New Trends of NDT-based Condition Monitoring of Industrial and Power Plants

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Abstract

Energy generation and industrial production sectors require a more exact condition-based structural assessment for predictive maintenance. Condition monitoring can be significantly improved by using new approaches for monitoring concepts including non-destructive testing. Couplant-free ultrasonic using electromagnetic acoustic transducers can be applied for monitoring of metal structures, for example light poles. A major step towards defect quantification will be attained by the development of an innovative ultrasonic tomographic method based on guided waves, which is currently developed at Fraunhofer IZFP. As will be shown, the quantitative determination of corrosion in non-accessible or hidden areas becomes possible, e.g. for pipe supports and under insulation. In addition the potential of ultrasound sampling phased array technology using full-matrix-capture and total focusing technique applied to difficult to inspect materials and structures will be presented.
Demonstrators for a permanent condition monitoring are currently being developed at IZFP. One of them is named "MoniDAQ" – a small, robust, cost-effective and self-powered platform concept. Individual inspection modules such as ultrasonic, eddy current or micromagnetic devices can be integrated and subsequent intelligent signal processing will enable a rapid data analysis.

1. Introduction

To assess structural conditions, adequate knowledge of the geometric dimensions of possible damage is required. Because the position of damage can often be unsuitable for visual inspections and possibly inaccessible for other inspection methods as well, detection and quantitative assessments can be difficult if not impossible. Accessibility of supply lines for gas and water, as well as their load-bearing structures such as columns and poles is very limited (e.g. through shelters) due to soil coverage, wall breakthroughs or similar obstacles. A solution to overcome this problem of limited access is by flaw detection through a special long-range ultrasonic inspection process using guided wave modes [1,2]. Quantification of the flaws detected is an additional challenge, which is far from being sufficiently solved by means of non-destructive testing, especially with respect to thin-walled structures. A difficulty in this regard is that material damage such as surface corrosion can result in very complex geometries often spread over large areas but may not exhibit any significant changes in wall thickness. Conventional guided wave ultrasonic testing methods generally only evaluate the amplitude of either the reflected or transmitted signal. Small damage, and thus small

wall thickness changes, can be problematic and hence easily overlooked due to a low signal-to noise ratio.
The approach presented here will, however, allow this problem to be overcome. Several methods of guided wave tomography [3-6] are based on the travel time of straight ultrasonic rays. Als will be shown in the following, the duration of the phase difference for a single angle and for different wave modes and wave types can be evaluated for a guided wave tomography with improved local resolution compared to existing approaches.
In order to use the full potential of condition monitoring, it is necessary to evaluate the the different non-destructive testing (NDT) inspection methods, which can be specifically used to measure the relevant key paramters, such as flaws, wall thickness, etc. In the following chapter a short overview about the different inspection methods such as ultrasonic phased array techniques and potential applications are given.
Continuous, long-term surveillance of structures poses an additional challenge to the application of NDT methods in the field, as mains power often is not available, the installation of cable-based networks is expensive and time-consuming, and cellular connectivity for remote maintenance cannot be taken for granted. The paper therefore also describes a novel, energy self-sufficient, non-networked data acquisition and logging platform for condition monitoring with NDT methods (MoniDAQ).

2. Inspection methods

2.1 Ultrasonic guided waves application

Inaccessible areas can be tested with long-range ultrasonic waves, so-called guided waves. Under ideal conditions distances up to 50 m are coverable, avoiding an expensive exposure, removement of insulation and/ or digging out of the component.
Electro-magnetic acoustic transducers (EMAT) have the advantage that the ultrasonic conversion takes place directly in the surface of the specimen by magnetostrictive interaction and Lorentz forces. This makes couplant-free and non-contact excitation as well as reception of the ultrasonic signals possible. Surface influences are minimized and coupling problems are widely excluded. These transducers operate without direct contact and are not influenced by non-conducting materials, so that even thin insulation layers must not removed

One example for a long-range testing system based on guided waves and EMAT technology is the inspection system for light poles, “LIMAtest” (figure 1).In case of only single side access, the inspection has to be performed in impulse echo technique. The guided wave propagates in axial direction of the component into some hidden areas (insulation, soil coverage, wall breakthroughs etc.). Each geometric inhomogeneity leads to total or partial reflection of the ultrasonic energy. The echo signal travels back and could be picked up by the transducer. The following figures show applications of the technique. In figure 1 a system for the inspection of light poles is shown. The probe rotates around the pole and the lower area is tested. The results are displayed in ultrasonic B-scan (figure 1 left side). A serious indication was confirmed after the pole was dug out. (figure 1 right side).

Figure 1. Inspection system for light poles LIMAtest

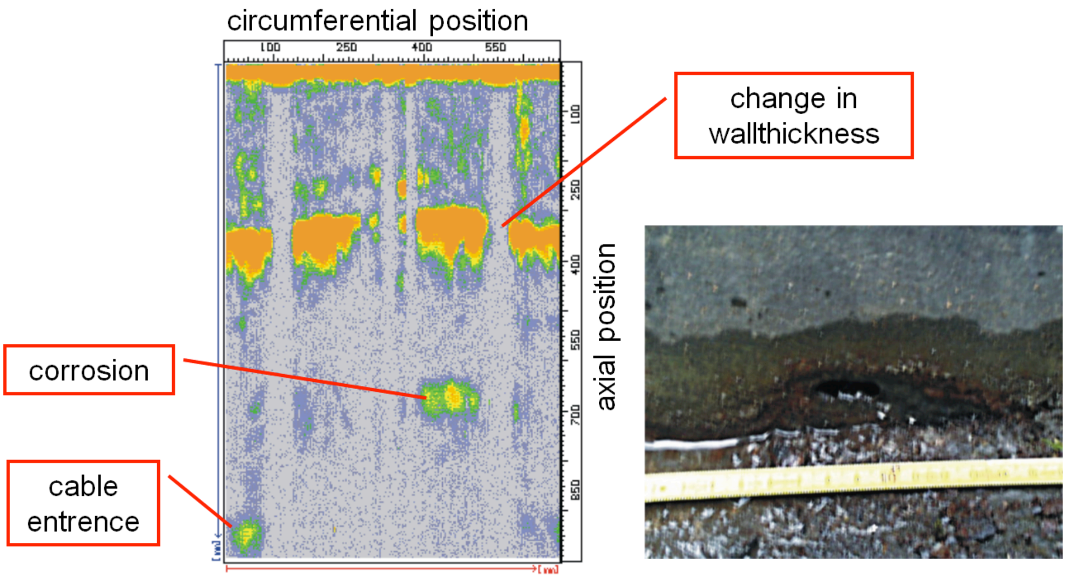

Figure 2. Inspection results: ultrasonic B-scan of hidden area of the light pole (left) and corrosion defect after dig out (right)

The LIMAtest system discussed so far uses the amplitudes of the reflected ultrasonic pulses and displays them in a well-known B-Scan image. However, an efficient pipeline testing system has to be capable to detect small corrosion-related damages. The use of dispersive ultrasonic guided wave modes provides the possibility to quantify very small wall thickness reductions in the sound path either in an ultrasonic transmission and / or a reflection setup. Both, the phase and group velocity of the dispersive ultrasonic wave mode depend on the wall thickness. Therefore quantitative information about the defects is accessible via the evaluation of the phase and / or time-of-flight of the received signal.

EMAT transducers as discussed above are used for mode-selective excitation and reception of guided waves. Only this couplant-free technique makes a precise phase measurement possible.

Due to a special transducer design a spatially periodic surface force can be induced. The periodicity of the surface forces is adjusted such that it corresponds to the trace wave length of the guided wave mode on the surface of excitation. As a result, pure modes of guided ultrasonic waves are excited in a particularly effective and selective way. In order to be able to cover a wide range of wave modes, EMUS converters have been developed which allow switching to different trace wave lengths. Thus, a large parameter set can be covered without changing the probe head, and various operation points can be addressed in the dispersion diagram in a targeted manner.

Within the framework of laboratory measurements, small wall thickness reductions in the sound path have already been detected using the phase tomography method. Using optimal operation points in the dispersion diagram of the guided wave modes, even locally limited wall thickness changes with a minimum depth of less than 10 percent of the nominal wall thickness can be reliably determined. A test tube made of steel with a length of 400 mm, a diameter of 220 mm and a wall thickness of 7 mm with artificially inserted flat areas for simulating surface corrosion areas was examined (figure 3 right side). The maximum depth of the flat areas is 16, 32 and 48 percent of the wall thickness. Figure 3 (left side) shows the phase shift of the transmitted ultrasonic signal for two different Lamb wave modes (A0, 214 kHz center frequency and S0, 366 kHz center frequency).

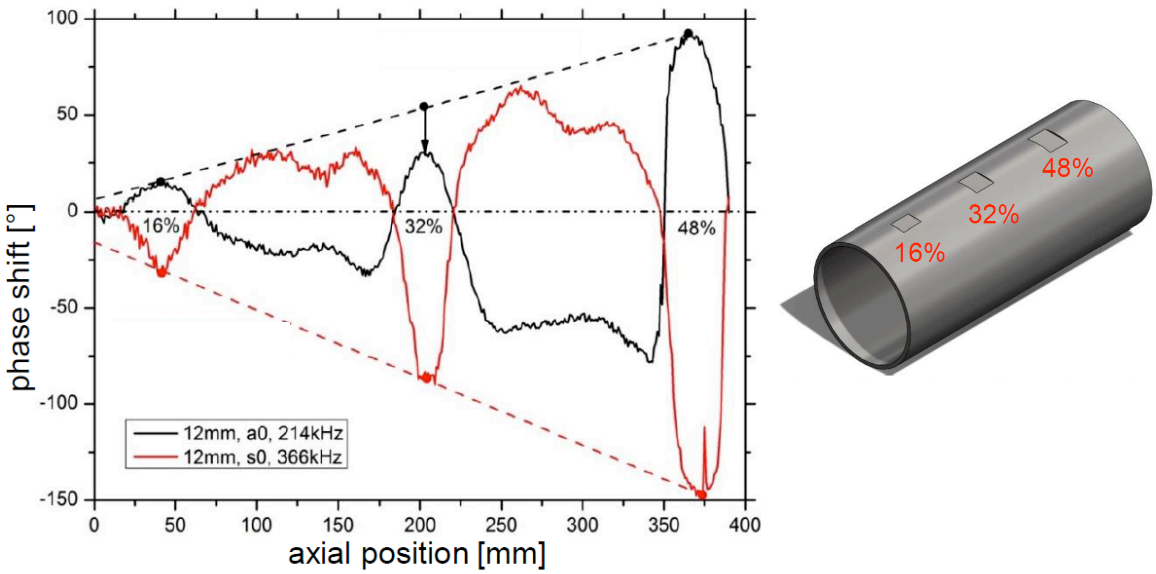

Figure 3. Phase shift of the transmitted ultrasonic signals of different Lamb wave modes (left) and sketch of the tube specimen with machined flat spots of different depth (wall thickness reduction) (right)

The tube was scanned in the axial direction and the sound propagation in the circumferential direction. The transmitter and the receiver probes are placed in a distance of around 90°, the artificial defects are located in the longer sound path (figure 4).

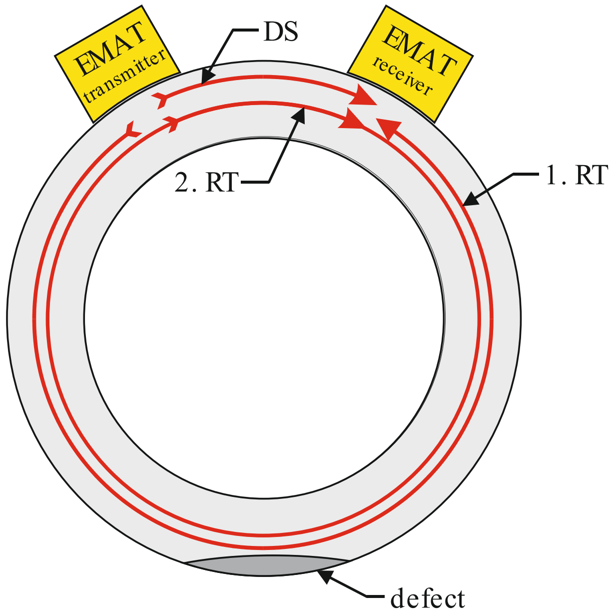

Figure 4. Experimental set up
DS: direct signal, which is not influenced by the defect
RT: round trip signal, that passed the defect area

As can be seen in figure 3, the areas of reduced wall thickness at 50 mm, 200 mm and 375 mm axial position induce a considerable phase shift variation of the transmitted ultrasonic modes. Due to the fact that the value and the direction of the phase shift for different guided wave modes are totally independent a charakterization and a quantitative sizing of the defect is possible.

2.2 Ultrasonic Sampling Phased Array

Conventional ultrasonic methods use bulk longitudinal or shear waves in pulse-echo or transmission modes. For non-destructive testing of components, imaging of defects and a quantiative assessment of defect size, the relevant surface area of a component is scanned with single or dual element transducers. This well-known and well-proven method is often implemented during service inspection, however, mechanical scanning requires very time-consuming procedures. For automotive applications for example, there is a strong need for a fast technique with 3D imaging capability. Since several years, ultrasonic phased array techniques in combination with full matrix capture (FMC) and total focusing methods (TFM) [7] are becoming more popular. The corresponding instrument developed at IZFP is called sampling phased array (SPA) [8, 9]. In this case, multi-element array transducers are used, which allow to emit typically 128 ultrasonic pulses at different positions without mechanical movement. In a conventional phased array, all elements are excited simultaneously with defined phase shifts to enable beam steering or focusing, while in SPA or FMC modes, each elements is excited individually in consecution. The received A-scans of all matrix elements are stored for each excitation event. This results in a large information matrix, which is used for 3D image reconstruction. Ultrasonic arrays in combination with fast reconstruction algorithms allow for a fast in-service and in-line inspection with high resolution also of components with curved surfaces combined with a quantitative 3D-signal analysis (see figure 5) [10].

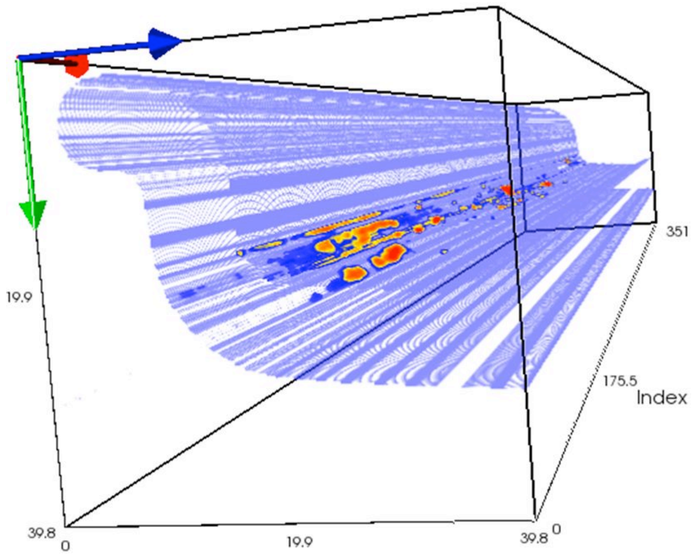

Figure 5: 3D-inspection using Sampling Phased Array (SPA) Ultrasound

2.3 Condition Monitoring

In a classical NDT inspection the specimens are tested periodically in certain intervals. Large areas of the component are scaned automatically or manually with a suitable sensor. The analysis of the measurents are used for the detection of defects. In most cases qualified personnel performes the inspection and the evaluation.
In opposite to that a condition monitoring needs autonomously operating and stationary systems. The whole inspection technique, sensor, driver and receiver electronic, has to be permanently installed. Thus the inspection area is limited to critical regions of the component. But the continuous monitoring leads to reliable indications of any kind of changes in the component due to defects, corrosion or microstructure, which activate the operator to perform more sophisticated inspection techniques for detailed analysis. Potential areas of condition monitoring are given in table 1.

Componente / Structure	Inspection Task
Pressure storage	Pressure, number of load cycles
Traffic sign gantries	permanent changes in position and orientation
Cable car components	crack formation and growth
Bridges, suspension ropes	traffic load, crack formation and growth
Wall anchors	Changes in position, orientation and strain
Pipelines	pressure, stress and strain, position and orientation, corrosion and cracks, leakage

Table 1. Areas of application for long term condition monitoring

2.3.1 General properties and requirements

Generally a NDT based condition monitoring system has to fullfil certain basic requirements:

- Detection of all relevant defect types and material deterioration
- Implementation of fully developed NDT inspection methods
- Replacement of the periodic inspection with fixed temporal intervals

Furthermore, for the system hardware itself the following criterias are relevant:

- modular and cost-efficient system architecture
- low power/ energy self-sufficient/ energy harvesting
- low-maintenance, long term sensor technology

2.3.2 System concept MoniDAQ

The condition monitoring platform MoniDAQ is designed under the above mentioned restrictions. The small main board contains several on-board sensors such as a temperature sensor, a three-dimensional accelerometer but also an eddy current impedance sensor (also suitable for micromagnetic inspection) as well as magnetic flux leakage (MFL), pressure and strain gauge options. A modular digital interface enables the system to be extended by ultrasonics and other NDT techniques in the future. Changes in the properties of the construction elements monitored (e.g. stress and strain) as well as material defects and defect growth (e.g. crack forming and growth, wall thickness reduction by corrosion) are detected as deviations from an initial temperature-effect curve. All data are stored in an on-board Flash memory. For energy reasons but also for safty reasons against cyber attacks the MoniDAQ system is equipped with a low-power, code-protected wireless communication interface.
The data of all measurements can be downloaded via a wakeup transceiver module (WUTRA) which communicates wirelessly to each MoniDAQ module and transferes the data to any WIFI-enabled end device. Moreover, WUTRA allows to perform the required settings in the individual MoniDAQ modules (see figure 6).

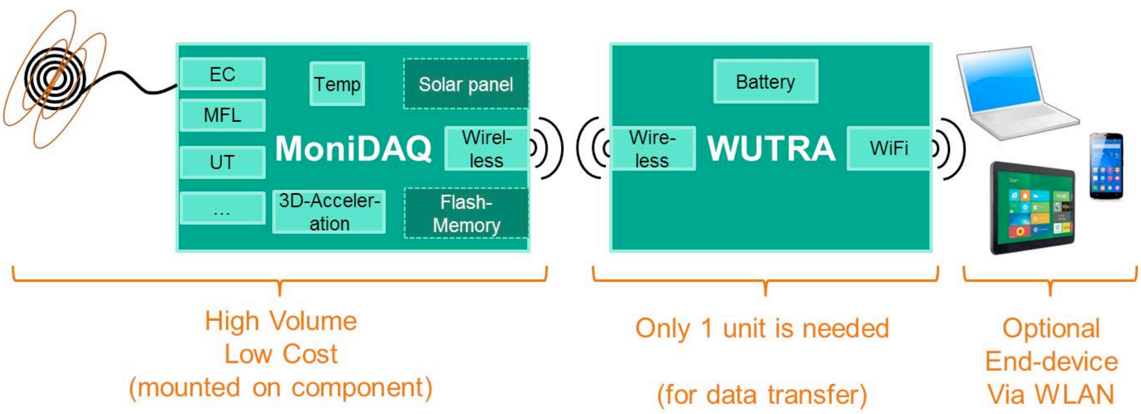

Figure 6. System concept of the MoniDAQ condition monitoring platform in combination with the wake up transceiver (WUTRA) for communication

Based on the measured parameter data (e.g. defects, corrosion size, etc.), the real current condition of a structure can be determined compared to the calculated condition according to the design. In case of less usage than calculated (see red point in figure 7) the operation strategy can be optimized to extend the lifetime of a component or to better use the remaining potential safety factor (see figure 7):

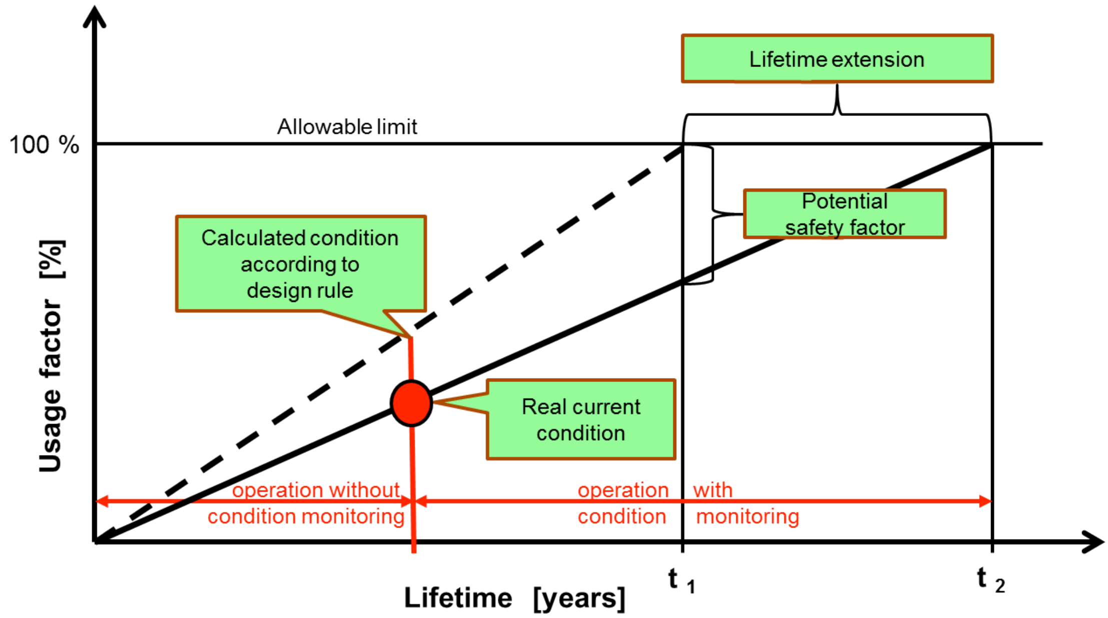

Figure 7. Determining the real current condition of a component using condition monitoring and potential for lifetime extension

3. Conclusions

Different high sophisticated NDT inspection methods were demonstrated which had a strong potential for an autonomous and continuous monitoring of industrial and infrastructure objects. Especial the use of ultrasonic techniques can give some quantitative information about defect position and size also for complex shaped defects (corrosion).
A new condition monitoring platform MoniDAQ based on a modular and cost-efficient system architecture with low power/ energy self-sufficient/ energy harvesting is proposed which allows to integrate fully developed NDT inspection methods replacing periodic conventional inspection and to ebable a lifetime prediction analysis for lifetime management.
For the future, more complex inspection techniques as e.g. thermography can be integrated in a multi-modal inspection system using data fusion of several parallel techniques. Thus, a deeper analysis of the inspected component and as consequence an improved data base for predictive maintenance can be achieved.

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