Offshore foundation monitoring by guided waves – challenges and perspectives

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Abstract. Offshore-foundations for wind turbines are expected to increase in significance over the coming years. Various wind parks are already producing energy. There are many more planned or currently being built.

The maintenance of these offshore wind turbines is challenging due to limited accessibility and expensive logistics. Currently, 25% of these structures have to be evaluated each year regarding their condition and stability. For this task, welded seams are in the focus of interest. At the moment, they are visually inspected by divers, in the oil and gas industry Alternating Current Focusing Technique (ACFM) is used as well. None of these are applicable e.g. on the inside of jackets due to safety issues. Visible inspection is often limited by the sight conditions and ACFM can only measure directly under the sensor.

The Fraunhofer IKTS therefore developed a transducer ring to be placed permanently on the foundations of offshore wind turbines. It is well suited especially for the monitoring of jackets. The measurement device CoMoSeam has been tested underwater successfully. Furthermore, an artificially initialized crack could be detected and located correctly.

The investigation is realized by guided waves which have a lower frequency range than commonly used NDT techniques. The advantage lies in the longer range and the therefore reduced number of sensors. Nevertheless, the resolution is decreased but still far better than achieved by the currently used inspection methods.

This paper presents the hardware used for building the sensor ring as well as the measurement technique. Especially the lamination to ensure water proof equipment is challenging regarding the demanded large diameters for offshore platforms. To detect cracks correctly even in harsh environments, a sophisticated data processing is necessary to eliminate all obviously incorrect data automatically. The method is just being introduced in the regulations and will be adapted to a diver free installation and operating regime.

Introduction

The permanent monitoring of subsea structures regarding defects in the welded seams is of significant importance for the growing wind energy industry. At present time, the monitoring is realized by visual testing by divers. Every foundation has to be inspected in certain time intervals either visually or alternatively by authorized NDT methods. Especially biological fouling makes visual testing difficult, small damages are difficult to detect reliably. As NDT method, so far only ACFM is certified for this monitoring task. The method has to be performed by divers and is very time consuming. The sensor has to be guided along the welded seam manually. An interpretation of the data is only possible by qualified personnel.

Sharp angle filled welded joints which are excluded due to the geometry and interior welds cannot be inspected due to safety regulation for divers.

Monitoring with permanently installed sensor rings operating with guided waves seems to be a good approach to overcome these deficits. The application of this technology leads to guarantied integrity of the wind turbine and to a significant increase regarding the safety of the operating staff (diver and service crew of the wind park). Defects can be detect in time to repair before a damage can cause complete failure. The productivity and the economics are increased. Furthermore, when applying this proposed technique, the operating times can be extended beyond the originally planned time frame.

Methodology

Guided ultrasonic Waves

Acousto Ultrasonics (AU) uses guided ultrasonic methods in a frequency range between 10 and 500 kHz. Various wave modes have different sensitivities regarding certain defect pattern (Fig. 1) and have to be selected according to the monitoring task. Guided waves are reflected at surfaces and interfaces, attenuated by dispersion and absorption, and undergo mode changes during reflection and transmission. These effects depend strongly on the frequency of the wave, its direction of propagation, its initial mode, and the location and orientation of surfaces and damage.

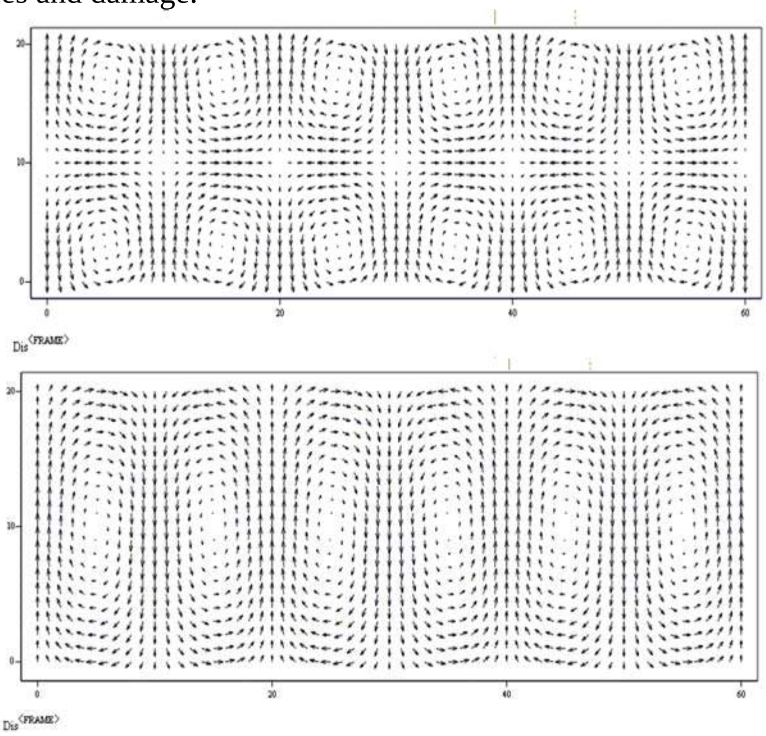

Fig. 1: Types of guided waves; above – symmetric mode, below - asymmetric mode [1]

When damage has occurred to a structure, changes in the signal and therefore the transfer function indicate the type of damage like cracks and wall thickness reductions caused by e. g. corrosion. By pre-calculating the expected changes in the signal from given types and degrees of damage, the defect can be evaluated from AU measurements. This kind of measurements are repeated according to the expected damage growth velocity. Using e. g. hourly measurement intervals, the growing of the damaged 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.

Sensor ring concept and lamination process

For the Acousto Ultrasonics based monitoring of large structures e.g. of weld seems, a large number of sensor actuator combinations are necessary due to the extensive geometry. The amount of transducer combinations enables an acoustic tomography. For being reasonably priced in hard and software implementation of such a measurement technique, a special solution based on smart sensor modules (SSM) connected by a bus system and controlled by a central controlling unit (CCU) was realized. The CCU generates necessary waveforms for the excitation of the AU signal including the power amplifier for driving piezo based actuators and receives the small signal from the sensors. The CCU also controls the SSMs via two wire interface for being an actuator or sensor alternatively. There are a microcontroller, some switching elements, preamplifier and a piezo disc which can operate as an actuator or sensor depending on switching conditions on board of the SSMs. So it is possible for the CCU to control the system by activating couples of SSMs being actuators and sensors by a bus system consisting of two wire interface, sensor, actuator and power supply lines. One measurement process consists of activating an actuator-sensor couple, addressing the actuator by a selected waveform and receiving the answer of sensing element. For a full tomography this has to be carried out for all of the sensor-actuator combinations in sequence. In Figure 2 a chain of SSMs coupled by the bus system (white band) embedded in a sea water resistent cover are shown.
The system bandwidth of the analogue signal equals 50 kHz up to 500kHz, the ADC sampling rate is 10MS/s at a resolution of 16Bit and a maximal number of 256 SSMs in the bus coupled chain.

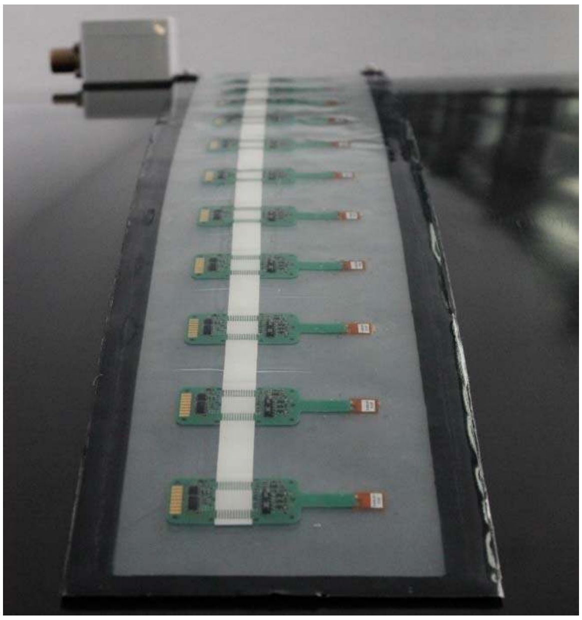

Fig. 2: Sensor ring modules developed at the Fraunhofer IKTS

The offshore operation of a sensor ring requires a high stability against seawater to maintain its function over the entire operating period. To achieve a long term resistance of the sensor ring, a three stage waterproof concept was developed. (Fig. 3). The first barrier is a diffusion resistant layer which is commonly used for flexible solar panels. The foil is two-sided at which the outer side consist of polytetrafluoroethylene (PTFE) and the inner side of polyethylene (PE). It prevents water from diffusing into the inner layers of the sensor ring. The second barrier is realized by thermoplastic PE layers between the diffusion resistant layers. This thermoplastic is necessary to bond the outer layers together and fill cavities within the laminate. The third protection consist of a socketing which entirely surrounds the printed board. The socketing is the last barrier to prevent water from entering the printed board. The socketing is fabricated by injection moulding. Small drill holes on the printed board allow the melt to completely surround the board which leads to a link between the melt on the upper and lower side. Flaking of the melt from the board is avoided. The whole package including diffusion resistant layer, thermoplastic material, printed board and transducer is processed in a laminator. The used temperature-time profile is adjusted for electric components, piezoelectric transducer and thermoplastic material. The laminate is processed for 30 minutes at 150°C and a partial vacuum with 800 mbar. The used materials in this process are complementary due to fluid resistance, mechanical rigidity, adhesion and electrical isolation.

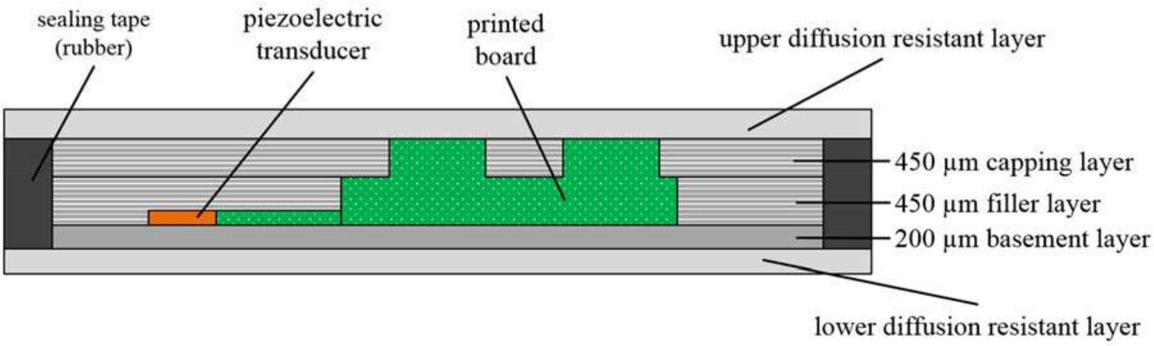

Fig. 3: Lamination setup for the waterproof feature of the sensor ring

Data processing

After conventional FIR-bandpass filtering mode selective pre-processing operators as already published in [2] and [3] were applied. Therefore a transfer function in short time domain were calculated for each signal path and regularized by truncated singular value decomposition afterwards. To obtain the transfer function, the measured baseline signal and an artificial single mode non dispersive measurement signal were calculated by a finite difference simulation of the linear undamped wave equation in time domain. To satisfy the Courant-criteria the space domain were discretized by an equidistant fourth order central difference stencil with a sample length about less than 0.1mm in each spatial direction. The time axis was discretized by an explicit second order Euler scheme with the same sample length of the measurement. A measured signal can be projected to an idealized non-dispersive single mode regime by the computed short time domain transfer function. Under the assumption that potential damages are sufficiently small so that they can be considered as Born scattering this projection is also applicable for scattered signals, which were calculated by subtraction of the baseline from the measured signal. As a result, side modes in the scattered signal are supressed and single component imaging procedures can be used for lamb modes in the terms of physics in a more precise manner. This circumstance will lead to better imaging results as shown in [2] and [3] due to the reduction of imaging artefacts. As imaging operator, the so called pre-stack Fresnel-volume migration operator was used. This technique was originally applied in field of geophysics [4]. It is comparable to the synthetic focusing aperture technique, which is well known in field of non-destructive testing.

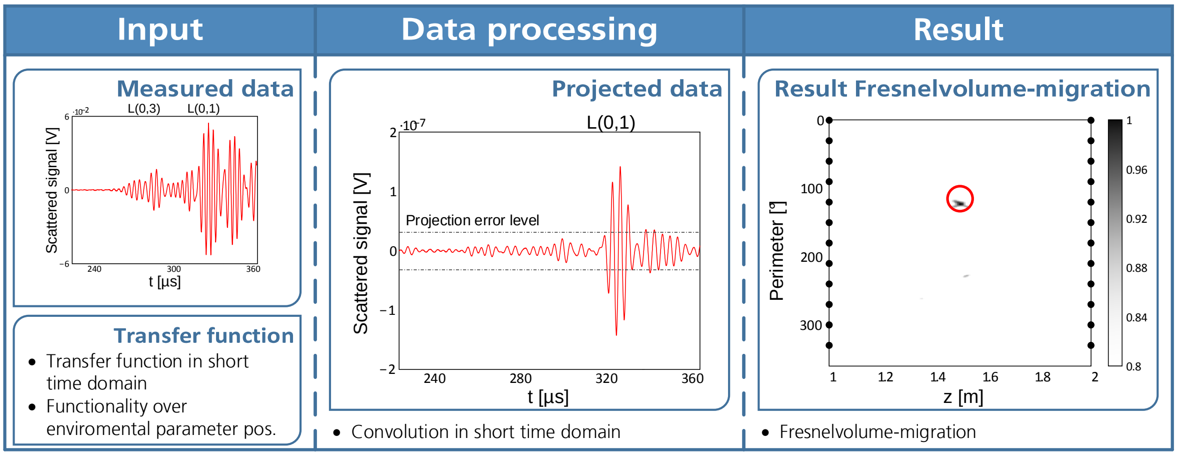

Fig. 4: Data processing algorithm for detecting welded seam defections

But there are two major differences. Firstly, the migration operator acknowledges the geometrical spreading by additional factors in the discretized Kirchhoff-Fresnel-integral and secondly, another factor restricts the wave field stacking procedure to zones of constructive interference only (Fresnel volume/Fresnel zone). In consequence, the operator will lead to better imaging results for sparse sensor networks due to the reduction of imaging artefacts as shown in geophysics [4] and for guided waves [2, 3]. Also the restricted stacking area will increase the computation speed because of a smaller amount of grid points being involved in the stacking process [2]. To prevent data aliasing effects, the pre-processed data is interpolated for each grid point and two-way traveltime, respectively. The needed two-way-traveltime for the complex model of the pipe junction was calculated by a grid based fast marching method (FMM) [5] with an third order stencil and an additional first order 45-degree rotated stencil to prevent errors in the region around the sensors modelled as point sources. The junction was modelled as two separate Cartesian grids (the two welded pipes) with periodic boundaries and a transition boundary which represents the welded seam. The results at the transition zone from the part of the pipe were used as starting conditions at the second pipe. To guarantee the correct travel time calculation, the two grids were calculated parallel with a global runtime variable for the upwind condition. Multi arrival times were not acknowledged. This was performed by performing the FMM iteratively and using the results as a starting condition for the next iteration.

Experimental proof

Port testing in Rostock

In order to test the newly developed sensor rings, they were applied to a demonstrator and tested at the harbour in Rostock. As measuring object a tube joint was welded at the SLV Rostock (Germany) with a pipes wall thickness of 20 mm (small pipe diameter 800 mm, large pipe diameter 1200 mm). The design was chosen in a way, that the ultrasonic signals are not interfered by any edge reflections and that the demonstrator can still be handled by a crane (**Fig. 5**). It was lowered in the water up to a depth of 2 m. The cable was situated at the pier and connected to the measuring device. The sensor ring was evaluated by divers under water.

An artificial defect with the crack size 45 mm length, 5 mm depth (correlates approx. with 1/3 of the wall thickness) and 0.9 mm opening width was introduced to the demonstrator (Fig. 6). Afterwards, the demonstrator was lowered into the water again to measure the influence of the crack to the measuring signal.

Fig. 5: Tube joint with sensor ring in the harbour of Rostock/Germany

Fig. 6: Left: introduced defect (45 mm length, 5 mm depth, 0.9 mm opening width); right: applied sensor ring.

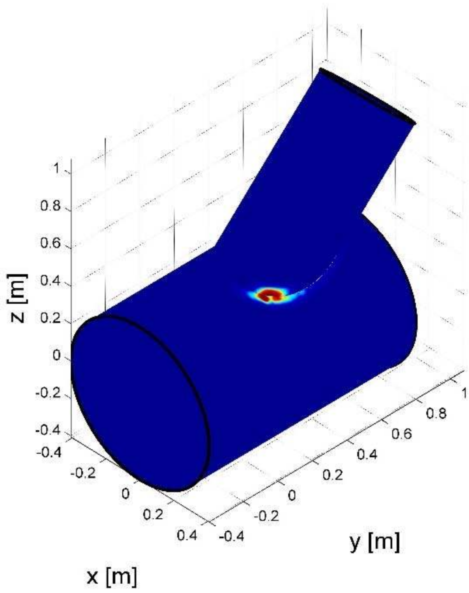

Fig. 7: Defect detection by the proposed technology of sensor rings

These measurements took place with one sensor ring to gather reflection data from the defect. The results are shown in **Fig. 7**. As it can be clearly seen, the defect is well detectable by this baseline processing. The data from the undamaged state served as reference. Any noise could be successfully removed by frequency filtering and tapering.

Testing at offshore wind park Baltic 1

As a next step, the sensor rings and the demonstrator were transferred by the project partner Baltic Diver (Rostock/Germany) to the offshore wind park Baltic 1. Goal of these measurements was mainly to test the equipment in a real marine environment at a depth of 18 m below sea level. Especially the tightness of the lamination was in the focus of work. Two sensor rings were applied to the demonstrator to measure not only in reflection mode but also in transmission mode (Fig. 8).

As in the harbour tests, an artificial crack was introduced to the demonstrator with the same dimensions (45 mm length, 5 mm depth, 0.9 mm opening width). As for the previous test, the crack could be well detected by the ultrasonic waves and the result data show a clear indication at the location of the crack.

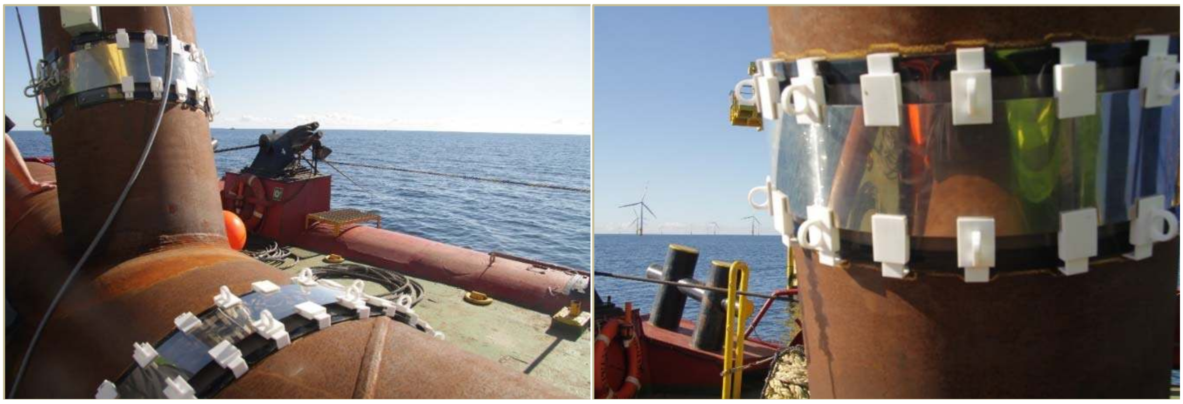

Fig. 8: Sensor rings applied to the demonstrator at Baltic 1 (Baltic Sea).

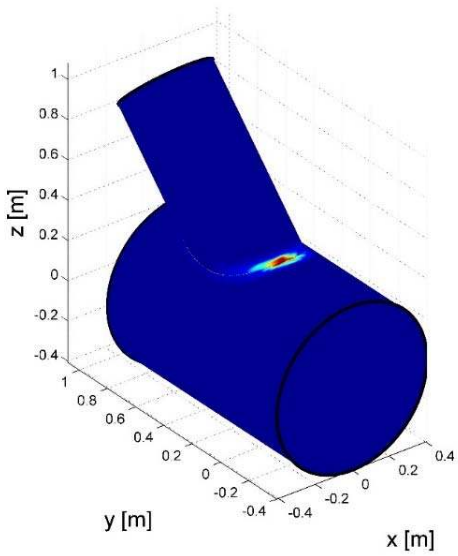

Fig. 9: Results of the measurements, detection of the defect, 45 mm length, 5 mm depth, 0.9 mm opening width.

As a next important step, the handling by divers was tested at 18 m below sea level (Fig. 10). The sensor ring was completely removed and successfully newly applied by the diver.

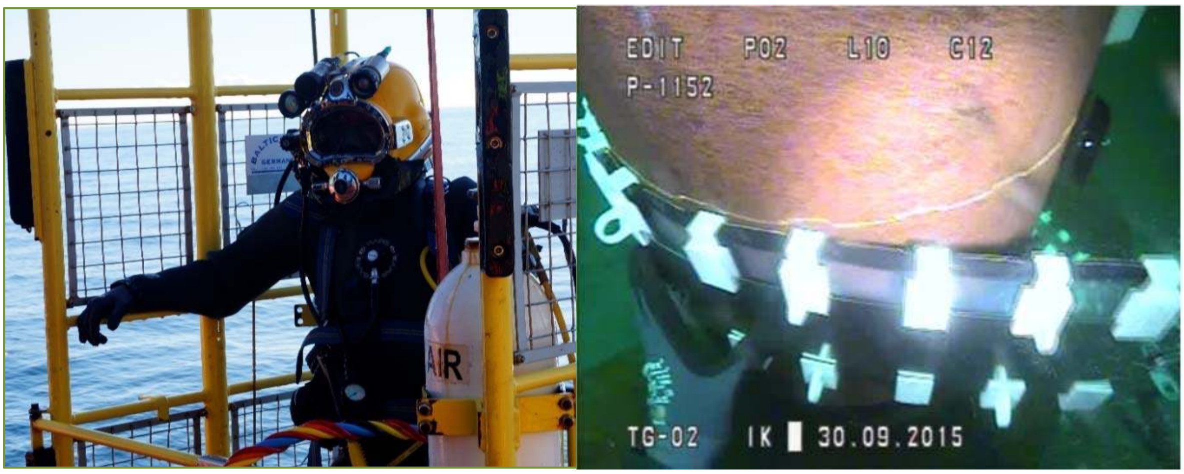

Fig. 10: Diver application of the sensor ring in depth of 18 m below sea level

Summery and outlook

This works shows a new possibility to permanently monitor welded seams on offshore structures by guided waves. A sensor ring was manufactured and laminated to ensure resistance regarding the harsh environmental influences over life time. First tests also show that the artificially introduced cracks can be reliably detected by the proposed method. Furthermore, the handling by divers was in the focus during the work in the offshore wind park Baltic 1. It was possible to apply the sensor ring correctly at a depth of 18 m below sea level. Future work will focus on calibration regarding marine fouling and also on the possibility to realize this measurements by wireless solutions and operated by Remote Operated Vehicles (ROV).

Acknowledgments

These works were founded by the Federal Ministry of Economics and Technology in the project “UnderwaterInspect” (funding code 03SX345B) and by the German Federal Ministry of Education and Research in the project “SensorMan” (funding code: 03WKP42F).

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