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Virtual prototyping of an actuator-based structural health monitoring system of wind turbine blades

D. Garcia [1], **D. Tcherniak** [2], **K. Branner** [3]
[1] University of Strathclyde, Department of Mechanical and Aerospace Engineering,
75 Montrose Street, Glasgow, G1 1XJ, United Kingdom
e-mail: **david.garcia@strath.ac.uk**

[2] Brüel & Kjær Sound & Vibration Measurements, Innovation group,
Nærum, DK-2850, Denmark

[3] Technical University of Denmark, Department of Wind Energy,
Frederiksborgvej 399, 4000 Roskilde, Denmark

Abstract
Testing and evaluating the performance of a Structural Health Monitoring (SHM) system is a challenging and costly task. A proper experimental assessment of the system is not feasible in most cases. A possible solution is a virtual prototype of the monitored object together with the SHM system. This study presents the initial steps of creating a virtual prototype, namely simulation of the elastic wave propagation due to impact of the actuator. It is shown that even this very initial investigation helps to understand the complex vibration pattern of the blade and how the presence of the damage alters it. Similarly, for the same damage size and location, different actuations locations were studied. The location of the actuator affects the wave propagation, as the interaction with the structural parts of the blade significantly complicates the vibration pattern before it actually reaches the damage region. The results clearly indicate that the actuator-based SHM system has a good wave propagation and damage resolution ratio for damage diagnosis in large blades.

1 Introduction

In recent years, the research community has built up a wealth of knowledge in the field of Structural Health Monitoring for Wind Turbines [1, 2, 3]. To reduce the cost of energy the wind energy industry requires technologies that will act as the basics for full lifecycle asset management. The components in the wind turbines will develop different failures depending on the nature of each of them and therefore it is rather difficult to create an unique SHM system for monitoring all kind of failures. This is one of the reasons why, the importance of SHM system is a must in this kind of structures.

Thought in the last 25 years the concept of SHM has been in continuous development but there are still some challenges that should be taken under consideration as presented in [4]. One of the first aspects to have in mind is the tolerance of damage for each component. It is assumed that there is not a perfect material and hence damage will occur in one way or other. Therefore, it is needed to make a decision whether the tolerance of the damage is acceptable or not [5]. One of the most common methodologies for SHM is to compare the actual status of a component against a reference state, which determine the original conditions of the component to be monitored. These methodologies need to be robust to eventually create a reliable system that will help in the decision making by reducing the number of wrong decisions (i.e. reducing the number of false alarms by maximising the damage detection rate) [6]. As known in the research community, sensors do not directly measure damage but they provide the information from where to extract a feature that could be used to monitor any deviation from the reference state and therefore detect the presence of damage.

The selection of these features is not a simple task and they should be *smart* in the sense that they should not be affected by operations and environmental effects. The development of a SHM system should be robust and flexible to learn from the past and present towards successful damage diagnosis (i.e. damage detection, localisation and quantification) and hence to project the learning onto future decisions and thus predict the remaining lifetime of the component in monitoring (i.e. prognosis) [7]. As it can be deduced, a reasonable balance of all these aspects should be taken into account when a SHM system is to be designed. More or less emphasis will be dedicated to each of these aspects depending on the case. Thus, it is clear that there is not an unique SHM system but it depends on the study or object under consideration. On the other hand, there is other aspect to be considered that will contribute towards the development of SHM not only in the wind energy but also in other sectors of the engineering. The SHM system should be designed as such as it will awake the interest of business in different sectors of the industry. Therefore, as mentioned before, the SHM should be able to assist the evaluation of the full lifecycle asset management. This will arouse the interest of the industry, with inputs that variate from new product design to decision making for decommissioning or life extension of a structure. All these considerations come together in this early stage study for creating a virtual prototype as a platform where to test new SHM systems.

The study in this manuscript presents the initial steps towards creating such a virtual prototype, namely simulation of the elastic wave propagation due to impact of the actuator. For the same damage size and location, different actuations locations were studied. The fruitful results were discussed to set the foundations for further investigations.

2 The need of a virtual prototype with SHM system

Testing a Structural Health Monitoring (SHM) system and evaluating its performance is a challenging and costly task. A solution to this problem could be a virtual prototype of the monitored object together with the SHM system. A virtual prototype is a multiphysics model allowing simulation of an as-built structure, component, infrastructure, etc., to mirror the life of the real structure, component, infrastructure, etc. [8, 9]. The virtual prototype should simulate sensor data from the structure under study. The main aim of this virtual prototype is to evaluate new SHM methodologies in a realistic and robust environment towards life-cycle sustainability. Some of the challenges that indeed still need further investigation are discussed bellow in order to reflect the relevance of these virtual environments.

Testing and evaluating the performance of SHM systems has been always under study. SHM methodologies are tested, on their majority, on simulated structures with more or less accurately representation of the nature of the damage This simulations are very useful to understand the philosophy of the new system before they are extended for real implementation in large scale experiments. A realistic experimental assessment of the system against even few types of damage is an extremely expensive exercise as it requires introducing damage artificially, which is not even feasible in some scenarios. The benefit of having a virtual prototype will allow to test the SHM system for different scenarios, localisation, size, nature of the damage, even a combination of all, etc. Similarly, different SHM systems, which include hardware (e.g. different types of sensors, DAQ systems,...) and algorithms (e.g. model and non-model based, supervised and unsupervised,...) could be implemented in the same prototype. Moreover, new sensor technologies such as fibre-optic sensors could be tested for further development as well as combination of multiphysics environments that simulate a more realistic situations (i.e. operational and/or environmental effects). Similarly, a different set of sensor-array could be investigated to optimise the sensor locations for enhancing successful damage diagnosis. In [6], the relation of accelerometer location and damage detection for different damage locations and sizes was investigated. It was observed that sensors closer to the damage did not always provide a good detection of the damage. With virtual prototypes, the damage sensitivity ratio could be better studied by considering different sensors' distribution and therefore assess the performance towards damage diagnosis in a faster, easier and more affordable manner. In this case the sensor distribution could be optimised by defining areas with higher or lower density of sensors. All these aspects and more will be possible because virtual prototypes combine adequate data fusion measured on real structures with high-fidelity models.

Reducing uncertainty and creating high reliability not only in the SHM methodology performance but also in an effective use of assets. One of the bigger challenges that SHM systems face is to provide useful but more important reliable information to help in the decision making. This can be observed in previous studies [11, 12], where the selected feature is not always able to track the growth of the damage. In this case, one can go into the virtual prototype and study the effect of each parameter individually by relating structural changes to the performance of the selected featured, in order words virtual prototypes will provide more understanding about the SHM system under study. Other important aspect in the development of SHM systems is the influence of the operational and environmental effects on the performance of SHM system. It is important to know if the deviation detected by the SHM systems is because of the damage or because other factors that influences the performance of the SHM system [13]. Similarly, as shown in [14], the observations measured in the repaired wind turbine blade experienced an irregularity and the damage indices did not follow the same pattern. Virtual prototypes rely on the data fusion and therefore data from weather conditions can possibly be taken into account to investigate its effects in the SHM performance.

Quantifying the avalue of the SHM systems is probably one of the most important aspects to be considered for the future of SHM. This aspect is the great interest for the industry and infrastructure's owners to make decisions about their interests. Having information about the life-cycle of a structure will add useful information towards the quantification of the value of SHM [16]. The concept of value of information (VoI) is currently presentend as a metric to quantify the value of SHM. It can be used to evaluate the total expected lifetime operation and maintenance costs for a wind turbine with SHM and without SHM [17]. The key factor of VoI is to include within the quantification of the cost of a SHM system not only the deterioration because of damage of the object, the failure of hardware system or the SHM's algorithm implemented but also the decisions to be made after the evaluation of the entire SHM system.

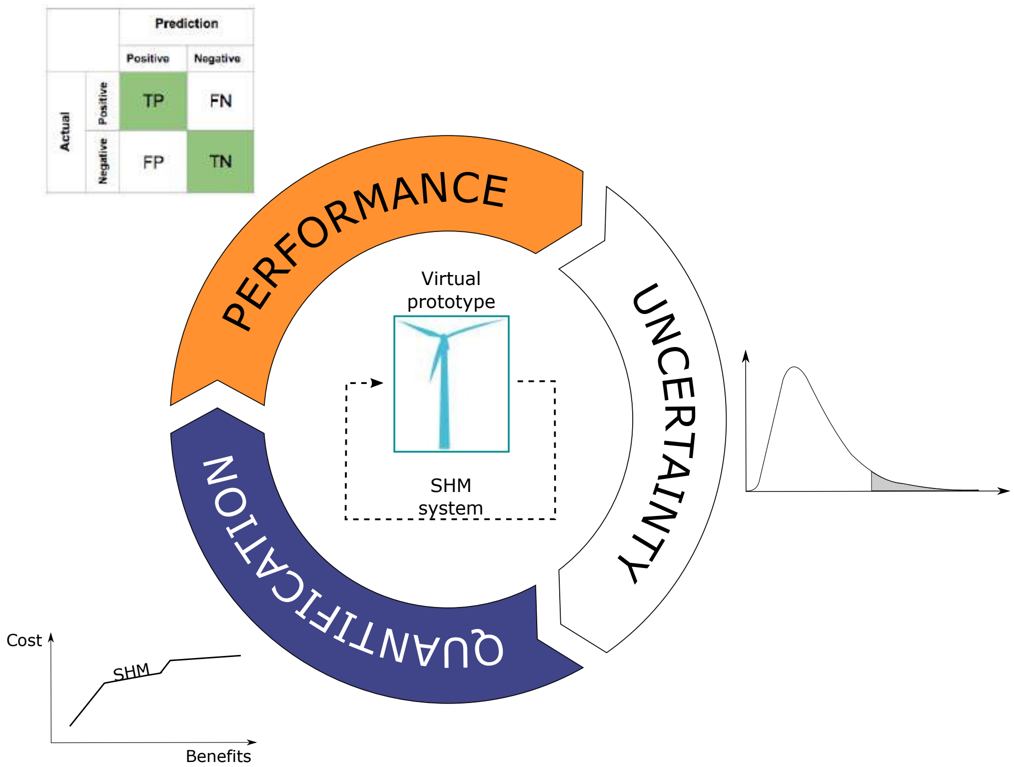


Figure 1: Conceptual representation of a Virtual Prototype for SHM systems

Other aspect that it is not directly included in the design of a SHM system but it is of great interest in the research community and industry is damage prognosis. Damage prognosis refers to the estimation of the remaining useful life of a component, structure, etc. and it is the real importance for life-safety and economic benefits quantification. The estimation of the remaining useful life is based on the combination of the analysis of models, simulations findings and the knowledge from past and present towards future predictions [15]. The consideration of these virtual environments for damage prognosis will act as a detailed model of the object and they will be beneficial for the development of prognosis studies.

To summarise, it is of great potential develop virtual prototypes for assessing the performance and value of SHM systems. In possession of a virtual prototype, one can evaluate different SHM systems for the same structure with strong reliability. This will help to understand the philosophy of each SHM approach as well as identify the limitations and alternatives to improve it towards the evaluation of interest. Additionally, these technologies will help in the quantification of the value of SHM at different states such as proof of concept, industrial implementation, decision making and economic driven with the aim of awaken the interest of the industrial stakeholders.

3 Creation on a virtual prototype of the monitored blade

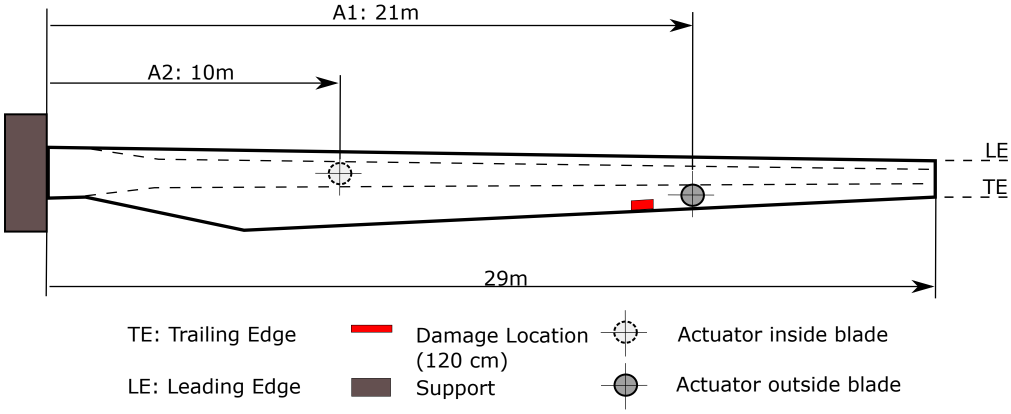
This study presents the intital steps of a numerical simulation of an actuator-based SHM system, which consists of an electromagnetic actuator and an array of accelerometers mounted on a wind turbine blade. Actuator's impact induce elastic waves that propagate along the blade; the response at different blade locations is measured by the accelerometers. Previous studies experimentally demonstrated that damage alters the vibration pattern and it can be used as a robust indicator of blade damage assessment [18]. The study presents the initial steps towards creating such a virtual prototype, namely simulation of the elastic wave propagation due to impact of the actuator. Similarly, for the same damage size and location, different actuation locations were studied.

3.1 Modelling and simulation details

This study is based on a numerical finite element model of a 34m wind turbine blade manufactured by SSP Technology A/S. The 34m wind turbine blade has extensively been studied both experimental and numerical at DTU Wind Energy [19, 20]. The blade was truncated at 29m in order to accommodate it in the blade test facility. A short description of the modelling considerations are described as follow. For further information refer to [20].

The model was simulated by MSC/PATRAN [21]. A volume representation of the geometry was required to use 20-noded layered continuum elements for modelling the blade structure. The outer geometry of the blade was modelled by 25 cross-section/aerodynamic profiles. The thickness of the laminates was represented according to the layup by the defined curves of the offset cross-sections. The individual cross-sections were connected by spline curves and interpolation surfaces to obtain a volume representation of the blade. This utilized 48 regions/solids to assign the different properties automatically by Blade Modelling Tool (BMT) developed by DTU Wind Energy. The approximate number of elements in this study was 40000. The composite layup was modelled with 15-44 plies though the thickness via BMT, and composite properties were assigned to layered 20-noded continuum elements. The blade was mounted on a test rig in a similar manner that it would be on a wind turbine hub. The rig is included as a spring/beam system, which is coupled to the blade via a MPC element in order to add some flexibility of the rig and therefore minimise its effect on the simulated eigenvalues and eigenvectors of the blade.

The model of the wind turbine blade was used to simulate the same experimental test campaign described in [18]. An electro-mechanical actuator was placed on the wind turbine blade to introduce an impact. The rationale of the experiment was to measure the vibration response of the wind turbine blade by accelerometers along the trailing and leading edge in order to apply a SHM system for damage assessment.



(a)

(b)

(c)

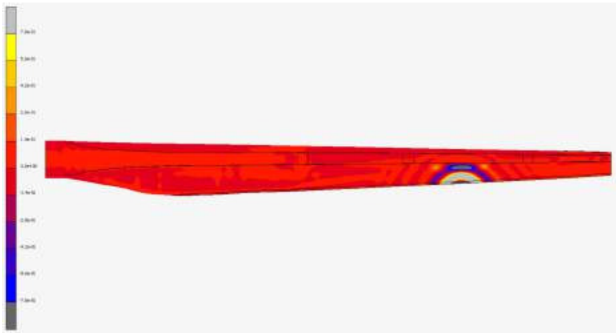
Figure 2: Blade scheme geometry and the actuators' locations. a) Blade scheme. b) Actuator location A1 c) Actuator location A2.

Therefore, the idea of this study is to create a virtual prototype of blade and hence simulate the experiment in a finite element model of the wind turbine blade. The simulation was first done in the undamaged wind turbine blade (no disbonding of the upper and lower shells in the trailing edge) and secondly in the damaged blade (with disbonding of the upper and lower shells in the trailing edge). The size of the damaged was 120 cm and it was in a location at approximately $\frac{2}{3}$ from the root and in the Trailing edge as shown in Figure 2(a). The simulation was done separately for two different actuator locations. First for the actuation location A1 and then for the actuator location A2 as it can be observed in Figure 2(b) and 2(c) respectively.

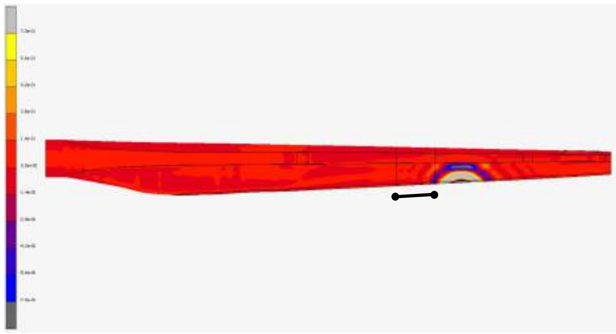
The propagation of the elastic waves is a transient phenomenon and it was simulated by MARC with its advanced nonlinear solver of MSC software [22]. The transient analysis was performed for a period of 0.1 seconds after the actuator impact and the accelerations in the vertical direction only were calculated for 2000 intermediate time steps. The impact was introduced in the closest node to the actuator under study.

4 Results and Discussions

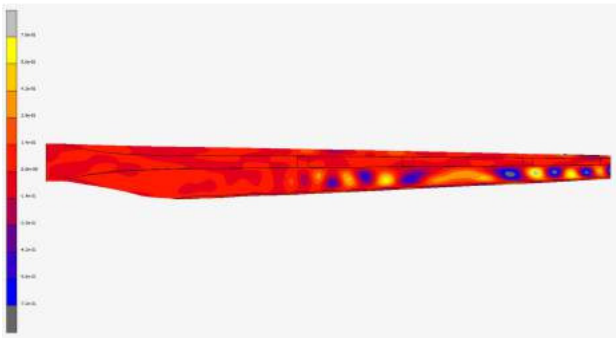
This section presents the results, reflections and discussions found in the simulation of the experiment presented in Figure 2. The initial study of this research is to compare two different actuator locations for a fixed damage location and size of 120 cm. Figure 3 presents the elastic waves (EW) on undamaged and damaged blade at different times for an excitation in the actuator location A1. It can be observed that at 0.0029s after the impact of the actuator the EW on the damaged and undamaged blade have the same patter as the EW did not reach the damage region yet (see Figure 3(a) and 3(b)). Therefore, before the EW interact with the damage region, there is not difference between both blade scenarios. However, once the EW interact with the damage region, there is a clear change in phase and amplitude as it can be observed by comparing Figure 3(c) and 3(d). At this time (0.0165s), the first EW arriving to the tip does not have any direct interference with damage. The comparison of the EW for undamaged and damaged blade did not present any clear visual change in the phase and it seems to travel at the same frequency without any visual delay. It might be seen a slight change in the amplitude but very small.



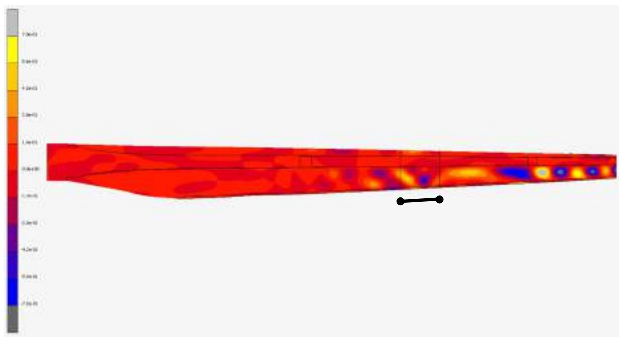
(a) A1 - Undamaged - Time: 0.0029s



(b) A1 - Damaged - Time: 0.0029s

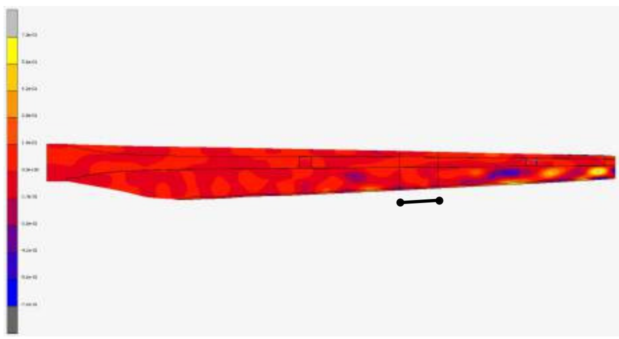


(c) A1 - Undamaged - Time: 0.0165s



(d) A1 - Damaged - Time: 0.0165s

(e) A1 - Undamaged - Time: 0.0265s

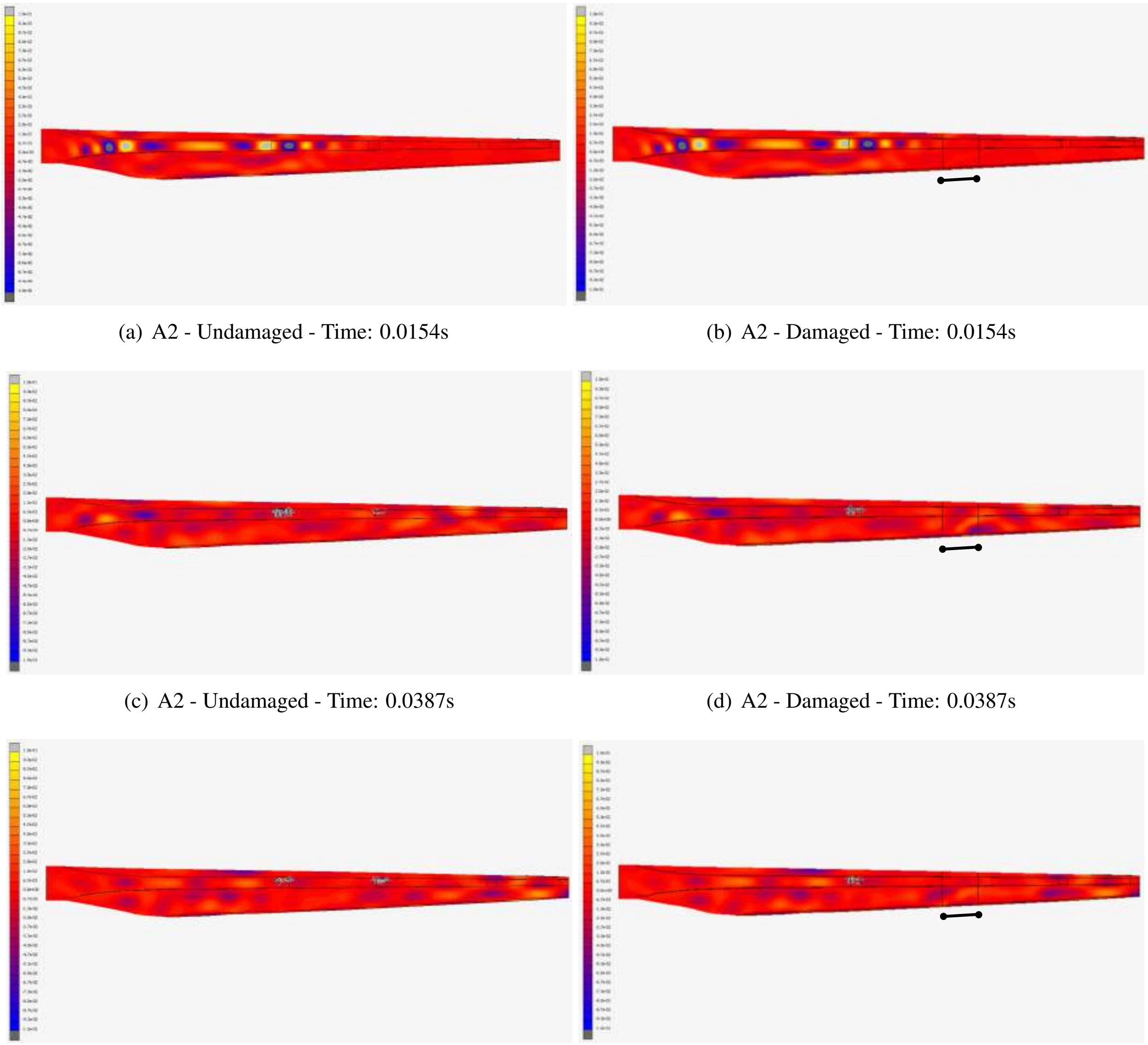


(f) A1 - Damaged - Time: 0.0265s

Figure 3: Undamaged and Damaged wind turbine blade for Actuation location A1. The damage location and extend is defined with a black line.

However, looking at the root-direction, it can be observed that the EW clearly interact with the damage region and it clearly shows a significant difference between undamaged and damaged blade. The EW breaks its normal pattern and split after the damage, this was also observed in [23]. At time 0.0265s, the reflection of the EW after interacting with the damage region travels towards the tip of the blade. A small difference in amplitude can be better observed between undamaged and damaged blade (see Figure 3(e) and 3(f)). Again for this time, in the direction towards the root, the vibration pattern is still significantly different between both blade scenarios.

Therefore, it can said that when the EW interacts directly or indirectly with the damage region a change in the vibration pattern was clearly observed. Following this assumption, any accelerometers located along the trailing edge will be able to detect some irregularities/differences. However, the differences in the leading edge are not very clear and therefore accelerometers located along leading edge might not be able to detect the damage.



(a) A2 - Undamaged - Time: 0.0154s

(b) A2 - Damaged - Time: 0.0154s

(c) A2 - Undamaged - Time: 0.0387s

(d) A2 - Damaged - Time: 0.0387s

(e) A2 - Undamaged - Time: 0.0449s

(f) A2 - Damaged - Time: 0.0449s

Figure 4: Undamaged and Damaged wind turbine blade for Actuation location A2. The damage location and extend is defined with a black line.

As for the actuator location A1 is presented in Figure 4 for undamaged and damaged blade at different times for an excitation in the actuator location A2. At 0.0154s after the impact of the actuator, the EW move towards the root and tip of the blade as it occurred by the actuation in the location A1. However, a clear observation can be made already at this short time - the EW got trapped in the spar beam and therefore most of the energy transmitted to the blade will dissipate inside the spar beam (see Figure 4(a) and 4(b)). Some of the EW were able to scape from the spar beam and travelled towards the trailing and leading edge as it can be observed in Figure 4(c) and 4(d) at time 0.0387s. At this time, the EW interacts for the first time with the damage region and it can be observed that the vibration pattern changes when the undamaged and damaged blade were compared after the damage region towards the tip. Therefore, the assumption that the interaction of elastic wave/damage provides information about damage presence by changing the vibration pattern is also observed. After the time 0.0449s, the difference in the vibration pattern between undamaged and damaged is very weak and there is not a visual difference between undamaged or damaged blade (see Figure 4(e) and 4(f)). As expected, there is not visual changes in the leading edge between undamaged and damaged for this actuation location. When the EW reach the damage region is already very weak and it will not contain enough energy to travel towards the leading edge with information about the presence of the damage.

5 Conclusion

This study presents the initial steps towards creating a virtual prototype of actuator-based SHM system, namely simulation of the elastic wave propagation due to impact of the actuator. It is shown that even this very initial investigation helps to understand the complex vibration pattern of the blade and how the presence of the damage alters it. The location of the actuator affects the wave propagation, as the interaction with the structural parts of the blade significantly complicates the vibration pattern before it actually reaches the damage region. The results obtained in the simulations clearly indicate that the actuator-based SHM system has a reasonable wave propagation and damage resolution ratio for damage diagnosis in large wind turbine blades.

Acknowledgements

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