The virtual tap test – a training system for wind turbine rotor blade inspectors

Gaetano ANDREISEK [1], Dominik KORTHALS [1], Christian U. GROSSE [2], Bernhard U. SEEBER [1]
[1] Technical University of Munich Audio Information Processing, München, Germany
[2] Technical University of Munich Chair of Non-destructive Testing, München, Germany

Contact e-mail: gaetano.andreisek@tum.de

Abstract. Wind turbine rotor blades are some of the tallest objects among modern civil structures. In order to ensure a lifetime of fifteen to twenty years, regular testing of their structural integrity is required. Advanced methods such as ultrasonic testing or thermography can be used, however, they are difficult to apply in the field, therefore more feasible yet robust and advanced methods are sought. The so called (coin-) tap test makes use of the human auditory system and its remarkable power for analysing the acoustic environment. This method is applied in everyday field inspection of rotor blades. Experienced engineers tap on the blade shell and listen to the emitted impact sounds which carry material- as well as geometry-related information. The change and disparity of certain perceived features between two adjacent tap locations indicate the transition towards a material defect. Although advantages like simple execution and the need for minimal equipment make it a feasible method for on-site tests, it is not an objective test method. Moreover, current practice offers no training for the inspectors of wind turbine rotor blades besides "learning by doing". In this regard, experience plays a major role in robustly identifying defects in rotor blades. In order to overcome the lack of experience, this work presents a training system that aims at advancing the inspectors' ability to robustly identify defects solely on acoustic information. The tap test training system (TTTS) mimics the execution of the tap test and features various types of defects, such as delaminations or deficient bonding at the trailing edge of the rotor blade. A test phase of the new system was carried out with inspectors of varying levels of professional experience. Preliminary results show that little experience can result in overlooked defects and false detections. Based on inspectors' feedback, the training system offers a realistic virtual environment for the tap test. Moreover, inspectors' feedback indicates that the idea of a training system is well perceived and the concept for this virtual system could lay the groundwork for further training in this field.

1. Introduction

Reoccurring, comprehensive inspections of wind turbines are a pivotal element of its life cycle. Especially for highly stressed parts, such as rotor blades, defects can cause severe problems and affect the downtime of the plant significantly. Robust and low-cost non-destructive testing methods are sought to check and ensure the material's integrity. The sheer size of rotor blades, their complex geometry and poor accessibility require lean methods that can be applied universally to detect the most important defects. Such defects mainly comprise material delaminations, deficient bonding of structural elements or cracks. Nowadays, they are still detected by experienced personnel that mainly undertake a visual inspection of the outer surface, and – if accessible – inner structures of the rotor blade. Additionally, local tapping on the structure with a hammer supports the inspection process since it allows for the detection of non-visual flaws.

In the field of non-destructive testing, this method is known as the (coin-) tap test, which uses a hard item, such as a metal coin, to locally excite the investigated structure. The elicited sound can then be analyzed on a subjective ("listening to the sound") or objective basis [1]. Cawley and Adams (1988) define the change of mechanic impedance of the material as a robust defect-indicating parameter [2]. In the case of a defect, a longer contact time between impact tool and specimen can be obtained, resulting in a lower peak impact force and different rebound behavior of the tool. Generally, this defect is found to be suitable for laminated materials, such as glass-fiber reinforced plastic (GFRP) that can feature voids, de-laminations or other mechanic impedance-changing defects.

In the case of subjective-based approaches, existing literature describes defects as sounding "dead" [2] or "hollow", while flawless material sounds "live" [3]. More recent findings show that the acoustic difference between intact and defective parts can faithfully be described with sound-describing adjectives, such as "sonorous", "high-pitched" or "blurry." Results further suggest that material-describing attributes, such as "stiff" or "hollow," also prove to be useful descriptors when identifying the material integrity of rotor blades [4]. Combining subjective descriptions with objective, acoustical parameters is of interest in the field of hearing research. More specifically, the study of sound source perception examines how listeners identify the material or geometry of an object based on its (impact) sound [5]. When it comes to robustly identifying said features of an object, studies show that experienced listeners who received extensive training outperform unexperienced by choosing a more robust combination of perceptual weightings of acoustic features [6].

The tap test is especially important during the inspection of wind turbine rotor blades since it allows detecting non-visual flaws by making use of audible and haptic information. The minimal costs, and sparse equipment needed for the inspection outweigh the fact that the inspection is based on visual, haptic and acoustic perception, thus subjective information. Current practice provides no training for the inspectors of wind turbine rotor blades besides "learning by doing". As research has shown, experience has a beneficial effect on the correct identification of the material and its geometry, two related features in the detection of material integrity. This work addresses this problem by presenting a system that aims at advancing the inspectors' ability to robustly identify defects of wind turbine rotor blades with acoustic means.

2. Tap Test Training System

2.1 Objective and key features of the Tap Test Training System

The objective of the Tap Test Training System (TTTS) is to create a virtual environment which focuses on advancing the inspector's ability to detect defects solely by listening to impact sounds, therefore, without visual aids or haptic feedback. The TTTS should allow the inspector to enter a rating indicating the perceived degree of defect at a certain tap point, and furthermore, feature an objective measure of feedback. Wind turbine rotor blades are complex with regard to the structural composition and type of defect. As a result, it is important that the TTTS covers a range of rotor blades with various types of defects in different parts of the blade. The first version of the TTTS focusses on defects that can be detected from the outside of the blade. While tapping on the rotor blade, the transition from one structural part of the rotor blade to the other may sound very different but it does not necessarily indicate a defect. This is why two additional features are of importance, (1), structural transitions with and without defects have to be included, and (2), the option for the inspector to give feedback on the structural boundary conditions.

2.2 Implementation of the Tap Test Training System

2.2.1 Hardware components

In order to facilitate the evaluation of material integrity with acoustic means only, and at the same time, mimic the execution of the tap test, the TTTS features two main hardware components. First, a calibrated sound playback system and second, an impulse hammer combined with an impact-resistant surface. The impact sounds are played back on each triggered event, which feature a tap point on the impact surface associated with an impact force. Impulse hammer and surface serve the purpose to control those attributes. There are various ways of designing the impact surface, so that the attribution of impact location to the tap point can be performed robustly. Here, as a first attempt, a drum pad with eight pads arranged in a rectangular is implemented. Each drum pad represents a tap point of the actual investigated tap area. The impulse hammer records the impact force by means of a force transducer and initiates the playback once a threshold is exceeded. Depending on the force, sound pressure level of the impact sound is adjusted – the harder the impact, the higher the sound pressure level. Here, a sigmoidal-based mapping of the dynamic range of the force sensor to the sound pressure level is carried out.

2.2.2 Hardware-user interface

The purpose of the hardware-user interface is to receive the inspector's input based on the sound perception, and in return, offer an objective perspective of the investigated area. The appearance is based on the two-dimensional matrix of tap points spanning over a certain area of the rotor blade – each cell represents a tap point. Tap points are boxed, where the four edges of the box represent possible structural transitions between the tap points. A tap points can be marked according to its perceived integrity. The system allows for three basic differentiations, intact, possibly defective and defective, whereas the defective option can be divided further into three magnitudes of defectiveness. In order to establish the connection between software and hardware, tap points on the rotor blade and the impact surface respectively, a layer is introduced in the user interface indicating retrievable sounds for the tap points on the investigated rotor blade area. The option for displaying the objective measure on the rotor blade is available at any time and will be discussed below. This way, each rating for a tap point can be compared to objective parameters. Figure 1 depicts given information on the TTTS.

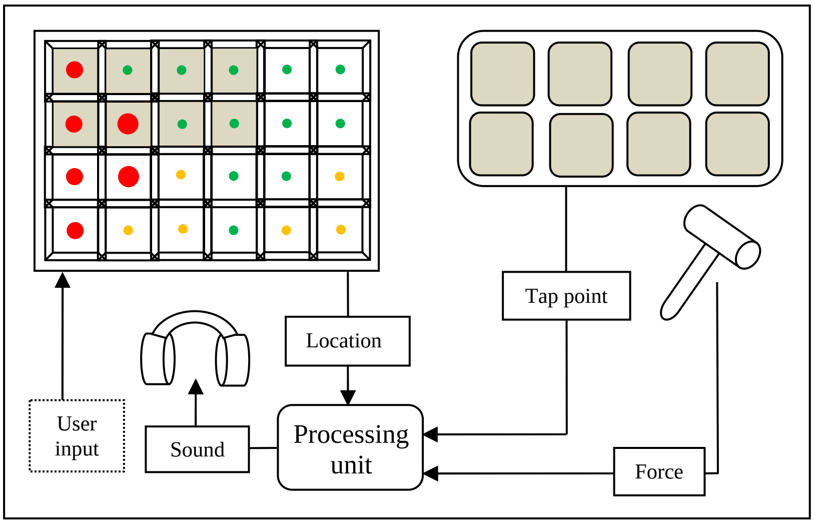

Fig. 1: General layout of the Tap Test Training System (TTTS). Upper left: User interface indicating active tap points, which can be tapped and edges for marking structural changes between tap points. Colored circles indicate ratings of the material integrity of the tap points. Upper right: Impact surface, here in the form of 8 discrete tap areas each representing one tap point of the recorded data. Processing unit combines all input data in real time and outputs the correct impact sound.

3. Audio-visual database of defects in wind turbine rotor blades

3.1 Rotor blade

The first set of sounds is retrieved from a 34 m long rotor blade built for a 1.5 MW power plant. The blade underwent a bending test resulting in the destruction of the blade accompanied by visible cracks on the surface. The blade is designed with epoxy-based GFRP. Two inner shear webs merging into the spar caps carry the loads to the root of the blade. Delaminations in different depths under the surface of the rotor blade and an area of deficient bonding at the trailing edge comprise a set of non-visual defects that can detected by the tap test method. Six areas on different parts of the rotor blade are found to be of interest and are investigated with the tap test. Five of which cover full laminated areas over the spar cap and structural transitions from the spar cap to the shells, while one spans over the trailing edge.

3.2 Sound recordings of impact sounds

Single-channel sound recordings are performed from tapping on each investigated area of the rotor blade. A measurement microphone is positioned in 50 cm distance perpendicular to the investigated surface. Single and multi-tap signals are recorded for each tap point individually with different types of hammer tips, varying from soft to hard. Hard tips shorten the contact time and a higher impact amplitude is obtained. As a consequence, a broader sound spectrum is available for the listener. As a first basis, a total of 5000 recordings covering a surface area of roughly 8 m² provide the database for the TTTS.

3.3 Phase sensitive modulated thermography

In addition to the sound recordings, phase sensitive modulated thermography measurements, also known as Lockin-Thermography measurements, are taken of the investigated areas and comprise the set of objective measures. The principle of this method is based on spatial and temporal temperature modulation of the object under investigation. The object is heated up, in this case with a heat lamp radiating frequency-locked sine-modulated thermal waves, and the thermal "answer" of the object during the measurement is recorded by a thermal imaging camera. Discontinuities in the material, such as voids between material layers or delaminations, create local amplitude and phase changes of the modulated response. These changes can be seen by comparing excitation and response in the Fourier domain. Longer excitation periods (lower excitation or lock-in frequencies) allow for a deeper excitation of the material [7].

Phase sensitive modulated thermography measurements are present for all investigated areas, with different excitation frequencies between 0.01 and 0.05 Hz. Figure 2 depicts a result for a spar cap featuring delaminations roughly 2 cm beneath the surface. Excitation frequency is 0.01 Hz and the covered area roughly amounts to 0.40 m x 0.30 m (width x height). The delaminated part is indicated by a phase change of about three degrees compared to the surroundings.

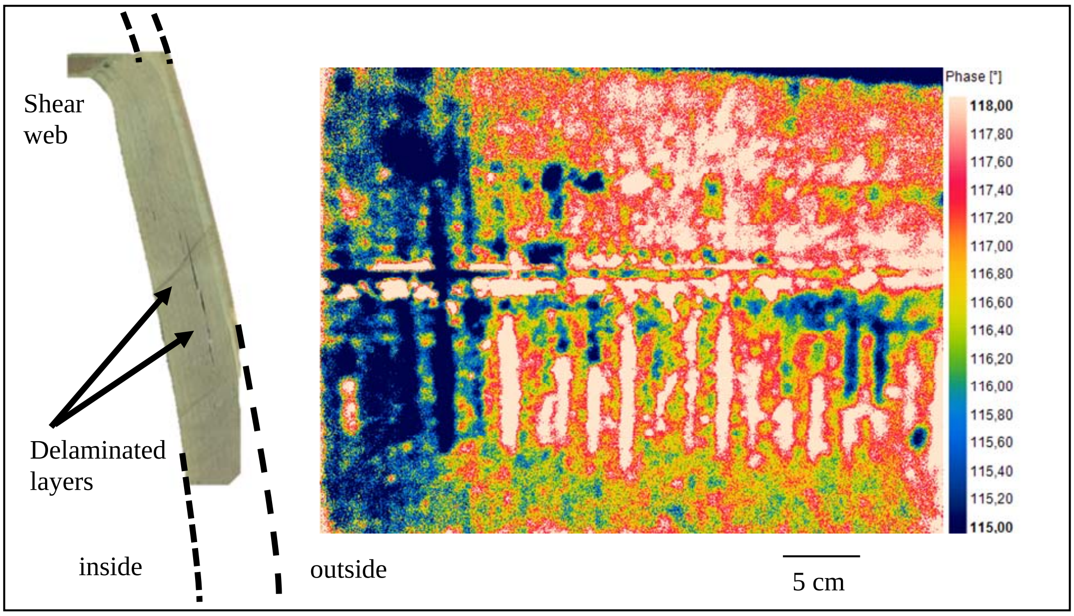

Fig. 2: Left: Cross section of spar cap (out of plane) featuring a delamination between material layers (arrows). Dashed lines indicate continuation of the cross section. Width of cross section: 4.8 cm. Right: Phase picture of modulated thermography measurement of roughly 30 cm height (in plane) and 40 cm width (out of plane).

4. Test phase with inspectors of wind turbine rotor blades

Five inspectors of wind turbine rotor blades were asked to perform virtual tap tests with the TTTS using the current database. This procedure aims at receiving valuable feedback on the TTTS to further improve the system. Each inspector performed the test on one tap area. Before the test started, basic information on the rotor blade and tap area, e.g. type of rotor blade, size and location of the tap area, was given to the inspector. After an introduction to the basic functions of the system, the inspectors were asked to rate the perceived material integrity. There were no further limitations on the execution of the test – the inspector could listen to the impact sounds as often as required. After finishing the tap test, the inspector was asked to complete a questionnaire, covering questions about the appearance and handling of the systems, and how realistically it can mimic the tap test.

4.1 Preliminary results of the perceived material integrity

The following depicts an area located at the trailing edge of the rotor blade with two types of defects. In figure three, a crack between bonding and shell can be seen in the upper left corner of the investigated area. Furthermore, a delaminated area, stretching horizontally from left to right, in the upper third becomes apparent, as can be seen by a white band in the phase picture in figure three. In addition, figure three depicts the ratings of the perceived material integrity with eight tap points in vertical and twelve tap points in horizontal direction and a separation of roughly 4 cm. The rating is performed by an inspector with have half a year of professional experience.

4.1.1 Discussion of the preliminary results

It can be gathered from figure 3 that the inspector identified the delaminated area in the fourth row. However, a definite declaration of the defect is missing – the inspector labeled it as being probably defective. The crack between bonding and shell could not be detected. In case of an inspection in the field, however, this severe defect could have been visually identified. In addition, some tap points were labeled “probably defective” or “defective” (7^{th} and 8^{th} row from the top), yet, no evidence can be found that any type of defect was present for these points.

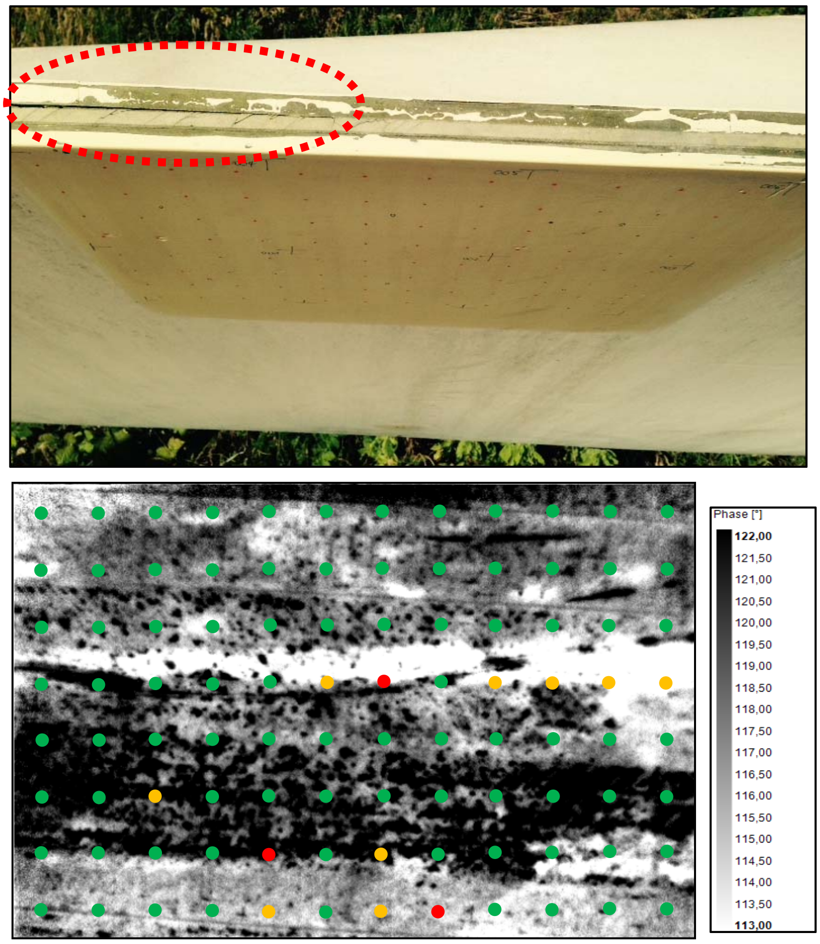

Fig. 3: Up: View of investigated trailing edge. Dashed encircled area: crack between bonding and shell located in the upper left corner of the tap area. Down: Results of an inspector’s rating comprising 8x12 tap points with 4 cm spacing. Green – intact, yellow – probably defective, and red – defective. Background: grey-scaled phase plot of modulated thermography method.

4.2 Results of the questionnaire on the Tap Test Training System

A questionnaire covering different aspects of the TTTS is used to receive feedback from five inspectors after the execution of one full tap test with the system. The rating system is based on a five-point scale with labels on either ends denoting “fully applies” (1), or “does not apply” (5). Imitating the tap with hammer and impact surface is positively perceived (M = 1.4, SD = 0.5). The presented signals represent realistic defects (M = 1.8, SD = 0.4), and in addition, the defects are classified as problematic damages (M = 1.5, SD = 0.5). Furthermore, ratings indicate that the impact surface, in this case rubber surfaces of a drum pad, impedes the realistic impression of the tap test (M = 3.4, SD = 1.1). Overall, the system is rated as useful for training purposes (M = 2.3, SD = 1.1).

5. Conclusion and outlook

The Tap Test Training System (TTTS) is developed to advance the inspector’s ability to detect defects in wind turbine rotor blades based solely on acoustic information. The tap test is of importance since it allows for detecting non-visual defects. The preliminary result indicates that (1) limited experience can compromise the detection rate of defects, and (2) lead to false detections. In addition, feedback shows that the general idea of advancing the performance with a virtual tap test generally wanted and accepted.

In order to verify the success rate of the system, more inspectors have to be tested and their performance monitored over time. According to the inspectors’ feedback, a soft impact surface can compromise the integrity rating since the acoustically perceived material hardness and the haptic feedback mismatch – a problem that can easily be solved with a harder impact surface, preferably, a GFRP-based surface. Furthermore, extending the database with more rotor blades and a more comprehensive database for the feedback system is recommended. For instance, a depth measurement of the defects can provide information on the limitations to defect detection.

References

[1] Jüngert A, Große C, Krüger M. Local Acoustic Resonance Spectroscopy (LARS) for Glass Fiber-Reinforced Polymer Applications. J. Nondestruct. Eval. 2014; 33:23-33.

[2] Cawley P, Adams RD. The mechanics of the coin-tap method of non-destructive testing. J. Sound Vib. 1988; 122(2):299-316.

[3] Wu H, Siegel M. Correlation of Accelerometer and Microphone Data in the “Coin Tap Test.” IEEE T. Instrum. Meas. 2000; 49(3):493-497.

[4] Andreisek G, Große CU, Seeber, BU. Attribute zur Beschreibung akustischer Unterschiede von Fehlstellen an Rotorblättern von Windenergieanlagen. Fortschritte der Akustik – DAGA ’15. Dt. Ges. f. Akustik, Berlin, 2015; 513-515.

[5] Lutfi RA. Human Sound Source Identification. In: Yost WA, Popper AN, Fay RR, editors. Auditory Perception of Sound Sources. New York (NY): Springer US; 2008:13-42.

[6] Giordano BL, Rocchesso D, McAdams S. Integration of Acoustical Information in the Perception of Impacted Sound Sources: The Role of Information Accuracy and Exploitability. J. Exp. Psychol. Human 2010; 36(2):462-476.

[7] Busse G, Wu D, Karpen W. Thermal wave imaging with phase sensitive modulated thermography. J. Appl. Phys. 1992; 81(8):3962-3965.