Determination of Defect Sizes with the help of Structural-Health-Monitoring Methods based on Guided Waves

Kilian TSCHÖKE [1], Bianca WEIHNACHT [1], Tobias GAUL [1], Eberhard SCHULZE [1], Lars SCHUBERT [1], Robert NEUBECK [1,2]
[1] Fraunhofer Institute for Ceramic Technologies and Systems IKTS, Dresden, Germany
[2] Institute for Geophysics and Geoinformatics, Freiberg University of Mining and Technology, Freiberg, Germany

Contact e-mail: kilian.tschoeke@ikts.fraunhofer.de

Abstract. Numerous industrial sectors request the permanently monitoring for damage of components with the least possible number of sensors. These industrial fields are construction engineering (e.g. bridge monitoring), renewable energies (e.g. monitoring of wind turbine rotor blades), chemical industry (e.g. monitoring of pipelines and storage tanks), mechanical engineering, vehicle manufacturing, aerospace industry (e.g. monitoring of lightweight structures) and others more.

The diagnosis of components for internal failures can be carried out with different NDE methods depending on the material and the defect size. Examples of such methods are X-ray, the pulse-echo-ultrasonic method, for certain kinds of materials magnetic particle inspection, eddy current methods, as well as radar and Terahertz methods. However, these methods are of limited suitability for permanent monitoring because of their limited range within the material to be monitored.

For permanent monitoring of components guided acoustic waves (also called Lamb waves) are most useful because of their large range within solid materials. Changes inside the material have great influences on the propagation conditions of the guided waves. Acoustic sensors are able to monitor large components even at a great distance from each other. Sensors and devices for the measurement of guided waves are already available. However, precise instructions for the use of these systems and the description of substitute defects are missing.

The aim of the government-funded research project QuantSHM is now to overcome these constraints of monitoring systems in order to allow the monitoring methods to be widely accepted.

Basically, research results of two fields of application will be presented. In particular these are acousto ultrasonic methods for isotropic materials (e.g. steel, pipelines) and acoustic emission methods for anisotropic materials (e.g. composites, rotor blades). Defect sizes can be clearly correlated with the defect size for isotropic materials whereas damaged areas are better addressed by acoustic emission for anisotropic materials.

Introduction

The permanently monitoring for damage of components is requested in numerous industrial sectors. Examples are construction engineering (e.g. bridge monitoring), renewable energies (e.g. monitoring of wind turbine rotor blades or offshore foundations of wind turbines), chemical industry (e.g. monitoring of pipelines and storage tanks), mechanical engineering, vehicle manufacturing and aerospace industry (e.g. monitoring of lightweight structures). The diagnosis of components for internal failures can be carried out with different NDE methods.

The choice of an appropriate NDE technique depends on the material and the defect size. One possibility is the X-ray technique which is in part complicated to apply due to the radiation safety regulations and therefore rather applied in lab applications. Another possibility are pulse-echo ultrasonic methods and Phased Array methods that are well established for aircraft components to be tested at certain time intervals. However, the component has to be well accessible to position the transducers on the surface. Especially for very curved components, testing gets more and more complicated. Further NDE methods are magnetic particle inspection, eddy current methods, radar and Terahertz methods. But all in all, these methods are of limited suitability for permanent monitoring.

For permanent monitoring guided acoustic waves are most useful, cf. [1]. Guided waves, also known as Lamb waves, are elastodynamic waves propagating along the longitudinal direction of plate and pipe like structures with minor damping compared to conventional ultrasonic testing. Due to the minor damping guided wave propagation can achieve large ranges within solids and so no direct access is necessary in the monitoring area. They propagate by specific modes with different dispersive phase velocities. Changes inside the material have influence on the propagation, so pitch-catch measurements with acoustic transducers are used to determine defect positions and sizes. The method is usually based on the comparison of received signals with a baseline and the extraction of characteristics of the difference signal. Guided wave techniques are already applied to a wide range of monitoring tasks like notch-, delamination-, abrasion- and corrosion-detection.

1. Acousto Ultrasonic methods for isotropic materials

Acousto Ultrasonic (AU) methods use guided ultrasonic waves in a frequency range between 10 kHz and 500 kHz. These methods are tested an established especially for isotropic materials like metals, e.g. for monitoring tasks at storage tanks or pipelines, cf. [2], [3].

The current work provides a concept for the determination of defect sizes in steel pipelines. The theoretical principles and basic experiments can be found in [2], [3] and [4]. More detailed research for the construction of permanently installed sensor rings for usage in harsh environments, e.g. offshore foundations of wind turbines, were published by Gaul et al. in [4] and by Weihnacht et al. in [5].

1.1 Experimental setup: Steel pipelines

The first test specimen are steel pipelines with a length of ca. 3 m. They represent the chemical industry or construction engineering as fields of application. Welded seams can be seen as weak zones, e.g. due to thermal material treating, and therefore can be regarded as potential sources of cracks. To initiate realistic cracks the test specimen were subjected to 4-point bending tests at IMA Dresden. The welded seam was planned and realized in an off-center configuration. This asymmetric measurement setup helps to avoid incoming reflections from the ends of the pipe at the same time at the corresponding sensors. The setup is given in **Figure 1**. The test stand at IMA Dresden can be seen in **Figure 2**.

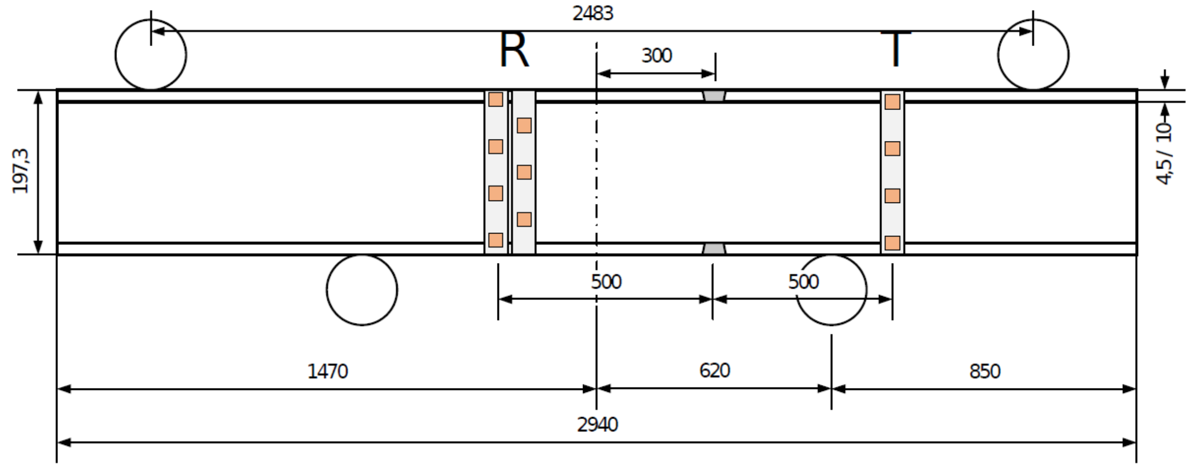

Figure 1 Dimensions of the steel pipelines used for the 4-point bending tests in section 1.1. All dimensions in mm.

In **Figure 1** and **Figure 2** the so called reflection ring (R) can be seen on the left side of the pipe. It is made of 2 rings with 15 and 12 piezoelectric transducers. They are arranged in a formation of equilateral triangles to obtain the wave incidence angle in further signal analysis steps. The distance between the transducers depends also on the wavelength of the applied ultrasonic signal of the measurement. The so called transmission ring (T) on the right side contains 13 transducers. One transducer of the reflection ring serves as actuator, the others as sensors. A sequential recording of all transmitting and recording paths gives numerous time signals for the signal processing procedures.

The chosen wavelength, the spatial distribution and the density of the network influence damage detection capabilities. All these parameter have to be selected according to the monitoring task. Based on the dimensions of the pipes used in the experiment, simulations based on finite differences algorithms were performed in order to identify suitable transducer configurations, wave modes and signal frequencies for the damage interaction of guided waves with the expected cracks.

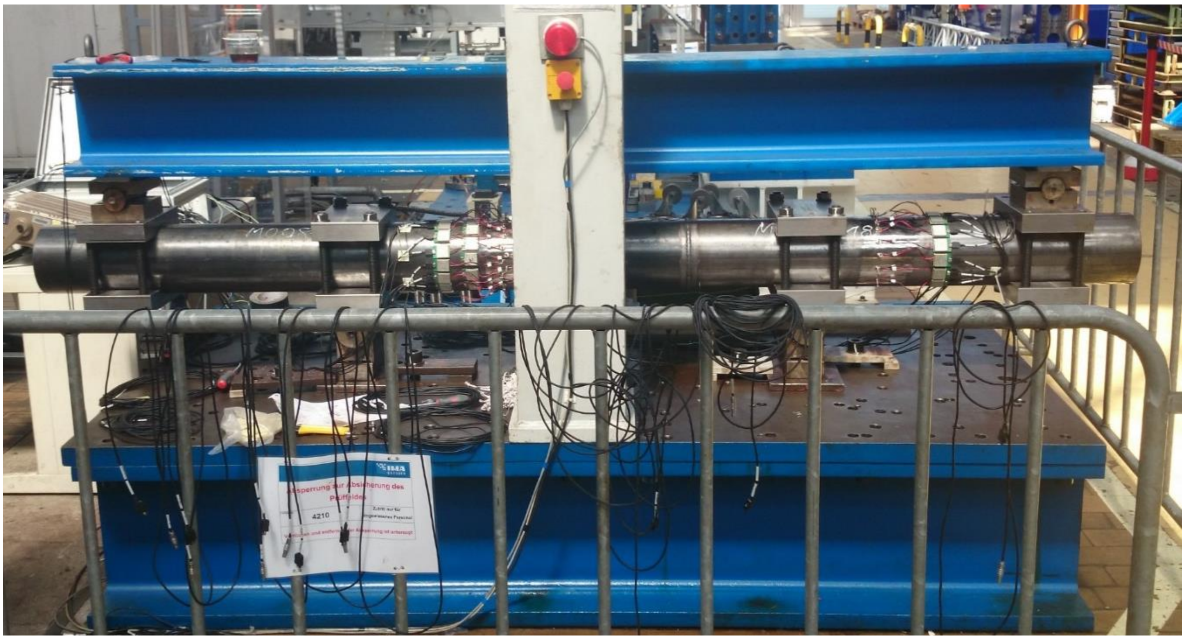

Figure 2 Test stand of the 4-point bending tests at IMA Dresden.

1.2 Detection of Defect

As mentioned before, a technique based on the use of guided waves to localize cracks in cylindrical structures was published in [4]. It is well known that guided waves propagate in several wave modes and that every wave mode induces a different interaction potential with a defect depending on frequency and elastic stress components. It is possible to separate modes in single component data sets from pitch-catch measurements by criterions like runtime or attenuation. Three options to do so are discussed in [6] and furthermore, an operator to select a certain guided wave mode in single component datasets is presented.

The pitch-catch measurements are repeated according to the expected damage growth velocity during the 4-point bending tests of the steel pipes. Using e. g. hourly measurement intervals, the growing of the damaged welded seam can be described with high time resolution. A high spatial resolution is achieved by using high frequencies with the disadvantage of shorter possible travel paths. An initial situation (baseline) must be measured to describe the undamaged situation at different load levels since the damage might be load dependent.

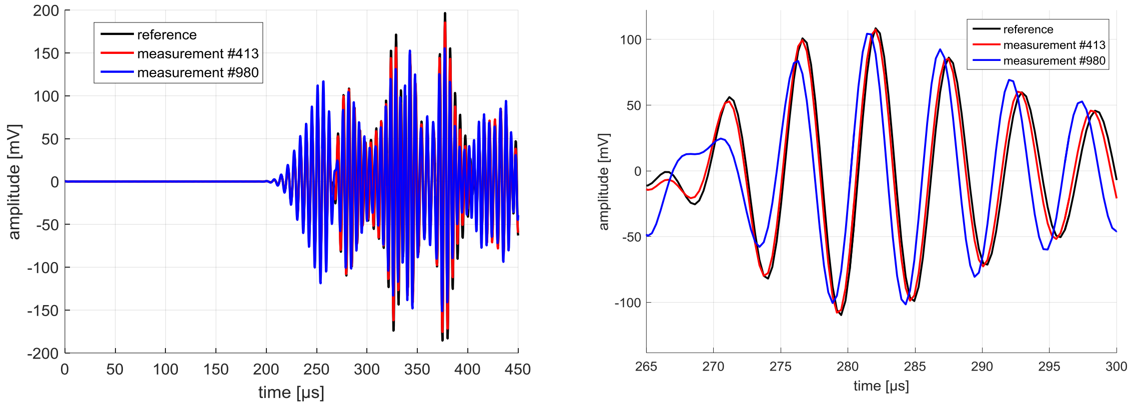

***Figure 3** Time signals of the pitch-catch measurements in section 1.1 on path actuator 8 to sensor 34, cf. **Figure 4**. Left: The whole signal after a recorded time of 450 µs. Right: Zoom into the time interval from 265 µs to 300 µs which corresponds to the L(0,1) wave mode.*

Figure 3 shows results of three measurements on the path from actuator 8 to sensor 34. The numbering of the transducers is given in **Figure 4**. A RC5 impulse with 180 kHz middle frequency was excited at the actuator. The whole time signals of the baseline and of the measurements #413 and #980 at the sensor are shown on the left side. Differences in amplitude and phase angle are noticeable. A more detailed zoom into the time interval from 265 µs to 300 µs is given on the right side. This wave package corresponds to the L(0,1) wave mode. The nomenclature of guided wave modes are given in [1]. To determine the difference between one measurement and the baseline the correlation coefficient between the corresponding time signals was evaluated. These results are given in **Figure 4** on the right side. The diagram shows the correlation coefficients for two possible paths as can be seen on the left side of **Figure 4**. It is expected that the changes in the time signal are higher in a path where the crack is directly between actuator and sensor. This consideration was confirmed as can be seen on the right side of **Figure 4**. The mode selective correlation coefficient is a clear indicator for the existence of a change on the path between two transducers. Under equal environmental conditions it is even an indicator for the existence of defects. Furthermore, it seems to be an indicator to determine crack sizes. A more detailed study is still under investigation. On the one hand with more test pipes to get a larger amount of data and on the other hand with the help of statistical analysis tools.

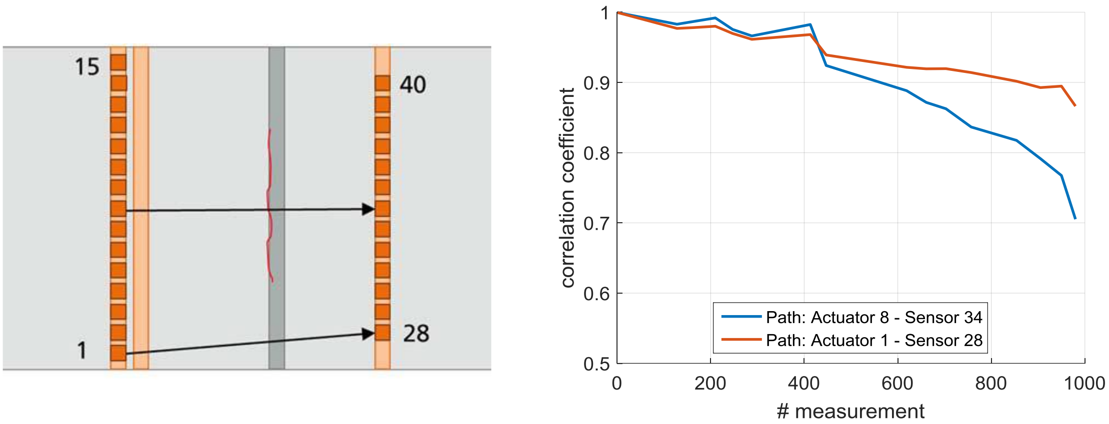

Figure 4 *Left: Draft of the numbering of the transducers within one of the reflection rings (1 to 15) and within the transmission ring (28 to 40) including the welded seam, a crack and two possible paths. Right: Correlation coefficient over 980 measurement for the given paths. The coefficient is determined by comparing the baseline and the current measurement.*

1.3 Imaging procedures

In addition to the results of section 1.2 the determination of defect sizes can be realized with the help of imaging procedures.

Usually, piezoelectric transducers measure only one scalar quantity, e.g. an electrical voltage. The displacement field of elastic waves within a solid media is in contrast characterized by three quantities, in particular the displacement or the velocity components. In the case of guided waves, this lack of information is critical under imaging conditions. Damage detection algorithms will lead to incorrect localization due to different dispersive phase velocities for each propagating mode. This is true for baseline based and also for baseline free methods.

In [6] Neubeck et al. present an approach that provides a heuristic operator to identify and to select certain Lamb modes in single component datasets measured by ultrasonic transducers. A specific pre-processing step gives the possibility to use single component imaging procedures like conventional Kirchhoff- and Fresnelvolume-Migration in a more precise manner. For more details we refer to [6].

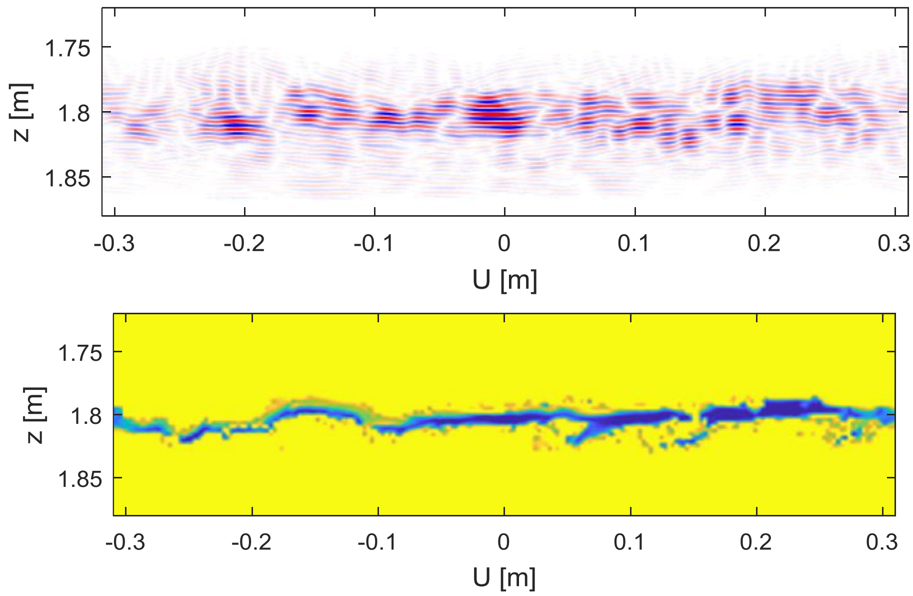

Figure 5 *Top: Results of the imaging method based on Fresnelvolume-Migration for one test crack. Bottom: High contrast photography of the corresponding crack to visualize the shape of the crack.*

One result of the imaging procedure based on reflected signals from an equivalent dataset as described in section 1.2 is given in **Figure 5**. On top the result of the Fresnelvolume-Migration is shown. On bottom a high contrast photography of the crack is shown. The shape of the crack can be recognized and moreover an estimation of its dimension is possible. Again, a more detailed study is still under investigation. Moreover, the comparison between the results of standard pulse-echo ultrasonic measurements and the imaging procedure is under progress to determine the reliability of the imaging procedure.

2. Acoustic emission methods for anisotropic materials

The evaluation of complex fiber composites regarding their current structural state is still a challenge for applications like aerospace, automotive and renewable energies (e.g. rotor blades). The technique of acoustic emission (AE) which is also based on ultrasound is one possibility to overcome this challenge.

Dynamical displacements at the surface of loaded components are detectable by highly sensitive piezoelectric transducers in the frequency range of 10 kHz up to 1 MHz. In fiber composites a strong acoustic emission is caused by fiber cracks and delamination processes. Thus, the AE method is successfully applied especially for fiber composite monitoring. Results of AE investigations for carbon fiber reinforced plastics, e.g. in automotive engineering, are presented in [7]. The current work deals with glass fiber reinforced plastics (GFRP). Therefore, occurring acoustic emissions events during tensile and bending tests have to be evaluated regarding there source and the damage mechanism leading to the emission.

2.1 GFP samples for tensile tests

For the 4-point bending and tensile tests specimen made of glass fiber reinforced plastic respectively GFRP-sandwich constructions were manufactured. These samples represent the application field of rotor blades. The samples have a length of 600 mm, a width of 80 mm and a strangling to 60 mm in the middle. **Figure 6** shows one of the sandwich samples inside the tensile test engine at IMA Dresden. The tensile tests itself were performed in steps of 500 N from 0 until the complete failure of the sample. The first step was from 0 to 500 N with 10 s of hold time at 500 N. After the stress relaxation at 0 the next step was from 0 to 1000 N with 10 s of hold time and so on. The acoustic emission results were clustered in the weighted peak frequency vs. partial power space. Due to [7] and [8] failure cases of the samples can be assigned. The results are shown in **Figure 7**.

Figure 6 *Test stand of the tensile test at IMA Dresden.*

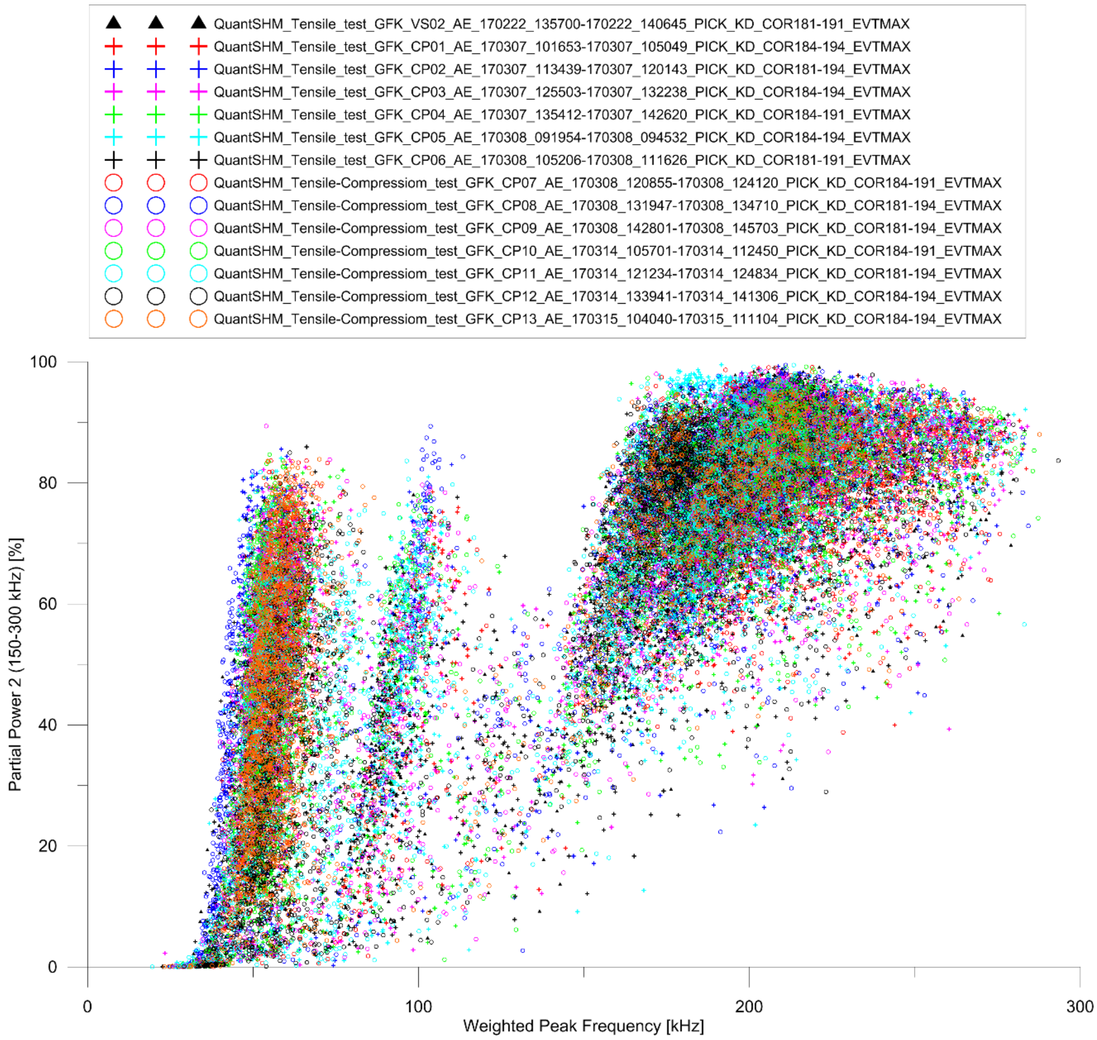

Figure 7 *Results of the AE measurements of the tensile tests with the GFRP samples as described in section 2.1. The clustering in the weighted peak frequency vs. partial power space of the acoustic events is based on the work by Hönig et al. in [7] and by Sause in [8].*

Three clusters of acoustic events are recognizable in **Figure 7**. The two clusters in the low frequency range are assigned to matrix failure and delamination, respectively. The high frequency events are assigned to fiber-matrix failure and fiber cracking. The results show that the AE technique provides suitable possibilities to evaluate the condition of complex composite structures. Moreover, the counts of amplitude peaks, the energy of an acoustic event and other AE parameters will be used to determine the appearance and the growth of defects. This study is still under investigation.

2.2 GFP samples for 4-point bending tests

In addition to the tensile tests in section 2.1 also 4-point bending tests were performed with the GFRP samples. Different types of prepared samples were used: some without damage, some with defects included.

The same procedure of clustering the acoustic events in the weighted peak frequency vs. partial power space was done and similar results as given in **Figure 7** can be received. The results only differ in the range of the weighted peak frequency per cluster, but nevertheless the three clusters can be clearly assigned.

Conclusion and Outlook

The current publication provides results of the government-funded research project QuantSHM. Two methods based on guided waves for SHM applications are presented. The AU method for isotropic materials in combination with a mode-selective signal analysis provides to determine the growth of cracks and imaging procedures help to determine their position and size. The AE method for anisotropic materials is useful to characterize and to localize defects in composites.

Next steps in the ongoing project are on the one hand a more detailed statistical analysis of the large amount of collected data to evaluate the reliability of the guided wave techniques. On the other hand a full scale test at a real rotor blade with a length of 37.5 m is under investigation to get AE data of an application with realistic dimension.

Acknowledgment

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