Damage detection in composite structures by multipoint measuring system using guided wave propagation method.

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Abstract. In this paper, the elastic wave propagation method was used in damage detection in composite cylindrical panels. The multipoint measuring system based on surface-mounted piezoelectric transducers was applied in the multistage measurement of the elastic wave propagation. The damage index definition based on the correlation coefficient was used to determine the state of the structure including localization and estimation of the damage size. Application of the PZT elements as actuators and sensors allows building a low-cost damage detection system that can be used in structural health monitoring (SHM) of composite parts. The resolution of the damage detection results depends on the number and localization of the sensors. However, the application of the multistage wave propagation analysis makes possible to improve the damage detection accuracy without raising the SHM system costs.

1. Introduction

The guided wave-based damage detection techniques are developed from the decades with other structural health monitoring (SHM) methods because of dynamic changes in the material engineering and manufacturing methods. Application of the advanced structures like composites which are characterized by a great number of possible failure forms leads to the increase in the importance of monitoring techniques in the design process. The fundamental axioms of the structural health monitoring methodology in damage detection were presented by Worden [1]. An effective SHM system based on wave propagation phenomenon should take into account several issues like signal processing, feature extraction, and data fusion techniques [2,3]. During the past decades, extensive researches were conducted in damage detection based on a structural dynamic characteristic of the analyzed structures [4-7]. Despite technological progress, the accuracy and effectiveness of non-destructive methods still do no give complete satisfaction. The assessment of the usability of particular measurement techniques in different applications is also analyzed in the literature [8,9]. The Lamb wave propagation method is successfully applied to damage detection in composite structures [10-13]. An accurate localization and damage size assessment in the curved composite panels is possible by application of the damage index with the wave propagation path definition [14]. Different measurement techniques were developed and effectively used in different materials and defects types. The pitch-catch technique is usually used in the inspection of the relatively small area [15]. The pulse-echo method is suitable for long distance wave propagation in structures like pipelines or marine structures [16]. Data analysis based on different statistical parameters and signal processing methods was validated in engineering applications. A lot of interest is concentrated around the time reversal
data analysis [17], time-of-flight (ToF) parameter [18] and a direct comparison of the pattern signal with the signal from the potentially defected structures. All mentioned analysis techniques allow for straightforward signal analysis in time-domain which is convenient from the practical application point of view. The detectable damage size is determined by the relation between the size of the analyzed part and the PZT transducers number. The sensors number is a crucial parameter in the assessment of the cost and usability of the damage detection system. The different approaches were considered in the literature to obtain the optimal configuration of the SHM system [19,20]. A summary of the sensor placement [21] and a current review dealing with the transducers localization optimization [22] can be found in the literature.

In this paper the active pitch-catch measurement technique was used in damage detection, localization and size assessment in the composite cylindrical panels. The multipoint measuring system based on the piezoelectric transducers was built. The multistage measurement without the change of the SHM system configuration was taken into account. The damage index based on the correlation coefficient was introduced in signal processing. The definition containing the information about transducers localization and the wave propagation path between current actuator and sensors made possible to determine the visualization of the damage index distribution that is especially valuable in the permanent monitoring of the structure during normal service life.

2. Experimental setup

The main assumption formulated in the SHM methodology axioms is the necessity of the comparison of two structure state. Generally, damage detection systems were classified into several levels of analysis. The systems of the first level allow only to confirm the presence of the damage. The main task of the second level system is to determine the localization and orientation of the defect. The assessment of the damage size is the aim of the third level systems. The mentioned levels create the diagnosis part of the damage detection systems. The data from the diagnosis part can be applied to determine the remaining life of the structures (the fourth level) in the prognosis part of the SHM. In this paper, the wave propagation phenomenon is compared with signals obtained from the intact structure to build a third level SHM system. The typical wave propagation analysis procedure is demonstrated in Figure 1.

![Figure 1. The wave propagation analysis procedure.](image)

On the measurement stage, one can observe the influence of environmental conditions like temperature or noise, etc. Both, the pattern signal and currently analyzed signal are prone to similar, predictable effects that can influence the final form of the measured data. Application of the specific excitation signal with defined frequency allows one to prepare the noise reduction filters which reduce the signal disturbance. The power amplifier is responsible for setting a signal amplitude which level is essentially higher than the measured noise. Feature extraction of the analyzed signal consists in the registration from all measured data information valuable for damage detection procedure. The direct comparison of the pattern signal and signal from potentially damaged structure allow one to obtain the
damage index value which gives quantitative or qualitative information about damage detection. Further signal processing depends on the assumed level of analysis and SHM system requirements. Figure 2 presents the schema of the proposed third level damage detection system.

![Figure 2. SHM system scheme based on the wave propagation method.](image)

The composite cylindrical panel was made of glass woven roving having the following properties: $E_{\text{long}}=E_{\text{circum}}=13.14$ GPa, $G_{12}=4.1$ GPa, $\nu_{12}=0.25$, $\rho=1100$ kg/m$^3$. The length of a panel was equal to $L=310$ mm, the mid-surface radius $R=92$ mm and thickness of the structures was $t=2$ mm. Analyzed specimens had different defects in the middle obtained during the uniaxial compression tests. The set of ten piezoelectric transducers determined the area of analysis (Figure 3).

![Figure 3. Composite panels with defects and configuration of the SHM system.](image)

A tone burst excitation signal modulated by a Hanning window was formulated as follow:

\[
f(t) = \frac{1}{2} \left(1 - \cos \left(\frac{\omega_0 t}{N_c}\right)\sin(\omega_0 t), \ 0 \leq t \leq N_c/f_0\right)
\]  

where $f_0$ is the excitation frequency, $\omega_0 = 2\pi f_0$, $N_c$ is the number of cycles. The classic form of the modulating window allows concentrating the energy to the defined excitation frequency limiting the dispersion phenomenon. The excitation frequency was equal to 100 [kHz]. Relatively small area of analysis as well as the assumed wave generation method cause that only antisymmetric $A_0$ wave mode was taken into account. The damage index definition based on correlation coefficient ($\lambda_{xy}$) with the wave propagation path defined in the form of ellipse between actuator and sensors was defined as follows:

\[
DI(x, y) = \sum_{n=1}^{N} \left(1 - \lambda_{xy}\right) \left(\frac{\beta - R(\Omega)}{\beta - 1}\right)
\]  

where

\[
R(\Omega) = \begin{cases} 
R_c(\Omega), & R_c(\Omega) < \beta \\
\beta, & R_c(\Omega) \geq \beta
\end{cases}
\]
\begin{equation}
R_c(\Omega) = \frac{\sqrt{(x-x_{ak})^2+(y-y_{ak})^2}+\sqrt{(x-x_{sk})^2+(y-y_{sk})^2}}{\sqrt{(x_{ak}-x_{sk})^2+(y_{ak}-y_{sk})^2}}
\end{equation}

\Omega = [x, y, x_{ak}, y_{ak}, x_{sk}, y_{sk}] \text{ is a function including the localization of the actuator (} x_{ak}, y_{ak} \text{) and sensor (} x_{sk}, y_{sk} \text{). The first component of the damage index definition was responsible for quantitatively comparison of signals from the intact and defected structures. The second component defines the geometry of the SHM system (localization of the actuator and sensors). For the multipoint measuring system, the damage index based on the definition with information of transducers localization is calculated for each wave propagation path. The multistage analysis was performed. One stage means that one of the transducers was an actuator and all others were sensors. In subsequent stages, the elastic wave was generated by subsequent PZT elements. It is worth emphasizing that the change of the wave generation between particular transducers was software implemented without the necessity of change the system configuration. The final form of the damage index distribution is determined as a sum of the DI obtained for all paths calculated in the classical form.}

\begin{equation}
I(x, y) = \frac{1}{N_a} \sum_{k=1}^{N_a} D_I(x, y)
\end{equation}

3. The multipoint measuring results.

The multipoint measuring system contains ten PZT elements localized around the analyzed area. At the first stage, the first transducer (left bottom corner) was an actuator. The signals detected by the sensors were compared with the signals from the intact structure. A comparison of the signals for the first stage of analysis is demonstrated in Figure 4. The damping effect can be easily observed in the results. However, this effect is the same for both compared structure. The visible difference between measured signals was observed when the wave propagation path went through the damaged area (sensors 6 and 7). For other measurements the differences were negligible.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure4.png}
\caption{Comparison of the signals from the intact and defected composite panels for the first stage of the measurement.}
\end{figure}
The exemplary wave propagation path between actuator and one of the sensors calculated according to the formula (2) is demonstrated in Figure 5.

![Figure 5. The exemplary wave propagation path between the actuator and one of the sensors.](image)

The elliptical shape of the wave propagation path was assumed. The width of the ellipse is controlled by the $\beta$ parameter in the damage index definition. Based on the comparison of the signals the damage index value is assigned to the particular point in the predefined wave propagation path. In this way, the damage index distribution can be obtained and analyzed in further steps. It is worth pointing out that multistage analysis is necessary in this case to indicate localization and to assess the damage size. The analysis based only on the first stage of measurements allows only to determine the wave propagation paths for which the damage index achieve the greatest value. It makes possible to determine only the direction (respect to the actuator position) of the damage localization without other detailed information. However, in some SHM systems for which the damage localization is less important than simple damage detection and cost-effectiveness utilization, only one stage of analysis is also allowable. In this study, the multistage analysis was performed. Each of the transducers was an actuator in a particular stage of measurement. All measured data was then converted by the proposed damage index definition to the visual information about damage localization and size assessment. The results of the data analysis for both considered composite panels is demonstrated in Figure 6.

![Figure 6. The damage index distribution for two analyzed composite panels.](image)

Comparing presented above results of damage index distribution with the damages presented in Figure 3 one can notice the correct indication of the damage localization and size assessment. Some inaccuracy was observed on the analyzed area edge when damage is localized directly between sensors on the edge. Nevertheless presented results are promising from the permanent monitoring of the structure point of view. Proposed SHM system makes possible damage evolution monitoring in the case of periodical measurement of the composite part prone to the fatigue loading conditions.
4. Conclusions
Based on the elastic wave propagation phenomenon this paper demonstrates the application of the multipoint measuring system to the damage detection and identification in composite cylindrical panels. The straightforward signal processing in the time domain and comparison of the signals from the intact and defected structures make possible building the cost-effective SHM system based on the PZT transducers. The application of the relatively small number of transducers causes that the resolution of the damage detection results is small. However, utilization of the multistage wave propagation measurement and well-designed signal processing algorithm improve the accuracy without raising the SHM system costs. Moreover, presented SHM system allows for divide the damage detection analysis to the two steps. At one step the goal is only damage detection without detailed information about failure character. In this case, a relatively small number of actuating stages is necessary to obtain the elementary information about structure state. When the damage is detected, then in the second step the multistage analysis can be performed to determine the character of the damage (localization and size assessment). This approach is especially valuable in the case of the permanent or periodical structure monitoring where the use of complex signal processing procedures is not necessary until the damage is detected.

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