Mechanical Systems and Signal Processing 107 (2018) 266–277

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

journal homepage: www.elsevier.com/locate/ymssp

Mass detection, localization and estimation for wind turbine blades based on statistical pattern recognition

L. Colone [a,*,1], M.K. Hovgaard [a], L. Glavind [b], R. Brincker [a,2]

[a] Department of Engineering, Aarhus University, Aarhus, Denmark
[b] Vestas Wind Systems A/S, Denmark

ARTICLE INFO

Article history:
Received 14 February 2017
Received in revised form 14 November 2017
Accepted 16 November 2017

Keywords:
Structural health monitoring
Operational Modal Analysis
Mass change detection
Localization
Estimation
Statistical classification

ABSTRACT

A method for mass change detection on wind turbine blades using natural frequencies is presented. The approach is based on two statistical tests. The first test decides if there is a significant mass change and the second test is a statistical group classification based on Linear Discriminant Analysis. The frequencies are identified by means of Operational Modal Analysis using natural excitation. Based on the assumption of Gaussianity of the frequencies, a multi-class statistical model is developed by combining finite element model sensitivities in 10 classes of change location on the blade, the smallest area being 1/5 of the span. The method is experimentally validated for a full scale wind turbine blade in a test setup and loaded by natural wind. Mass change from natural causes was imitated with sand bags and the algorithm was observed to perform well with an experimental detection rate of 1, localization rate of 0.88 and mass estimation rate of 0.72.

1. Introduction

The detection of changes, whether these are related to damages, marine growth or ice build-up on civil structures, is decision-making under uncertainty. With reference to the large variations in modal parameters caused by varying operational conditions, it was argued at the turn of the century by Farrar et al. [1] and Worden et al. [2] that the detection of damage in civil structures is a problem of statistical pattern recognition. Since then, a significant part of the Structural Health Monitoring (SHM) research community has proceeded in the direction of statistical methods. Rytter [3] has argued that the SHM process is naturally hierarchical, where detection is followed by localization. Worden et al. [4] noted that the first level could be approached using novelty detection, which is a common denominator for statistical discordance tests and outlier analysis, generally of the unsupervised learning type. In the same work it was argued that the severity of damage as localization and estimation, which reside in the higher levels of Rytter's hierarchy, can only be achieved in a supervised learning framework, i.e. data corresponding to the structure in the damage state must be available. However, this argument only holds for global sensing, where damage sensitive features are obtained from a global response, as opposed to a local response.

Localization can also be approached by using localized sensing as was shown in Flynn et al. [5]. Statistical methods for localization and estimation were used by Worden and Lane [6], who used Support Vector Machines (SVM) as a damage clas-

* Corresponding author.
E-mail address: lcol@dtu.dk (L. Colone).
[1] Technical University of Denmark, Frederiksborgvej 399, 4000 Roskilde, Denmark.
[2] Technical University of Denmark, Anker Engelunds Vej 1, 2800 Kgs. Lyngby, Denmark.

https://doi.org/10.1016/j.ymssp.2017.11.031
0888-3270/

sifier and applied the concept to the experimental cases of a ball bearing and a frame structure. Another more recent work by Worden and Manson [7] shows how supervised and unsupervised learning algorithm such as Neural Network and SVM can be applied for damage detection, localization and assessment on an aircraft wing. Figueiredo et al. [8], underlined the important issue of operational and environmental variations concealing the damage related features. A similar problem was tackled by Weijtjens et al. [9] on SHM of wind turbine foundations. A more complete application on fault detection, which includes an experimental full scale validation is provided by Nguyen et al. [10], who applied remote sensing technologies based on SVM validated on the Sydney Harbor Bridge.

Furthermore, it should be remarked that for most applications training data cannot be experimentally obtained and must instead be synthesized from a model of the damaged structure. For instance, Hovgaard [11] used a finite element (FE) model and a two-step statistical approach to successfully localize damage in a laboratory blade structure. Thus, the main idea of the present study is the extension of Hovgaard's approach of stiffness change localization, unto mass change localization and estimation by using only natural frequencies of the structure. A numerical simulation study is presented, along with an experimental validation on a full-scale wind turbine blade positioned in a test rig. Although the idea of using only natural frequencies and pattern recognition for mass change detection on wind turbine blades in not novel [12], the further contribution of this paper is the combination of the FE model and statistical analysis to localize as well as estimate the size of the additional mass on the blade. The term detection relates to the topic of deciding if a change has occurred, localization relates to the topic of deciding the location of the occurred change, and estimation relates to the topic of deciding the severity of the occurred change. The advantage of using statistical information in a supervised learning mode is robustness towards environmental noise and towards numerical errors from the feature extraction. The method is vibration based which means that the information collected from the system is a local acceleration or time derivative quantities.

2. Ice aggregation on wind turbine blades

Ice build-up on wind turbine blades is treated e.g. by Hochart et al. [13]. It is a concern in northern sites where low temperatures and atmospheric conditions cause icing on the blades, either as glaze-icing in wet conditions or as rime-icing in dry conditions. The ice build-up causes increased surface roughness, which affects the aerodynamic profile of the blade resulting in reduced power production [14]. Another issue is the ice-throw, which is the event where a chunk of ice detaches and is hurled from the rotating rotor at great speed. Finally, the added mass from the ice may cause rotor imbalance and overload. The amount of ice on the blade is up to several percent of the initial blade mass, which to some extent separates the problem from typical SHM problems, where the modal changes caused by damage is in the per-mille region, as described by Hovgaard et al. [15]. Current methods of ice-detection are reviewed e.g. in Homola et al. [16] and Parent and Ilinca [17]. A recent work by Tsiapoki et al. [18] presents a modal based SHM framework for ice and trailing edge damage detection.

Fig. 1 shows two different blades in operation carrying an amount of ice typically accumulated over few hours in case of favorable environmental conditions.

3. A statistical classification approach to mass change detection, localization and estimation

The approach originally presented in [11] for damage detection is briefly summarized in the following and is then extended to mass-change detection. Damage detection and localization is cast as a two-step problem of statistical pattern recognition [4], concerning the following questions

- Is there any change?
- Where is the change?

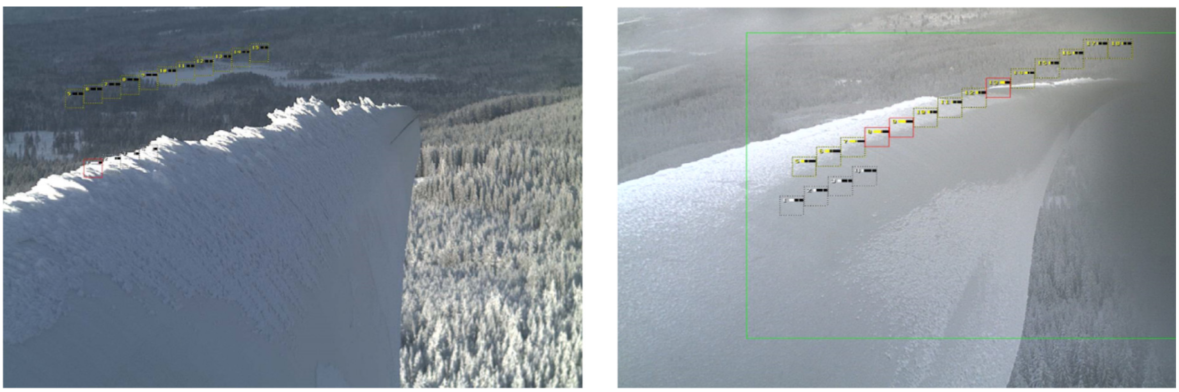

Fig. 1. Icing of a wind turbine blade. Icing can occur over few hours. Photo: Vestas.