# Application of ultrasonic measurement on concrete foundations of the modern wind energy plants: approaches and experience

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**Key words**: Wind Turbines, Foundation, Ultrasonic Measurement, 3D-Point-Cloud, Quality assurance

## SUMMARY

For dynamically and highly stressed wind energy plants effective quality control is of vital importance. It is known that dangerous defects in the concrete foundations are not just made by external influences, such as temperature changes or by time dependent material behavior, but also through covert construction defects and design errors. A recording of the damage inside the wind energy plant foundations shows that the damage is much more complicated than in the visible cracks. With the method of acoustic discharge measurement, internal damage and material defects in the wind energy plant foundations can be seen before cracks or water damage are visible on the surface. The precise knowledge of the location and the extent of such anomalies in the foundations are important for the safety of the structure and the temporal evolution. The already performed test measurements on special test blocks and real wind turbines confirm that this method has a great potential in the assessment of wind turbine foundations. However, the gained knowledge also shows that the interpretation requires a certain degree of experience and must be further improved. In these conditions, quality assurance and calibration for survey measuring instruments play a special role.

## ZUSAMMENFASSUNG

Wie alle komplizierten Ingenieurbauwerke unterliegen auch die modernen Windkraftanlagen einem hohen Schadensrisiko. Es ist bekannt, dass gefährliche Defekte im Bereich ihrer Betonfundamente nicht nur durch äußere Einwirkungen, wie z.B. Temperaturänderungen oder durch zeitabhängiges Materialverhalten, sondern auch durch verdeckte Baumängel und Planungsfehler hervorgerufen werden. Eine Erfassung der Schäden im Inneren der Fundamente ist wesentlich komplizierter als bei den sichtbaren Rissen. Mit dem Verfahren der Ultraschallmessung lassen sich auch die inneren Schäden und Materialfehler in den behandelten WEA-Fundamenten frühzeitig, d.h. bevor sie z.B. als Risse an der Oberfläche oder Wasserschäden sichtbar werden, feststellen. Die genaue Kenntnis der Lage und der Ausdehnung von solchen Anomalien in den Fundamenten helfen somit deren Bedeutung für die Sicherheit des Bauwerkes und die zeitliche Entwicklung besser zu beurteilen. Die bereits durchgeführten Testmessungen an speziellen Testblöcken und realen Windkraftanlagen bestätigen, dass diese Methode ein großes Potential bei der Begutachtung von WEA-Fundamenten aufweist. Die gewonnen Erfahrungen zeigen allerdings auch, dass die Interpretation der gewonnen Erkenntnisse ein gewisser Grad an Erfahrung erfordert und weiter

verbessert werden muss. Eine effektive Qualitätskontrolle von Auswertungen und ein umfassendes Kalibrieren des Messsystems sind dabei von einer entscheidenden Bedeutung.

# Application of ultrasonic measurement on concrete foundations of the modern wind energy plants: approaches and experience

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## 1. INTRODUCTION

Wind energy is the largest source of electricity production from renewable energy in Germany. Currently there are more than 24 000 wind turbines in use. More than 10 000 of these wind turbines were built before 2003 and reach the limits of their planned lifespan over the next few years. Therefore, control of their bearing structures plays a particularly important role now.

The increasing number of foundation defects in wind turbines shows that one of the main problems is the connection between the tower and the foundation (Grünberg & Göhlmann 2013). The damage symptoms are the cracks or spalling in the top of the foundation as well as the water intrusions inside the foundation (Fig. 1). The main causes for these damages are irregular huge movements on foundation components of the wind energy plant. The reason for this are maybe construction faults or planning errors. The earlier these damage are detected, the better are the possibilities to repair faults. According to the current rules of modern wind turbines, it is necessary to test the foundation structures and frame structure at regular intervals by an expert (DIBt 2012).

Spalling inside    Spalling outside    Water intrusion    Circumferential cracks

**Fig. 1:** Typical faults of a wind energy plant (exemplary)

The aim of the tests is to control the irregular movements of the built-in part of the tower. Unfortunately, it is impossible to measure within the foundation. Measurements on its surface and at the tower provide the important information about the connection between both parts. There are the main differences between periodic inspections and condition monitoring. There are the important differences between periodic inspections and condition monitoring. Inspection of a wind turbine is a periodic check of its important parts. In the case of bearing constructions this is as a rule a visual check. Special measurements such as dynamic stress test are only required for selected endangered constructions. In this case, the impulse generated at the rotor after an emergency stop is introduced into the tower and via the built-in part into the foundation. The corresponding deformations (for example the maximum swing) between both parts can be measured and interpreted. Condition monitoring is the continuous measurement of different parameters of machines, in order to identify a developing fault. Contrary to special dynamic stress test, the usual movements between the tower and the foundation (for example the average swing over the time interval) can be recorded and analyzed for a condition monitoring (Resnik 2017).

## 2. DETECTION OF FOUNDATION DEFECTS BY PERIODICAL CHECKS

The visible cracks on top of the foundations are first signs for deformation processes (DIBt 2012). These cracks arise by local exceedance of recordable tension in concrete. Through the cracks rainwater can enter and attack the reinforcement. The reinforcement can corrode, which in turn will reduce stability. In winter the water freezes and expands and produces more new cavities. The analysis of the existing cracks in regular intervals is very important. The form, the width, the depth, the position and the age of the existing cracks must be captured. One of the most important parameters is the temporal change of cracks, which should also be captured. The limit of the crack width is 0.3 mm. The registration of defects inside the foundation is much more difficult. In the past there were destructive testing methods to inspect the interior of structural components. These methods are not useful in foundations of wind energy plants. With current technology, it is possible to inspect the interior of structural components in a non-destructive fashion. One of these non-destructive-methods is based on ultrasonic-technology. As a result it is possible to localize the internal damage or material defects before it is visible on the surface. It can be useful to determine the location of the damage and will give an overall impression of the foundation.

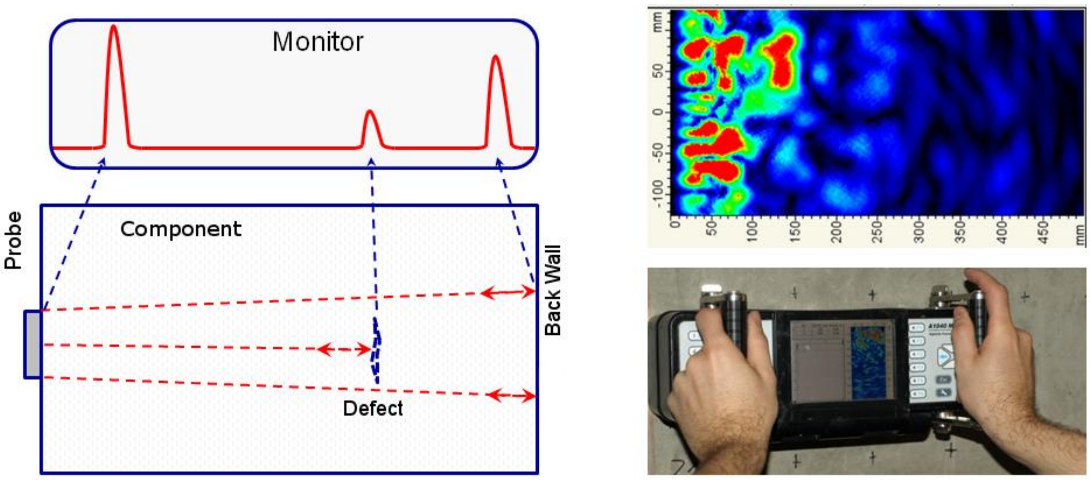


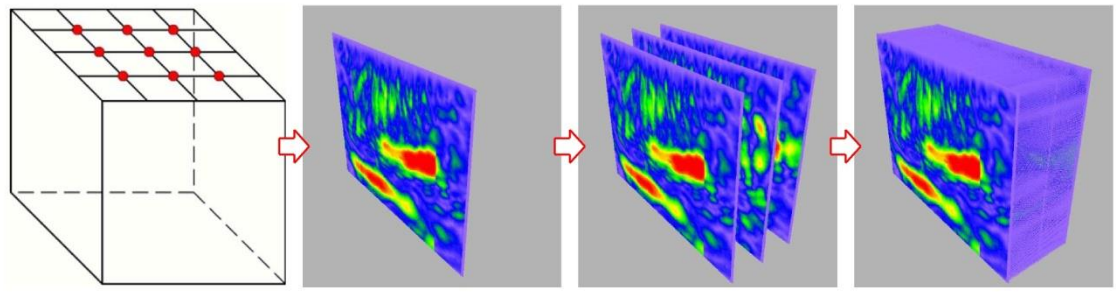

**Fig. 2:** Principle of ultrasound examination on a wind turbine foundation

Ultrasonic measurements based on principle of the propagation of the sound waves within the material and occur in the low frequency range. The transmitter sends an impulse into the component (Fig. 2). The first amplitude is the transition into the component. If the impulse hits a flaw, a reflection is generated and a second amplitude is visible on the screen. Without any flaws, the impulse will pass the component and reflected at the rear wall. Another amplitude is recognized. If there just been too many barriers, no impulse reached the rear wall. Even though the ultrasonic measurement has already been used in medical technology, ultrasound systems in the building industry are only used since few years and currently in applied research. As a result of an ultrasound scan it is possible to get colored two-dimensional or three-dimensional models. In the development of evaluation strategies it is possible to use knowledge from comparable techniques like remote sensing or laser scanning, which is used in the surveying sector. In the course of the research project at the Beuth University of Applied Sciences it was investigated, how useful three-dimensional evaluation procedures are at the wind turbine foundations and how realistic the results are.

## 3. THE MEASURING TECHNOLOGY AND SOFTWARE

In the content of the research project "Development of concepts for an early identification of security-relevant defects in concrete bases of wind turbines in terms of Condition Monitoring Systems" (WESAFE 2016) the measuring system A1040 Mira by company Acoustic Control Systems are used by the authors. The measurement was carried out at a frequency range between 20 and 100 kHz. The transducers are pressed onto the surface of the component (Fig. 2). At the touch of a button, the measurement starts. The advantage of the A1040 Mira is the dry point contact. No coupling agent is needed. According to the manufacturer it is possible to measure in a depth of more than 2 meters, depending on the material properties. For the measuring there are two measuring modes available:
– View-Mode: For getting a fast insight into the component, with just one measuring position. It is optimally for checking concrete structural element.
– Map-Mode: For getting an overall impression of the concrete structural element. It is advantageous to measure the previously marked measuring grid.

With respect to the following remarks, only the Map-Mode was used. An Image is the result of an ultrasonic scan (Fig. 3). Those images are created by raw data with the aid of so called Ultrasonic SAFT-Imaging. The distance between each image are the same distance between the marked measuring grids. As a general rule the distance is 10 cm. For getting a spatial impression of the data, the authors developed an evaluating workflow for generating a three-dimensional point cloud. The third dimension was created by linear interpolation between ultrasonic images.



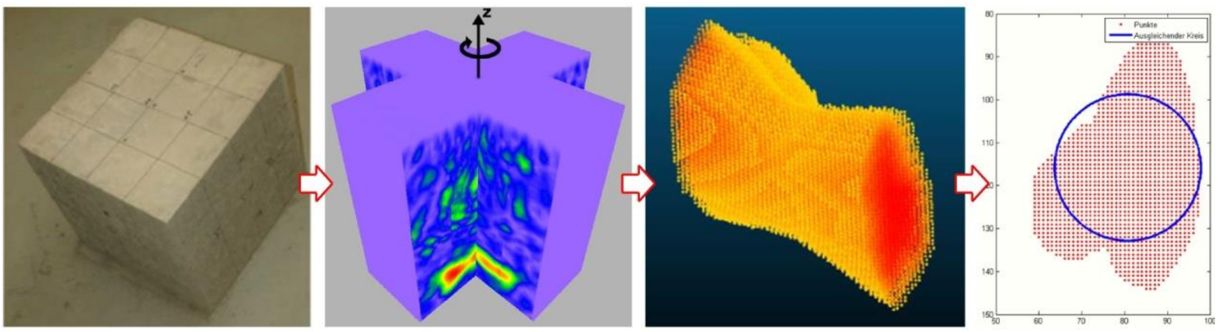
Data capturing 2D-Image Interpolation 3D-Point-Cloud

**Fig. 3:** Principle of data evaluation

In the first evaluative steps two commercial software products were employed. The IDEALviewer (I-DEAL Technologies) and Voxler 3 (Goldensoftware) were used. Both products have advantages and disadvantages. The advantage the IDEALviewer is the visualization of many scans of a map. In Voxler 3 are many exports opportunities available for further processing. After the preliminary, the next steps were made in Matlab (MathWorks). Many small scripts were created in Matlab for generating a three-dimensional point cloud.

## 4. RESULTS AND EVALUATION OF MEASURING ON TEST PIECES

The interpretation of ultrasonic measurements requires a certain degree of experience. In these conditions, quality assurance and calibration for survey measuring instruments play a special role. For these purposes 5 concrete test pieces were manufactured under laboratory conditions. They are cubic (40 by 40 by 40 cm) and have five different defects inside, which should simulate the defects inside the wind turbine foundations. In addition all cubic test pieces had a formwork anchors inside in form of a tube, which has a radius of 11 mm. The data collection was made on the top surface of the test pieces by a 3 by 3 marked measuring grid. Goal of the examination was to get information about the location and accuracy of the defects.




Test piece Overlapping of measurements Extracting Model

**Fig. 4:** Expiration of the evaluation

The description of all measurement- and evaluation results would go beyond the scope of the discussion. Therefore, only the evaluation results of the formwork anchors will be shown exemplary, which are inside of all test pieces. In the evaluation process, the area of formwork anchors were extracted (Fig. 4), adjusted and exported for the next steps, which have been made in Matlab. For modeling the cylindrical objects, there were tested many solutions. One of the solution is the fitting-circle-algorithm, which was extremely promising. The results of the five test pieces are listed in Table 1. The quality of adjustment were statistically analyzed by the well-known radius of 11 mm. The standard deviation $s_R$ and the average $R_M$ of each test pieces are also listed in table 1. The list compares two measurements. There is an one-time measurement and a two-time measurement, where the second measurement was made orthogonal to the first. The results represents the geometry of the formwork anchors very well, as an exception of test piece 4. The overlap of two measurements couldn't increase the accuracy.

**Table 1:** Results of the data evaluation

| Test piece | Without overlapping | | With overlapping | |
|---|---|---|---|---|
| | $R_M$ (mm) | $s_R$ (mm) | $R_M$ (mm) | $s_R$ (mm) |
| 1 | 11,4 | 1,5 | 11,5 | 1,6 |
| 2 | 10,9 | 3,7 | 10,8 | 3,6 |
| 3 | 12,6 | 3,7 | 12,1 | 3,2 |
| 4 | 20,0 | 10,4 | 20,0 | 10,4 |
| 5 | 13,1 | 3,0 | 12,4 | 1,6 |

## 5. RESULTS OF MEASURING ON WIND TURBINES FOUNDATION

After the measurements on the test pieces, tests on wind turbines foundations were made. The peculiarity is that there are visible cracks on the surface. Two different measurements were made. The first was along north direction and the second in west direction, which is the main wind direction. The basic idea of the measuring arrangement was to find a different between the two wind direction and the different of both stress levels. It is to be expected that more defects in west direction than in north direction. The differences will be on the ultrasonic images.

In this way there were found irregularities which indicates possible cracks. The shape of these irregularities was often quite abstract. So that a definitive response in this regard cannot be presented. For the further definition of these anomalies it could be helpful to use an insolvency proceeding. Maybe the radar technique can be useful, which can confirm or revoke the current results.

The conducted measurements on many wind turbine foundations had shown that ultrasonic technology can be successful for the assessment of the concrete structure. Defects and cracks may be visible. The experience gained, shows that the main problem is the interpretation of the data. This requires a high level degree of experience.

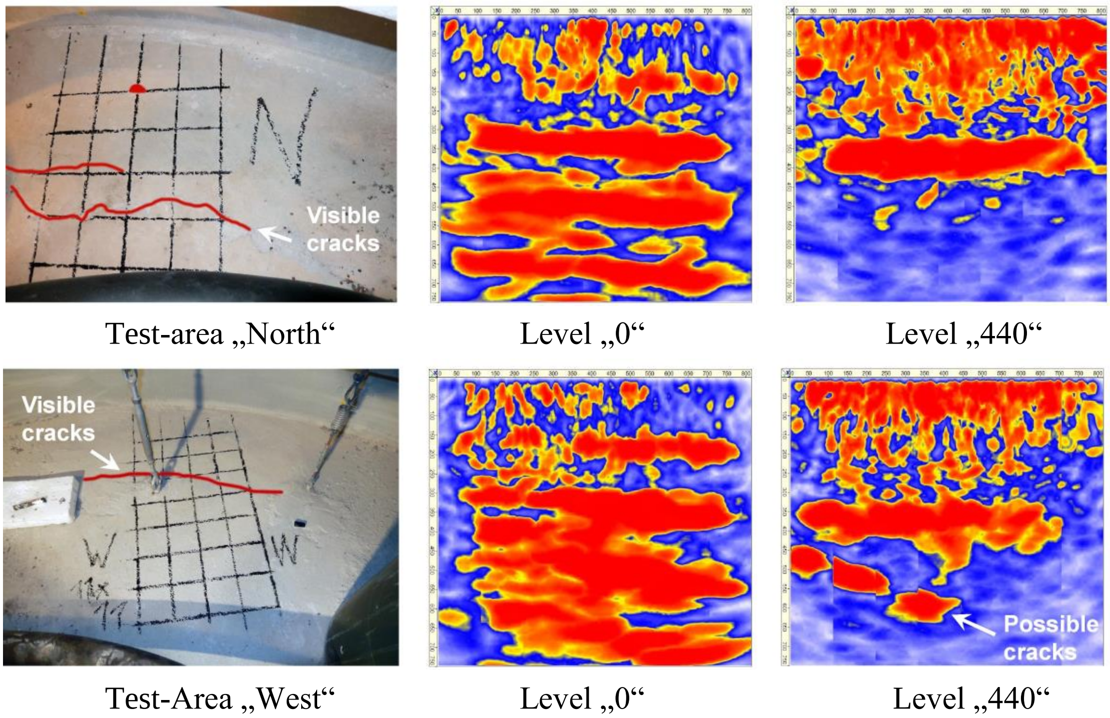



**Fig. 5:** Test measurements on wind turbines foundation (exemplary)

## 6. CONCLUSIONS

Like all complicated buildings subjects wind turbines face a high risk of damage. Many wind turbines reaching the limits of their planned lifespan in the next couple of years, which makes verification of security more important. The evaluation based on the presented evaluating workflow provide partially very good results. In this way it could generate a three-dimensional point cloud, which makes it possible to combine several measurements of one marked measuring grid. The statistical work has shown that combining these can increase the accuracy. In principle, the interpretation of the data represents the greatest challenge. Partial forms are not shown in detail so that a high level of experience is required to interpret the data correctly.

The use of ultrasound measurements in this area has so far been little studied. Main reasons are the necessary substantial investment in the development phase and the need for intensive interdisciplinary research. Based on the insights gained in the meantime the authors want to bundle in the coming years the existing research potential with longstanding experiments of cooperating consultants. In what follows all these approaches shall be realized at a high scientific level and then tested for their immediate practical suitability.

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