and applied to the mechanical model. By doing so for different s-values and repeating this for each measurement sequence, numerous stress fields are obtained. Finally, outlier analysis - in analogy to the procedure for damage detection - is conducted for each element in the combined stress fields for each measurement sequence.

Results

- **Damage detection during operation at 43 RPM [4]:**

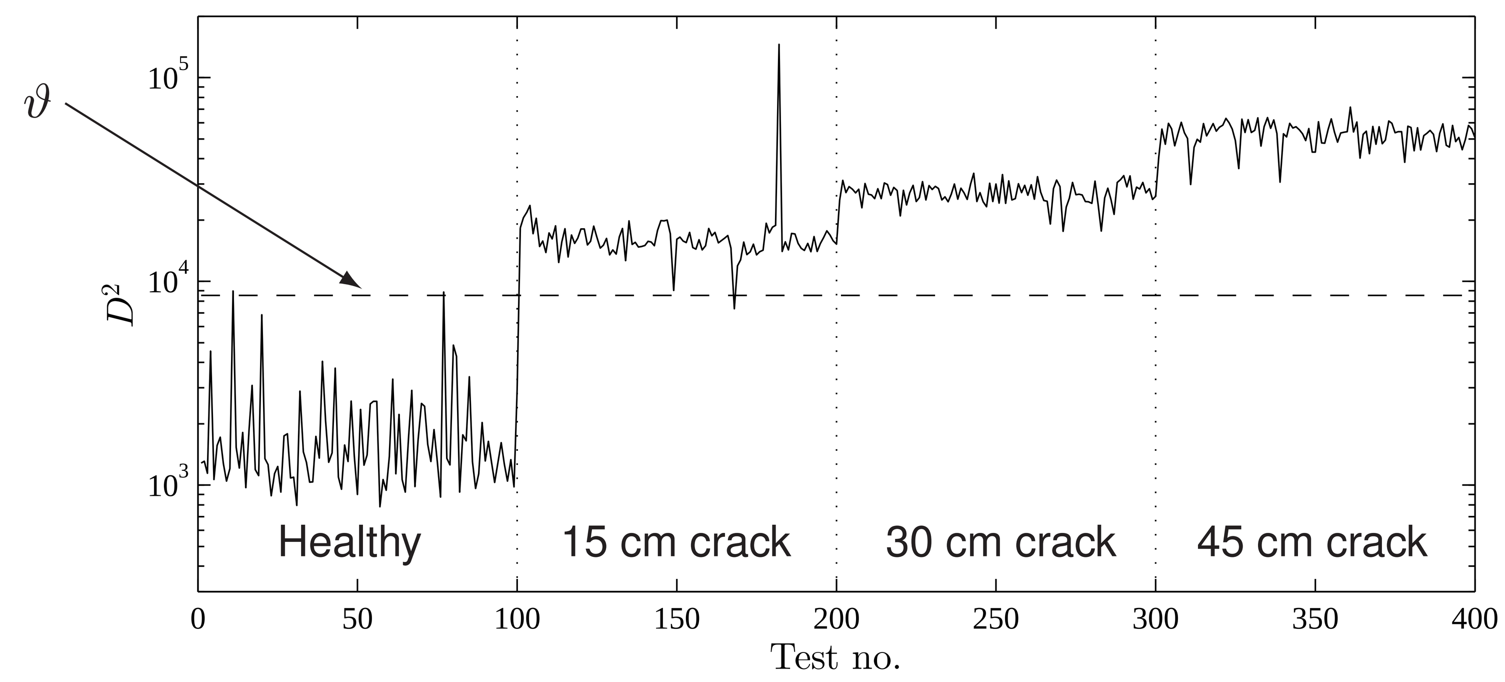

Fig. 2: Damage detection in V27 blade during operation at 43 RPM.

- **Damage localization and assessment during idle condition [5]:**

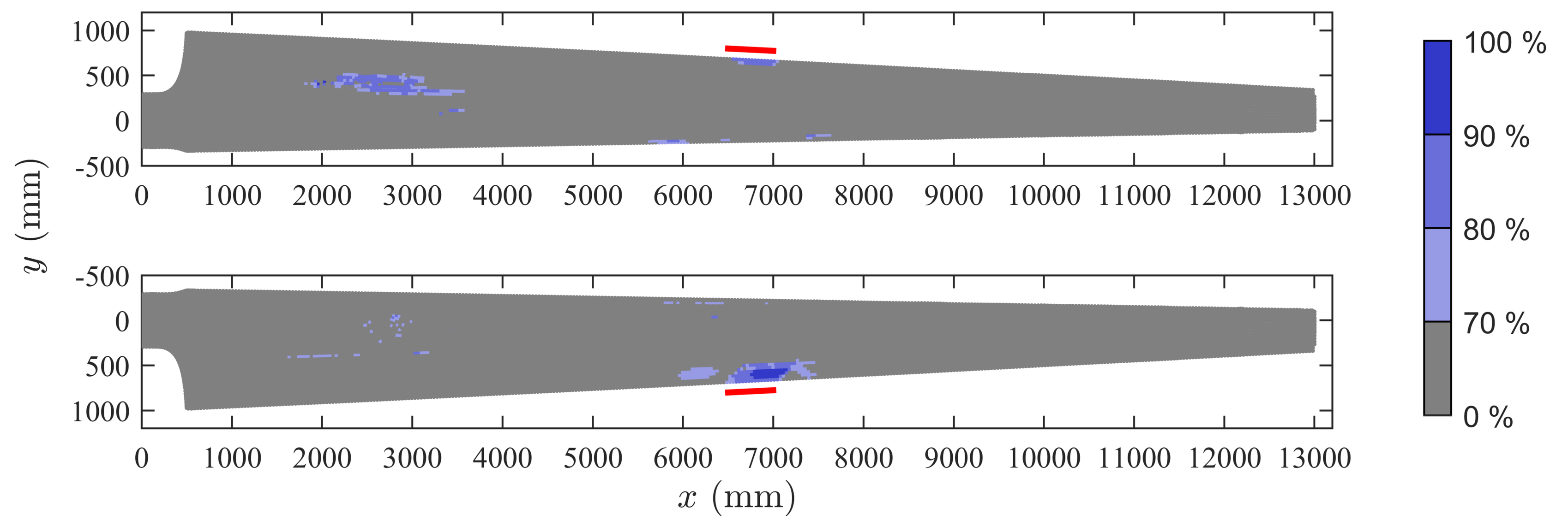

Fig. 3: Localization and assessment of 45 cm crack in idle-conditioned V27 blade. The percentage scale indicates how many times each element has been classified as damaged. The red lines mark the damage location.

Conclusion

An approach for monitoring structural deterioration in in-field wind turbine blades based on statistical evaluation of derived features from measured vibrations has been proposed. In the context of a Vestas V27 wind turbine, it has been proved that the proposed approach facilitates valid detection, localization, and assessment of trailing edge cracks.

Future research: study of sensitivity towards damage location and type (cracks, debondings, etc.); study of robustness against instrumentation concept, that is, type, amount, and placement of sensors and excitation source.

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