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Structural Health Monitoring strategies based on the estimation of modal parameters

Emilio Di Lorenzo[a,b,c,*], Simone Manzato[a], Bart Peeters[a], Francesco Marulo[b], Wim Desmet[c]

[a]Siemens Industry Software NV, Interleuvenlaan 68, 3000, Leuven, Belgium
[b]University of Naples Federico II, Department of Industrial Engineering, Via Claudio 21, 80125, Naples, Italy
[c]KU Leuven, Division PMA, Celestijnenlaan 300B, 3001, Leuven, Belgium

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Abstract

Rotating machines have always been used in a wide variety of industrial applications. Nowadays it is very difficult to find machines or mechanical systems which do not have any rotating component such as gears, bearings, shafts, wheels and so on. Wind turbines, gearboxes, combustion and electrical engines, generators and gas turbines are just few examples of objects with several rotating substructures. These machines face very complex and non-linear conditions during their operating cycles. they are often subjected to the fatigue problem and it is fundamental to detect faults or damages well in advance in order to reschedule the maintenance cycles. This is especially true for big machines (i.e. wind turbines) where the maintenance costs are a huge part of the total costs. Structural Health Monitoring (SHM) is a technology which is able to provide a continuous indication of the health and the reliability of the structure along its lifecycle. A damage detection technique is an essential part of any SHM system. Its scope consists in the identification of some structural and environmental parameters which have to be monitored regularly during the operation of the machine. This technique should be able to distinguish if the damage is present or not in the structure, but it should also locate and quantify the same damage. A damage can be seen as a change in material and/or geometric properties of a structure, including variation of boundary conditions and structural connections. Several studies have been performed and two different SHM strategies have been defined. The first one is based upon the whirling phenomenon. The whirling modes are the most identifiable modes in operating conditions and they appear to be very sensitive to changes of stiffness. Their amplitude and phase can be used as damage indicators because they allow to identify the loss of isotropy in the rotor. A second parameter which is quite sensitive even to small changes of stiffness is the curvature of the mode shapes. For beam-like structure it has been demonstrated being a very good damage indicator. Several simulations have been run together with some experimental validation on a wind turbine blade.

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Keywords: Structural Health Monitoring; Wind Turbines; Damage Detection; Whirling Modes; Mode Shape Curvatures.

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* Emilio Di Lorenzo. Tel.: +3216384542.
E-mail address: emilio.dilorenzo@siemens.com

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1. Introduction

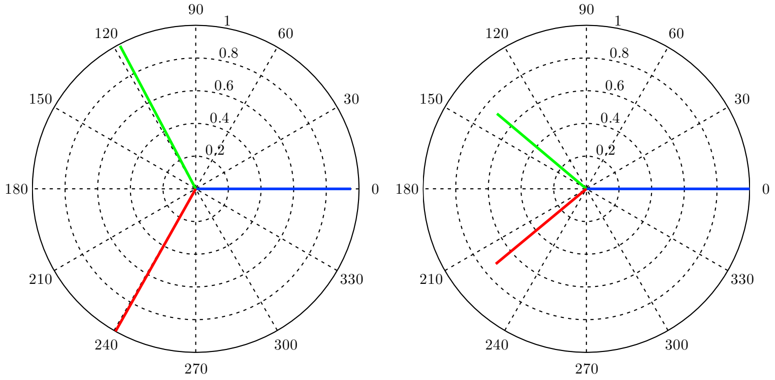
In recent years, wind energy has become one of the most exploited renewable energy technologies. In fact, even if wind turbines exist since decades, in the last twenty years huge improvements have been realized in terms of technology, size and produced mechanical power. Nowadays, 6-8 MW wind turbines with up to 160 m diameters are already in the market and the trend shows that in the next years a power higher than 10 MW will be reached by offshore wind turbines. On the other hand, by increasing the power and consequently the size of the wind turbines, structural problems can arise and they need to be solved in an early stage to avoid catastrophic effects. This is one of the main reasons why wind turbine owners, operators and customers would receive a huge benefits if a proper Structural Health Monitoring (SHM) strategy is set in place. This technology can provide an indication of the health and reliability of the entire structure or of its substructures during the operating lifecycle of the wind turbine. Several researchers are active in this field and a few techniques have been proposed and can be found in the literature [1], [2]. Their aim is to identify damages in wind turbine components such as blades, gearbox, generator, tower, etc before they actually occur in a real life situation. A SHM strategy should be able to identify damages well in advance in order to reschedule the maintenance ahead of time and reducing the associated costs. If damages or failures have already occurred, the maintenance can be up to 5 times more expensive or the situation can be already compromised and a substitution of single or multiple components can be required.

2. Damage detection techniques

In the last years, several damage detection techniques and algorithms have been developed. Among the most promising ones there are the AE method [3], [4], the impedance-based method [5], the wave propagation-based method and the vibration-based (VB) methods [6]. The AE approach can be considered a standard practice for damage detection purposes during blade tests, but it requires the availability of a lot of AE sensors in order to cover the interested regions [3], [4]. The VB methods are based on the fact that when a damage is occurring and growing, it affects mainly the structural stiffness of the system . At this point, changes in the model parameters of the structure, such as natural frequencies, damping ratios, mode shapes and derived properties can be seen. All these methods are based on the comparison between an healthy condition and a damaged one. Some techniques are based on the mode shapes and their derivatives effectiveness for damage localization [7], [8], other methods use the Frequency Response Functions (FRFs). For instance, the frequency response curvature method considers the FRF at different locations along the structure for each frequency and compares the curvatures in the damaged and undamaged cases [9].

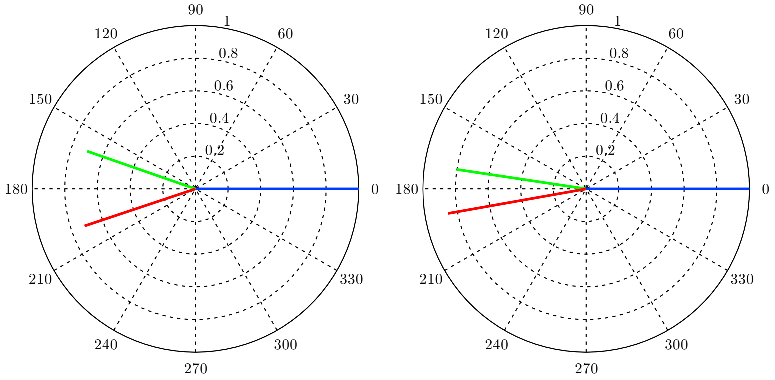
3. Whirling modes as damage indicators

The first step in a Structural Health Monitoring (SHM) algorithm is the identification of damage sensitive parameters. It has been proven that the so-called whirling modes are the most identifiable modes for a wind turbine rotor in operating conditions both in a simulation and in a test environment. They can be considered as damage indicators. The whirl mode behavior is associated with the rotor shaft whirl and with the in-plane (or edgewise) motion of the blades. This phenomenon started receiving a lot of attention in the last years because it can lead to high vibration levels. The whirl-causing force is generated by two cyclic in-plane modes of the rotor. In a single-frequency whirl mode, the rotating force vector on the shaft is a resultant of two components: a regressive force vector rotating at lower frequency and a progressive force vector rotating at higher frequency. It can be distinguished between backward and forward whirling mode. Figure 1 shows the polar plot for the backward whirling mode. In green, blue and red there are the three blades. In a perfectly symmetric case it can be noticed that this mode is characterized by the fact that all the blades have the same amplitude and they are shifted in phase by a factor equal to 120°. This is a characteristic behavior of both backward and forward whirling modes. This feature could be used for SHM purposes. If these properties get lost during the operation of a three-bladed system, then there is an asymmetry which could be associated to an incipient damage. It is also possible to identify which one is the damaged blade. Of course, in real life the three blades are not equal to each other because of the manufacturing process and the material properties. This will lead to an asymmetry at the initial stage, when the blades are all healthy. Anyhow the underlined features could be used by looking at the differences between the initial conditions and the actual ones.



Figuur 1: Healthy case (left) vs Stiffness reduction (k1=0.99).

In a preliminary study a reduction of the stiffness of one of the blades has been applied in order to simulate a possible damage. Figure 1 and Figure 2 show a progressive reduction of the stiffness of blade 1 (blue color) of a percentage (99%, 97% and 95% respectively) of the nominal value.



Figuur 2: Stiffness reduction (k1=0.97) vs Stiffness reduction (k1=0.95).

It can be clearly noticed how the phase lag between the blades is not anymore equal to 120° and the amplitude of the damaged blade is higher than the ones of the other two blades. So finally, both amplitude and phase of these modes can be used as damage indicators since they are able to detect even small changes in the stiffness of the blades.

4. Mode shape curvatures as damage indicators

It is well-known that the presence of a crack or a damage in a structure will cause a reduction of stiffness which can be seen as a reduction of its natural frequencies. Many researchers [10] [11] have attempted to detect damages in structures by comparing the natural frequencies of the undamaged and the damaged structure. Normally, in order to detect the presence of a damage, the natural frequencies of the undamaged structure need to be carefully estimated. In fact, the change in percentage of these frequencies can be lower than 1% for small cracks propagating in the structure. A mode shapes approach (as shown also for the so-called whirling modes) can lead to better results both in term of identification and localization of the structurally damaged regions. The need for an accurate evaluation of mode shapes in a starting condition (healthy or undamaged) and in case in which damages are occurring must be emphasized. This is not always possible in case of complex structure and in operating conditions. On the other hand, several kind of structures (i.e. aircraft wings, bridges, wind turbine blades) can be considered as beam-like structures with their own boundary conditions (i.e. clamped-free in case of wings and blades, clamped-clamped in case of bridges and so on). In these cases it is possible to reduce the complex structure to an equivalent beam and its dynamics can be studied by analyzing the equivalent beam. The first step is the evaluation of the modal curvatures of the undamaged structure. They can then be used as normalization parameters of the modal curvatures of the damaged structure. The Modal Shape Curvature Index ($MSCI_i$) can be defined as shown in Equation (1) [12].

$$MSCI_i = \ddot{\Phi}_{i,r}^{undamaged} - \ddot{\Phi}_{i,r}^{damaged} \tag{1}$$

i stands for the measurement point location and $\ddot{\Phi}$ is the second derivative of the mode shape Φ. If $MSCI_i$ has a discontinuity in some regions, a structural fault can be identified in these regions.

5. Damage detection on a wind turbine blade

5.1. Wind turbine blade

The wind turbine blade under investigation is a 6.5 m fiberglass from a small wind turbine (30kW). Eolpower Group performed the needed aerodynamics and structural design of the blade under the project Wind4Life [13]. A Finite Element (FE) model of the blade has been developed based on the geometry and structural information. Several configurations for what concerns the sequence and the number of plies of the composite material have been used. The most common approach for understanding the dynamic behavior of a structure is to construct a FE model and validate it with measurement data. Then, once the model is able to reproduce the behavior of the real structure, it can be used for vibration-based SHM purposes. The full-scale model can be very accurate, but on the other hand it requires a high computational power. In order to simplify it and reduce the computational cost, it is common practice to reduce blade models to beam-like structures. Therefore the complex 3D full blade model was converted into a simplified equivalent 1D beam model. The new model simulates the mass and stiffness characteristics of the 3D one with a minimum loss of accuracy. The same distribution of dynamic stiffness (bending stiffness EI and torsional stiffness GJ) along the span has been guaranteed.

5.2. Experimental results

Operational Modal Analysis was used for estimating the dynamic properties of the blade. Two tests were performed: pre-buckling and post-buckling. They were useful for investigating the change of modal parameters due to the presence of a damage. The phenomenon of the buckling consists of a failure of the structure caused by a strong deformation which distorts the geometrical topology and the associated load-carrying capabilities. The wind turbine blade under investigation was fixed to a rigid structure by using bolts at only one end resulting in a cantilever beam. On the other side, it was artificially excited by hands. Ten tri-axial accelerometers were used for recording the response of the system. They were placed on two lines along the blade with the objective to evaluate both the flexural and the torsional mode shapes. In this case, the shift of the natural frequencies toward lower values can be easily noticed. This is due to the stiffness reduction of the structure. In fact a damage can be seen as a reduction of the mechanical properties of a structure. Table 1 lists the natural frequencies and the damping ratios obtained for each mode and a huge increase in the damping values can be seen with reference to the second mode.

Mode n.	Pre-buckling		Post-buckling	
	[Hz]	[%]	[Hz]	[%]
1	3.93	2.06	3.20	1.98
2	7.92	0.74	6.09	2.90
3	11.33	1.35	9.98	1.01
4	24.78	0.65	22.93	0.47

Tabel 1: Experimental natural frequencies and damping ratios of the blade.

Mode no.	Full-scale model [Hz]	1D model [Hz]	Experimental results [Hz]
1	3.24	3.41	3.20
2	6.84	7.18	6.09
3	11.91	11.13	9.98
4	22.78	22.19	22.93

Tabel 2: Numerical and experimental natural frequencies of the damaged blade.

5.3. Damage detection in standing still conditions

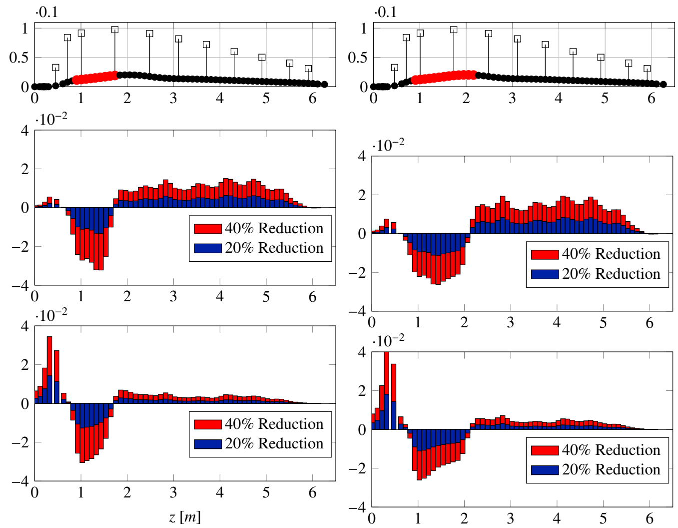
The wind turbine 1D model discussed in the previous sections has been used for studying natural frequencies and mode shapes variations in case of a damage located in a specific area. A damage can be introduced by reducing the mechanical properties of the beam material in a certain region. The $MSCI$ technique has been used for identifying and localizing the damage. In order to replicate the same damage occurred during the experimental campaign, the damage was simulated in a section close to the root of the blade. A sensitivity study for defining the proper damage extension and material properties reduction has been performed. Several damage extension (40cm, 80cm, 120cm and 140cm) and percentage stiffness reduction (10%, 20% and 40%) were used in this study. The parameters to optimize were the natural frequencies of the 1D model to be as close as possible to the experimental ones. From all the investigated configurations, the beam with a damage extension of 140cm and a reduction of 40% of the mechanical properties of the material was selected. The same study was performed also for the 3D model. In this case the presence of a damage was modelled as a local reduction of the mechanical properties of some elements of the entire structure. In order to replicate the damage occurred during the experimental test, the damage was simulated in the section close to the blade root also in this case. The same damage extension of the 1D case was chosen (140cm) and a stiffness reduction equal to 22%. Table 2 shows the first four natural frequencies obtained for the full-scale model, the one-dimensional model and the experimental results.

In case of small damages it is quite difficult to detect them by only looking at the mode shapes. In this case the first, second and third derivatives of the displacement mode shapes, that are the slope, curvature and rate of curvature, respectively, of the cracked cantilever beam provide a progressively better indication of the presence of a crack. However, ”noise effects”due to the difference approximation error also begin to be magnified at higher derivatives. For the healthy structure, these derivatives are smooth curves, so the local peaks or discontinuity on the slope can be used to indicate abnormal mode shape changes at those positions. For both cases of first and second derivatives the detection of damage is evidenced by the crossing behaviour of the damaged curves with the undamaged ones. In particular, the second derivative can be used to evaluate the position of the damaged region of the structure: the intersections between the curvature of healthy structure and the curvature of damaged structure, indicate the beginning and the end of the damaged area, as it can be seen in Figure 3. The curves representing the 2^{nd} derivatives of the first two mode shapes were normalized with respect to the undamaged ones. The curves representing the damaged structure are negative in correspondence of the damage. In this case it can be highlighted both the presence of the damage, its position and its extension. The damaged area has been indicated on the blade by using red dots instead of black ones.

6. Conclusions

This paper looks into Structural Health Monitoring (SHM) which is often a reason for which OMA is used in industrial environment. In fact, it is common practice to define SHM strategies based on the differences among the modal parameters in healthy and damaged conditions. Two main strategies have been defined for rotating machines (e.g. wind turbines):

- Whirling modes as damage indicators;
- Mode shape curvature as damage indicators.



Figuur 3: Normalized curvatures of the 1*st* and 2*nd* mode shapes.

The first one is based upon the well-known (in the rotating machinery community) whirling phenomenon. The whirling modes appear to be very sensitive to changes in stiffness and they are among the most identifiable modes in operating conditions. The changes of stiffness are identified and localized by considering the differences among the three blades. The whirling mode shapes (both backward and forward) are affected by these changes. It can be clearly noticed how the phase lag between the blades is not anymore equal to 120° and the amplitude of the damaged blade is higher than the ones of the other two blades. The second strategy is based on the curvature of the mode shapes (second derivative) which demonstrated to be a very good damage indicator for beam-like structures such as a wind turbine blades. It allows to identify the presence of a damage, its position and its extension. The intersection between the curvature in the undamaged and damaged case indicates the beginning and the end of the damaged area.

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