A BENCHMARK FOR VIBRATION-BASED STRUCTURAL DAMAGE ASSESSMENT OF COMPOSITES USING WAVELET ANALYSIS

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ABSTRACT

The presented benchmark is a result of 5-year simulation and experimental studies on damage assessment in composite structures. In a group of cases the damage was modelled using finite element analysis software, while the other group of results was obtained during bench tests. The benchmark consists of 143 problems of damage detection, localization and identification in beam-type and plate-type structures with various types of damage including cracks and notches, surface damage, delamination, impact damage etc. Applied algorithms use the modal shapes of vibration of tested structures with damage as an input, and using developed wavelet-based methods the diagnostic information about the damage presence, its location and type is obtained during the analysis. Numerous methods based on various types of wavelet transforms are available for the analysis of damage presence and location basing on modal shapes of vibration. They include classical wavelet transforms (continuous, discrete, stationary and undecimated ones) as well as more advanced transforms like fractional discrete wavelet transform or quincunx wavelet transform. Some of these algorithms are combined with optimization procedures, which allow to select optimal parameters of wavelets in order to improve detectability of damage. Several additional benchmark problems consist of 3D problems obtained from computed tomography. The wavelet-based algorithms are applied there in order to detect, localize and classify internal defects in composite structures. The graphical user interface in Matlab environment was provided for testing purposes of the benchmark.

1 INTRODUCTION

Increasing demands to integrity and safety of composite structural elements being in operation in aircrafts and other vehicles has induced the development of non-destructive testing (NDT) methods, which should be sensitive to various types of damage occurring in composites considering the specificity of their different internal structures and the specificity of damage initiation and propagation. These methods should also fulfil additional criteria, e.g. they should allow for early damage detection and identification; should be reference-free (i.e. the conclusion about the damage presence, its type and shape should be determined basing only on results of inspection of a damage structure without necessity of its comparison with a healthy structure or a model); they should allow performing the testing procedures in environmental conditions and be inexpensive.

From a great variety of NDT methods developed to-date a group of methods based on vibration testing with advanced processing of measured signals seem to fulfil above-mentioned criteria and can be successfully used both for laboratory tests as well as in industrial studies. The acquisition of experimental data is usually based on the modal analysis. The classical modal analysis, i.e. the analysis of changes in natural frequencies and modal shapes when the tested structure is excited to vibration by an external source, can be considered only if a damage is sufficiently large. Moreover, this approach is not reference-free and allows for detection of damage only. Considering additional factors, e.g. the great variability of mechanical properties of composite structures, the testing approach which bases on evaluation of changes in natural frequencies of a tested structure is not effective in engineering applications.
A great potential of vibration-based NDT lies in the analysis of modal shapes of vibrations. Usually the resonant shapes are taken into consideration, however it is not a necessary condition for such analysis. The idea of damage assessment based on modal shapes is that a damage occurred in a tested structure causes local changes in its stiffness, the modal shapes reflects such changes much better than natural frequencies. Several studies on analysis of curvature of modal shapes can be found in available literature [1]. However, these changes depend on size of damage and in case of small damage the changes in modal shapes are not recognizable. In order to detect, localize and identify the damage properly, additional signal processing procedures are necessary. Several approaches have been applied in such problems to-date. A simple and quite effective approach is based on higher-order derivatives of modal shapes of vibration. Although, this approach has numerous disadvantages such as error propagation and amplification, quite low sensitivity and difficulties in results interpretation, it can be successfully used in numerous applications. Several attempts in this area were presented in [2-4]. In order to improve the sensitivity of this approach to structural damage detection various techniques have been applied to-date. The approach originated by Ratcliffe [5] was based on application of modified Laplacian operator on modal shapes of vibration, which allows for detection and localization of structural damage. The authors of [6] have developed the curvature damage factor, which indicates the nodal position of a damage basing on comparison of healthy and damaged structure. An original algorithm of precise detection and localization of damage in beams was proposed by Chandrashekhar and Ganguli [7]. Another interesting approach was presented by Sazonov and Klinkhachorn [8], where the authors used strain energy mode shapes in order to detect and localize damage. This approach reveals relatively high sensitivity and accuracy in damage detection and localization.

One of the most promising approaches used for structural damage identification (SDI) in composites is based on wavelet analysis. This approach involves application of wavelet transform to modal shapes of vibration. It has gained a great popularity over the last decade mainly due to the outstanding sensitivity and ability of identification of abrupt changes in modal shapes caused by local changes of stiffness of a tested structure. The first studies on application of wavelet analysis for SDI were reported in late 1990th [9]. Most of early studies of wavelet-based SDI were based on the continuous wavelet transform (CWT) [10,11]. The studies using CWT-based approach were then continued by the Greek scientific group. The researchers from this group studied the influence of applied wavelet during SDI in beams [12] and plates [13] and found that it has a great impact on sensitivity and thus detectability of damage. Independently, the studies on application of CWT-based approach in SDI problems were performed by the Polish scientific group. Rucka and Wilde performed experimental studies on SDI in pre-damaged beams and plates using spatial CWT-based approach [14]. They also presented a comparative study of various wavelets applicable to the investigated problem with respect to specific parameters of wavelets: number of vanishing moments, symmetry and a width of the effective support. Basing on this comparative study they selected Gaussian and reversed biorthogonal wavelets as the most effective for the CWT-based damage identification.

Additional approach of wavelet-based SDI developed by Zhong and Oyadiji uses stationary wavelet transform (SWT). SWT has several limitations with respect to CWT (e.g. orthogonality and a compact support of applied wavelets), however it is more computationally efficient and more accurate in SDI problems than CWT. The authors applied their SWT-based algorithm for detection and localization of cracks in simply-supported beams [15] with high accuracy. The authors stated that their approach had better detection and localization abilities than CWT-based algorithms and the algorithms based on the discrete wavelet transform (DWT).

Several studies were also performed using DWT-based approach. Probably the first application of this approach to SDI in composites was presented by Sung et al. [16], where the authors used DWT for detection of low-velocity impact damage. Then, DWT-based approach has not been developed except the hybrid SDI algorithm of combination of CWT and DWT proposed by the authors of [17]. The first attempts in application of DWT-based algorithms were made by the author of this paper. Several experimental studies were performed on cantilever composite beams with single and multiple damage using DWT and B-spline wavelets [18]. Then, the approach was extended to 2D problems and verified both on numerical as well as on experimental modal shapes of vibration of pre-damaged composite plates [19]. Although DWT has several limitations with respect to CWT (same as for SWT-CWT – mentioned above), CWT and SWT are redundant with respect to DWT. The results of comparative
analyses performed for the mentioned transforms and a lifting wavelet transform (LWT) have proved that DWT is the most effective transform in SDI problems [20]. The comparative studies also cover the estimation of the effectiveness of particular wavelets applied for SDI of numerical modal shapes of a rotor blade with two locations of cracks.

Recently, the improvement of wavelet-based SDI algorithms has been basing on adaptation novel transforms and hybridization of the existing ones with supporting computational methods including the approaches based on soft-computing and artificial intelligence. An effective approach in SDI problems was proposed by Bagheri et al. [21], who used a discrete curvelet transform in order to detect a crack-like surface structural damage. Several studies on improvement of SDI algorithm were performed by the author’s team. The novel approaches in wavelet analysis were adapted for SDI problems, e.g. the discrete multiwavelet transform (DMWT) [22], quaternion wavelet transform [23] (HWT) and quincunx wavelet transform (QWT) [24] were used for damage identification in composite structures. Considering the great properties and results obtained by Unser and Blu [25], who originated the fractional discrete wavelet transform (FrDWT), this approach was adapted to SDI problems. The first studies were performed on numerical modal shapes of a cantilever composite beams [26] and obtained results revealed a significant improvement with respect to previously applied algorithms. Further, the algorithm was extended for 2D SDI problems basing on the transform developed by Chaudhury and Unser [27] and applied for identification of various types of damage in composite structures [28,29].

Due to the intensively developed wavelet-based algorithms for SDI problems over the last years it was essential to develop a benchmark, which contains numerical data and data obtained from the vibration tests for testing of new algorithms. The detailed description of the benchmark capabilities with several examples are presented in the further part of this paper.

2 BENCHMARK GENERAL OVERVIEW

The Wavelet-based Structural Damage Assessment (WavStructDamAs) benchmark is a Matlab®- based GUI application, which consists of the algorithms of various types of wavelet transforms and supporting tools and can be applied to the experimental and simulation data obtained during vibration-based testing of composite structures in order to detect various types of damage. In order to make the benchmark available for a wide community it was fully automated, that no programming is necessary for using it. Moreover, it is freely distributed both in the form of Matlab® routines as well as a stand-alone application, which does not require the Matlab® environment. The benchmark includes 143 example problems of various composite structures with various possible damage that may occur (cracks and notches, voids, delaminations, impact damage). Most of them were described in separate papers listed on the home-page of the benchmark: http://ipkm.polsl.pl/wavstructdamas (the optimization studies were not included into the benchmark due to the very time-consuming algorithms – they are available upon request).

The benchmark is based on the Matlab® environment with using the Matlab® Wavelet Toolbox™. Several wavelet transforms were implemented for various problems: for 1D problems – CWT, DWT, SWT, undecimated discrete wavelet transform (UDWT), dual-tree (complex) wavelet transform (DTWT) and FrWT; for 2D problems – DWT, SWT, UWT, DTWT, DMWT and QWT; for 3D problems – DWT and DTWT. Additional post-processing tools cover the boundary effect removal functions and a tool for performing the isotropic analysis (i.e. addition of coefficients after decomposition) using four algorithms. At every stage of processing the data can be exported to the Matlab® workspace (or to the text file in the case of stand-alone version), which does not limit the user to perform additional analyses or modify the existing routines.

The main objective of WavStructDamAs benchmark is to enable comparing the wavelet-based algorithms applied for the structural diagnostics and damage assessment of composite elements as well as analysis of detectability of various damage types using the vibration-based testing and wavelet-based processing of measurement data. The benchmark is intended to be applied for supporting the vibration-based structural diagnostics in laboratory, academic and industrial environment. A possibility of uploading own user data causes that WavStructDamAs can be used also as a toolbox.
3 EXEMPLARY BENCHMARK PROBLEMS

In order to demonstrate benchmark functionality the analyzes of several SDI problems using WavStructDamAs are presented. The first demonstration is performed on numerical data of modal shapes of laminated composite beam with a single crack (see [26]). The analysis was performed using DTWT-based algorithm. After performing the analysis the damage is detectable, however, the resulted coefficients are highly biased by the boundary effect. In order to remove this effect the boundary effect removal tool was applied. The periodization technique was applied for the signal extension (10 points). When analyzing the obtained results one can observe that the 3rd and 5th modal shapes are sensitive to the damage. In order to visualize the results of SDI for the discussed demonstration problem the isotropic analysis was performed, where all obtained detail coefficients were squared and added up. The resulted view of a benchmark window is presented in Fig. 1.

![Figure 1: A benchmark window with results of SDI of a single crack in a composite beam.](image)

The next demonstration of benchmark performance is based on example problem of debonding between a core and a face sheet in a sandwich plate following the case described in [29]. Four modal shapes are available for this example problem. The analysis was performed using 2D DWT-based algorithm with the B-spline wavelet of order 3 as a single-level decomposition. After performing the analysis the absolute values of obtained horizontal and vertical coefficients were added up. A window with obtained results is presented in Fig. 2. The square-shaped debonding can be easily identified.

The benchmark allows for analysis of circular-shaped structures. In the next demonstrated example problem the circular laminated composite with PTFE sector-shaped inclusion is analyzed (for instance see [30]). The analysis was performed using 2D FrWT-based algorithm using wavelet of order 0.45 and a shift factor of 0.9 on selected modal shapes of a plate (2-5, 7 and 10-12). Afterwards, from the obtained coefficients the real and imaginary ones of types 1-4 were added up for the considered modal shapes. The sector-shaped PTFE inclusion is detected and localized properly (see Fig. 3).
Figure 2: A benchmark window with results of SDI of debonding between a core and a face sheet in a sandwich plate.

Figure 3: A benchmark window with results of SDI of a stiff inclusion in a circular composite plate.

One of the 3D example problems is also demonstrated. The analysis was performed on data obtained from computed tomography of a carbon fibre-reinforced composite plate with a hole and delamination (the study is described in [31]) using 3D DWT-based algorithm. A biorthogonal spline wavelet of order 3.3 is applied. The performed decomposition allows for detection of delamination directions in particular cross-sections of the tested plate. In Fig. 4 the exemplary results are shown. Obtaining the detail coefficients of type 4 (detail-detail-approximation) allowed detecting the
The performance and capabilities of WavStructDamAs benchmark is not limited to the demonstrated cases and can be used both for studying of available example problems as well as own problems (which can be uploaded by user) using available wavelet transforms and supporting tools for wavelet-based SDI.

4 CONCLUSIONS

Basing on the results of numerical and experimental studies performed by the author and his collaborators over the last five years the WavStructDamAs Benchmark has been developed and implemented in Matlab® environment. The developed benchmark has several advantages. First of all, it contains 143 example problems based on numerical and experimental data obtained from testing of real composite structures with a wide range of types of possible damage. Making this data openly available the researchers in the SDI field can test the implemented algorithms or use their own ones to this data. Moreover, it is possible to upload own user data, thus WavStructDamAs can be used as a toolbox. Finally, the benchmark has been developed as a fully GUI application, thus the coding for performing the analyses is not necessary. This creates a possibility of performing analyses easily and quickly and additionally using the benchmark by unexperienced Matlab® users. The benchmark is distributed as an open-source software (users are able to modify and/or use available code in their own application) and a stand-alone application, which does not require Matlab® installed on the user’s system. The benchmark can be useful for researchers working in the area of non-destructive testing, structural damage assessment and structural health monitoring as well as for students attending to the corresponding university courses.

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