Spectral Finite Element Method for Propagation of Guided Elastic Waves in Wind Turbine Blades for SHM Purposes

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ABSTRACT

Certain results of numerical simulations obtained by the use of the spectral finite element method in time domain are presented by the authors. They were selected in order to show the effectiveness of the spectral finite element method for investigation of problems associated with propagation of guided elastic waves in a wind turbine laminated composite blade. Results of these simulations were subsequently evaluated in order to detect and localise simulated damage in the form of cracks or delaminations.

INTRODUCTION

Wind turbine blades made out of laminated composites are very sensitive to fatigue cracks or impact damage. Specific environmental conditions together with large costs of their failures results in intensive research that aims to ensure their safe and long–time operation. An interesting approach used to increase the strength and durability of wind turbine blades comes from the application of various structural health monitoring (SHM) techniques. These techniques are meant to provide necessary information about the state of the blades as well as the location, size and extent of potential damage offering crucial information and help in order to estimate the operational remaining life time of the blades [1–3].

A very promising SHM technique used nowadays for that purpose is the technique based on the propagation of guided elastic waves and their coupled interaction with damage. Guided elastic waves can propagate for relatively long distances as wave packet signals and allow one not only to detect small scale damage, but very often also to differentiate and classify damage thanks to the conversion of propagating wave modes at structural discontinuities [4–6].

In the case of wind turbine blades numerical simulations of these complex

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coupled interaction phenomena can be a source of very interesting and important information that can help further development of new, and improvement of the existing, SHM systems used in the field. It is worth to mention that many traditional modelling approaches based on the use of the finite differences fail at complex geometries, while at the same time the classical finite element method breaks down for high frequency signals as are guided elastic waves. Contrary to this the spectral finite element method in time domain, as originally proposed by Patera in 1984 [7], is very well suited for such problems as is investigation of the phenomena associated with wave propagation in structures of complex geometries. The method originates from the application of spectral series for solution of partial differential equations [8, 9], while at the same time its basic ideas are very similar to the classical finite element approach The characteristic feature of the method is the use of special approximation polynomials (based on orthogonal Legendre polynomials) together with the Gauss–Lobatto–Legendre points integration numerical rule. As a consequence of that the inertia matrix obtained in this spectral approach is diagonal making the total cost of any numerical calculations much less demanding. Additionally, thanks to the discrete orthogonality of the approximation polynomials the spectral finite element method in time domain is characterised by exponential convergence. Because of all these properties, robustness and flexibility nowadays the spectral finite element method is frequently used to solve various problems in fluid dynamics [10], heat transfer [11], acoustics [12], seismology [13], etc.

Certain results of numerical simulations obtained by the use of this approach and presented by the authors were related with propagation of guided elastic waves in a scaled model of a laminated composite wind turbine blade, scaled down 10 times for the purpose of numerical and experimental investigations, in order to detect and localise damage in the form of small cracks or delaminations. Various damage and excitation scenarios were considered by the authors in this study together with signal processing techniques that can next be applied for damage visualization purposes.

NUMERICAL SIMULATIONS

Numerical model

Figure 1 shows the geometry of the composite wind turbine blade under investigation. The skin of the blade was assumed as made of 6 layers of glass–epoxy composite [14] with equal thickness and orientation [0°/90°/±45°/0°/90°]. The resulting total thickness of the blade was 3 mm, while the relative volume fraction of the reinforcing glass fibres was assumed as 0.4.

Based on this geometry a numerical model of the structure was built. For this model the total number of 2160 isoparametric shell spectral finite elements was employed, previously developed by the authors (36–node shell elements of 6 degrees of freedom per each node according to the classical shell theory [6]). This resulted in the total number of 275,000 degrees of freedom of the numerical model.

As structural damage to the wind turbine blade two types of failures were considered. As the first an open transverse fatigue through–crack was taken into account [6] located at the distance 30 mm from the left end of the blade, marked as L_1, modelled by separation of appropriate element nodes. Its total length was 15 mm. As the second a delamination of layers was assumed, located at the same distance L_1 for the left end of the blade, position between the 3rd and 4th layer, covering the total area of 210 mm^2, and modelled by degradation of the elastic properties within appropriate material layers that are associated with shear stresses.

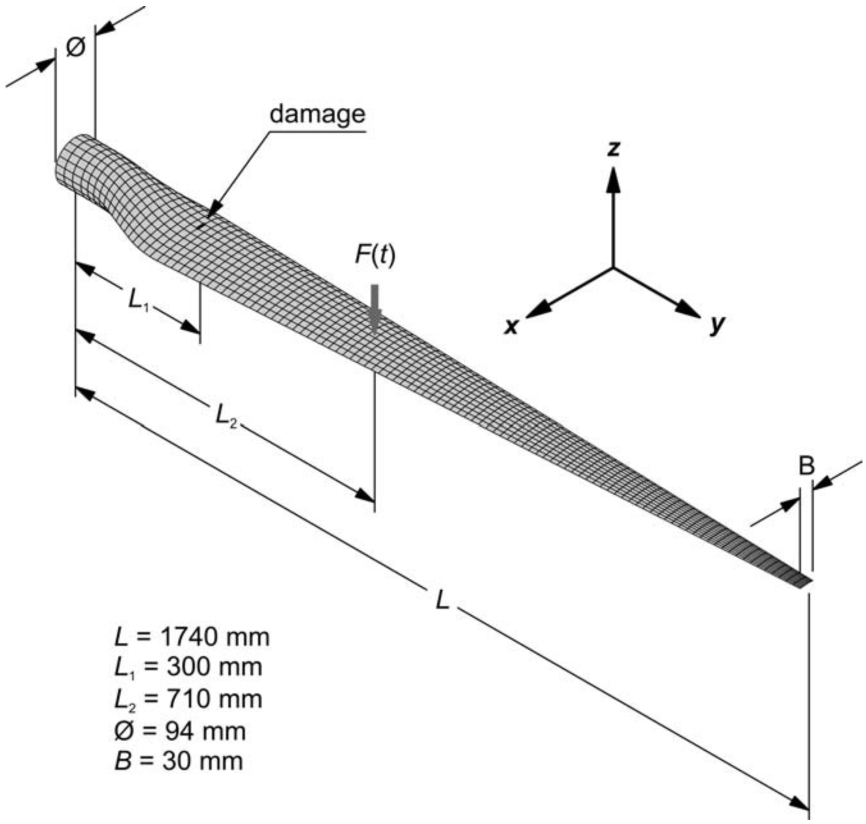

Figure 1. Geometry of a laminated composite wind turbine blade.

Strong structural damping observed in the case of laminated composite materials can drastically reduce the wave propagation distance. Due to this fact and based on results of experimental observations it was decided to reduce the carrier frequency of the excitation signal $F(t)$ in order to minimise this undesired effect. As a consequence as the signal excitation $F(t)$ a transverse 15 kHz 5 period sine force pulse modulated by the Hann window was considered. The amplitude of the excitation was 1 N. Boundary conditions of free type were used.

The total computation time T was assumed as covering 1.5 ms and was divided into 24,000 equal time steps. In order to solve the equation of motion the central different method was chosen as the most effective time integration scheme due to the diagonal form of the global inertia matrix.

Calculation programme

The main objective of the calculation programme was not only to demonstrate the effectiveness of the spectral finite element method in time domain but also to demonstrate the application of the RMS measure for damage detection based on small disturbances in wave propagation patterns that can be observed. The application of RMS maps seems particularly attractive in the case of wind turbine

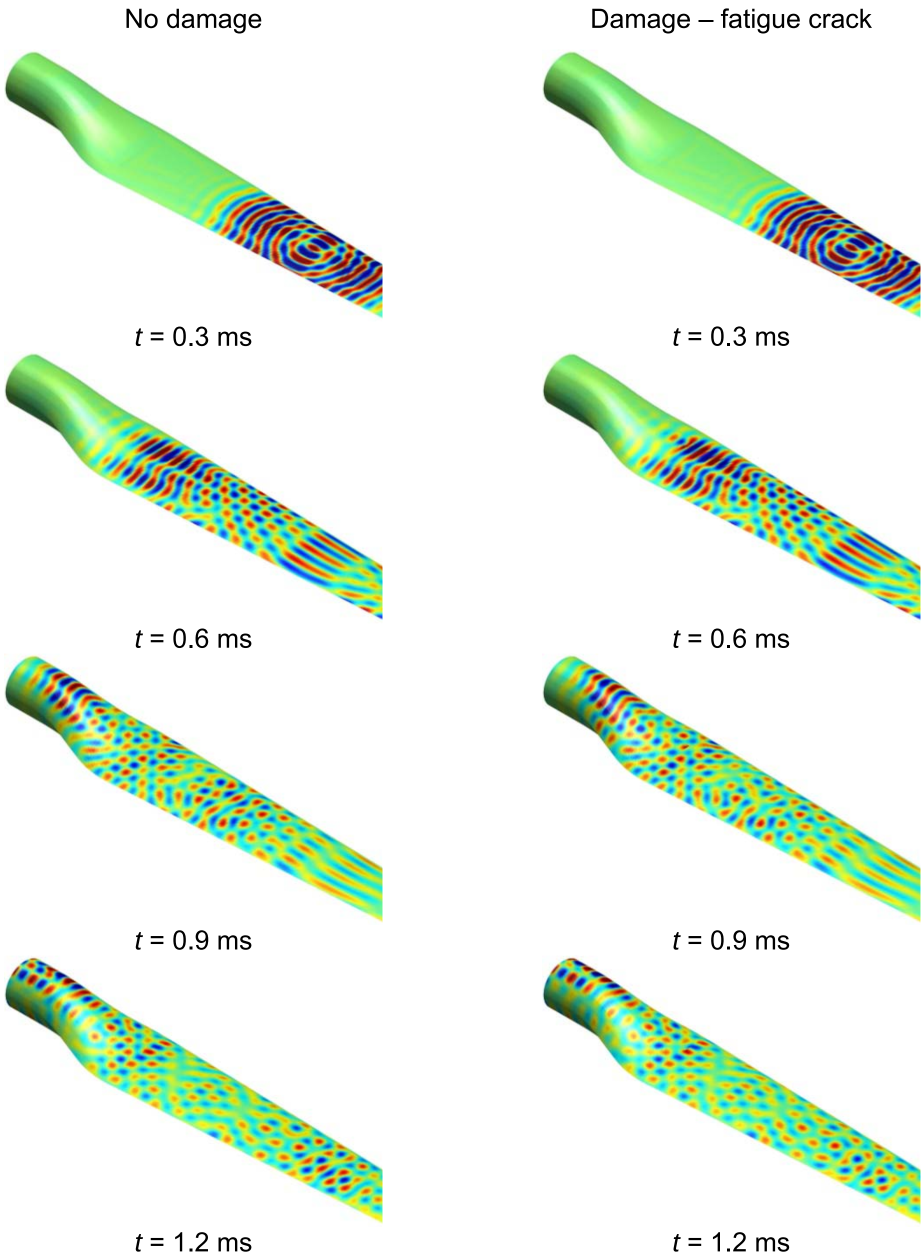

Figure 2. Wave propagation patterns obtained for a laminated composite wind turbine blade based on the transverse displacement component.

blades as structures of very complex geometries, where classical SHM approaches based on the use of phased arrays or pitch–catch techniques turned to be unsuitable due to multi–mode characteristics of propagating signals as well as multiple mode conversions and boundary reflections.

First results of numerical calculations are related with propagation of guided elastic waves within the wind turbine blade with no damage as well as in the case of the presence of the open transverse fatigue through–crack. They are presented in Fig. 2 as snapshots taken at various time instances for the transverse displacement component only.

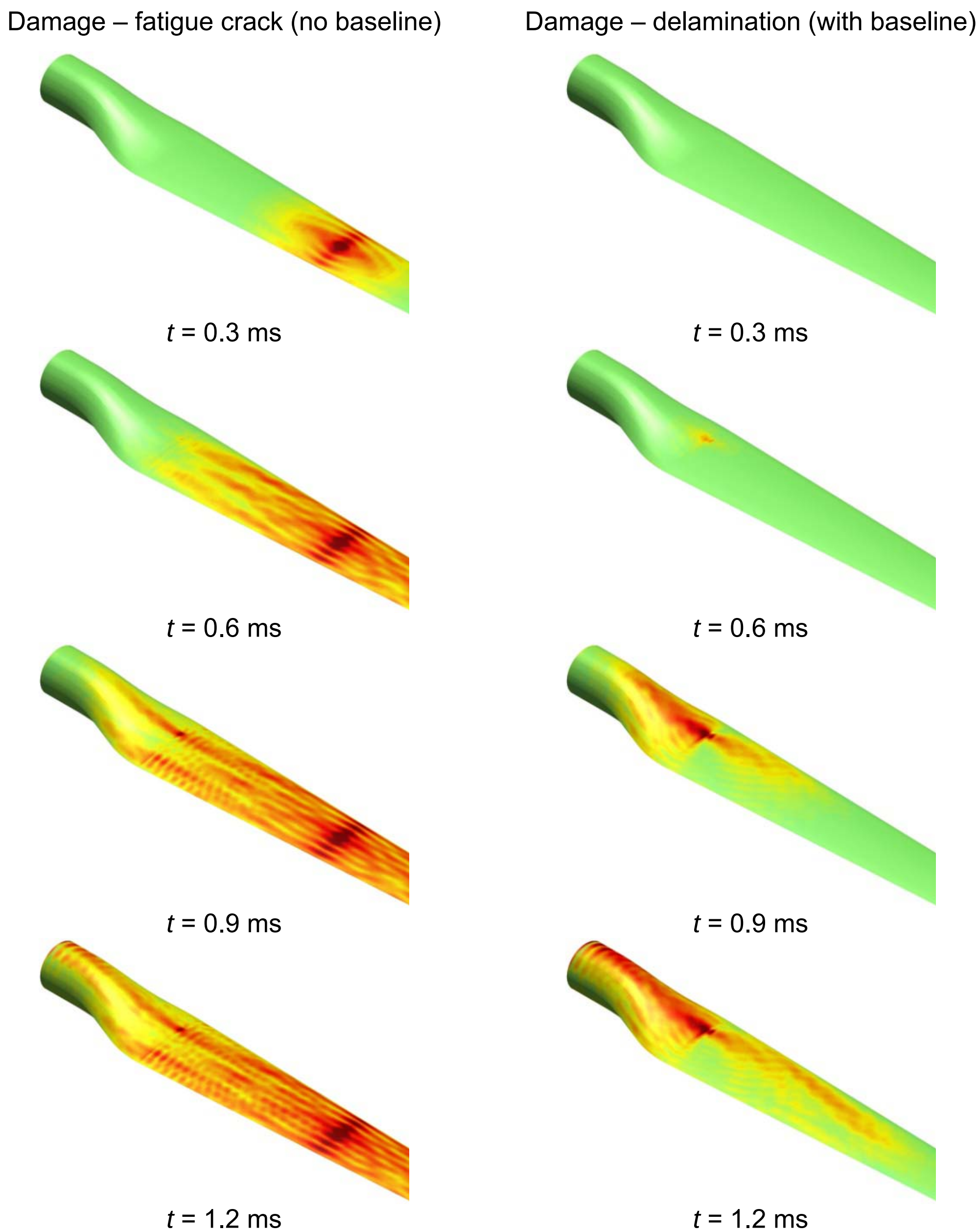

Figure 3. Evolution of RMS maps calculated for a laminated composite wind turbine blade based on the transverse displacement component.

As can be seen from Fig. 2 the wave propagation patterns are only moderately affected by the presence of the crack. This is most clearly visible at the time instance $t = 0.6$ ms. This result, significantly different from similar results obtained for structural elements of simpler geometries as plates or pipes, is strongly affected by both directional material properties as well as geometrical complexity of the blade itself. Due to the relatively high length of the blade in comparison with its other dimensions, propagating elastic waves are strongly affected by structural boundaries at the very early stage of the wave front development. For this reason classical SHM approaches usually fail in such circumstances.

In the case of a known baseline state of the structure under investigation the problem mentioned above can be avoided in a relatively straightforward manner, if only appropriate signal processing techniques are employed in order to remove any noise from the signals being subtracted. On the other hand RMS maps, because of their white noise filtering properties, come as a good alternative.

The following examples of numerical calculations concern the evolution of the RMS maps based on the calculated wave propagation patters for the case of the wind turbine blade with the open transverse fatigue through–crack as well as the delamination. They are presented in Fig. 3 as snapshot taken at various time instances also for the transverse displacement component. Detailed information about various definitions and calculation routines used for RMS maps can be found in [15]. From Fig. 3 it can be noted that both types of damage could be successfully detected and localised, however, it should be reminded that damage in the form of delamination presents a serious challenge due to very small amplitudes of signal disturbances observed in the transverse displacement component.

CONCLUSIONS

The application of the spectral finite element method in time domain for analysis of wave propagation patterns in a laminated composite wind turbine blade was successfully demonstrated. Two different numerical examples were considered showing the effectiveness and robustness of the approach proposed by the authors and comprising wave propagation analysis in the blade with an open fatigue transverse through–crack as well as delamination.

Based on the results of numerical simulations it can be stated that both types of damage could be successfully detected. However, in order to accomplish this task application of appropriate signal processing techniques was required. As shown in this work one of such signal processing techniques can be a technique be based on calculation of RMS values of wave propagation signals registered over the whole or selected area of the blade leading to so–called RMS maps. It should be mentioned that practically such measurements can be performed on real structures of complicated geometries by using laser scanning vibrometry. Thanks to the application of RMS maps all undesired effects resulting from geometrical complexity of the blade, directional properties of blade material and noise influence may be easily overcome. In special cases additional information about the baseline state of the structure under investigation can additionally enhance damage detection sensitivity of the approach proposed by the authors. In SHM practice this type of information is usually gathered during required planned periodical inspections of the monitored structure enabling one to track the evolution of any previously detected damage.

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