Wall Thickness Measurement Sensor for Pipeline Inspection using EMAT Technology in Combination with Pulsed Eddy Current and MFL

Frank NIESE, Andre YASHAN, Fraunhofer IZFP, Saarbrücken, Germany
Herbert WILLEMS, NDT Systems & Services, Stutensee, Germany

Abstract. An electromagnetic acoustic transducer (EMAT) is presented for excitation and detection of linear polarised shear waves at normal incidence with the use of a horizontal magnetisation of the specimen. The sound field is optimised for the measurement of the wall thickness of steel plates and pipe joints. Special focus is on determining the remaining wall thickness in case of metal loss (e.g. general corrosion, pitting corrosion).

If metal loss is present at the transducer-near side, it is not possible to determine the remaining wall thickness because the lift-off of the EMAT sensor caused by the wall thickness reduction may lead to a complete loss of the ultrasonic signal. In order to ensure reliable measurement for this case, the EMAT technique is combined with the eddy current (EC) technique and the magnetic flux leakage (MFL). The EC technique, that uses the EMAT excitation signal as a pulsed EC excitation, is able to detect metal loss at the transducer-near side by measuring the transducer lift off, simultaneously to the electromagnetic ultrasonic inspection. Additionally, a MFL signal is derived by making use of the horizontal magnetisation and the EMAT receiver coil as flux leakage sensor. The MFL signal can be separated and analysed by appropriate filtering because it contains mainly low-frequency components as compared to the high frequency EC signal respectively ultrasonic signal.

By combining the different inspection technologies the disadvantages of the individual techniques are eliminated. As a result, a sensor has been developed, that is able to measure the (remaining) wall thickness of a component as well as to determine the location in the wall of a detected metal loss. A further advantage of the new sensor conception is that essential hardware components can be used in parallel.

Results obtained so far show that the new probe meets the requirements for high-resolution in-line inspection.

1 Introduction

Pipelines are often exposed to corrosion because of the environmental conditions as well as the properties of the transported media. In order to prevent pipeline damages the pipeline operators inspect the pipelines at regular intervals using in-line inspection tools also called intelligent pigs. These tools are moved with the medium while testing the pipewall with standard NDT techniques such as ultrasonics or MFL.

In liquid pipelines ultrasonic inspections with piezoelectric transducers are readily applied as the medium is used as couplant for transmitting the ultrasonic impulses into the pipewall. By measuring the time of flight between the entrance echo at the internal surface and the

back wall echo from the external surface the (remaining) wall thickness can be determined. Additionally, the location of a metal loss in the wall (internal or external) is obtained by measuring the distance between the sensor and the internal wall.
However, in gas pipelines it is not possible to use the classical ultrasonic inspection techniques because of the absence of the needed liquid couplant. Here the magnetic flux leakage (MFL) technique is usually applied for metal loss inspection. The pipe wall is tangentially magnetised by permanent magnetic yokes. Between the pole shoes of the yoke Hall sensors are mounted to detect the magnetic flux leakage in case of thickness change of the pipe wall.
The use of MFL has some limitations:

- The detection sensitivity with regard to external corrosion is limited (especially in case of larger wall thickness).
- The MFL signal depends on the material properties as well as on the wall thickness. For the determination of (remaining) wall thickness a calibration is needed.
- The accuracy of depth measurement is reduced due to the indirect method as compared to the direct measurement when using ultrasonics.

In this paper we present an alternative to MFL for metal loss inspection in gas pipelines which is based on the dry working EMAT technique. In a similar way as the classical ultrasonic technique the wall thickness (e.g. the wall thickness reduction by metal loss) can be determined by the time-of-flight of the back wall echo signal.
As an EMAT sensor needs to be close to the surface in order to efficiently generate ultrasound, ultrasonic measurement is no longer possible if metal loss is present at the transducer-near side. In order to ensure reliable measurement for this case, the EMAT technique is combined with the eddy current (EC) technique and the magnetic flux leakage (MFL) integrated in a single sensor.

2 Sensor Development and Optimisation

2.1 EMAT Sensor Arrangement

Common EMATs for normal incidence and wall thickness measurement use a normal magnetic field excited by a magnet unit above the coil [1]. The magnetic field provides a strong attractive force between the magnet and the specimen. Therefore the coil that is located between the magnet and the specimen is exposed to strong mechanical stress and strain. Due to the strong force acting on the sensor system heavy wear has to be taken into account in case of a dynamic inspection especially when the sensor crosses weld beads.
The EMAT design described here avoids the wear problem because the magnetiser unit and the coil system are mechanically decoupled. The new magnetiser is designed like a u-shaped yoke similar to an MFL magnetiser that generates a horizontal magnetic field between the pole shoes. The coil system is mounted in the region between the pole shoes. A slight suspension is needed to keep the coil near to the surface of the test object. The coil that is designed as a simple air coil is no longer affected by magnetic forces.
The superposition of the horizontal magnetic bias field and the electromagnetic fields excited by the coil generate an ultrasonic oscillation in the surface of the test object by magnetostrictive interaction [1, 2]. The oscillation is a source for an ultrasonic pulse travelling normal to the surface into the material. The magnetostrictive coupling mechanism is a very effective one as compared to the Lorentz mechanism used in EMAT design with normal magnetisation.

Figure 1 shows the basic sensor arrangement of the new EMAT design.

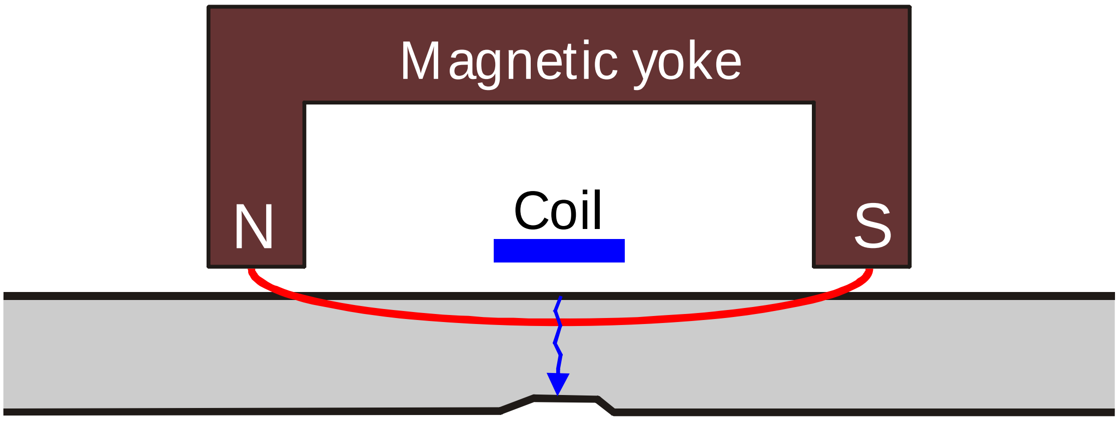

Figure 1: Sensor arrangement

2.1.1 Magnetostrictive Operation Point

The magnetostrictive acoustic coupling depends strongly on the applied bias magnetisation. This dependency has been examined for different pipeline steels. Figure 2 shows the behaviour for the different steel samples. In principle the shape of the curves is similar the field values of the maximum amplitudes are all in the region of 300 to 350A/cm. However, the height of the maximum amplitude varies to some extent.
The optimal bias magnetisation for the generation of ultrasound is not the field value at the maximum amplitude because of the fact that thickness reductions in the pipe wall (e.g. metal loss) lead to an increase of the magnetic bias field at those positions. The effect (see Fig. 3) is well known and exploited in the MFL technique. However, in case of the magnetostrictive generation of ultrasound it is undesirable, because deep wall thickness reductions increase the magnetic field strength and the efficiency of the ultrasonic generation may be considerably reduced. Therefore the operation point is chosen to about ¾ of the maximum amplitude in the raising part of the curve. Then the signal-to-noise-ratio for the ultrasonic backwall echo is sufficient in undamaged areas as well as in damaged regions.

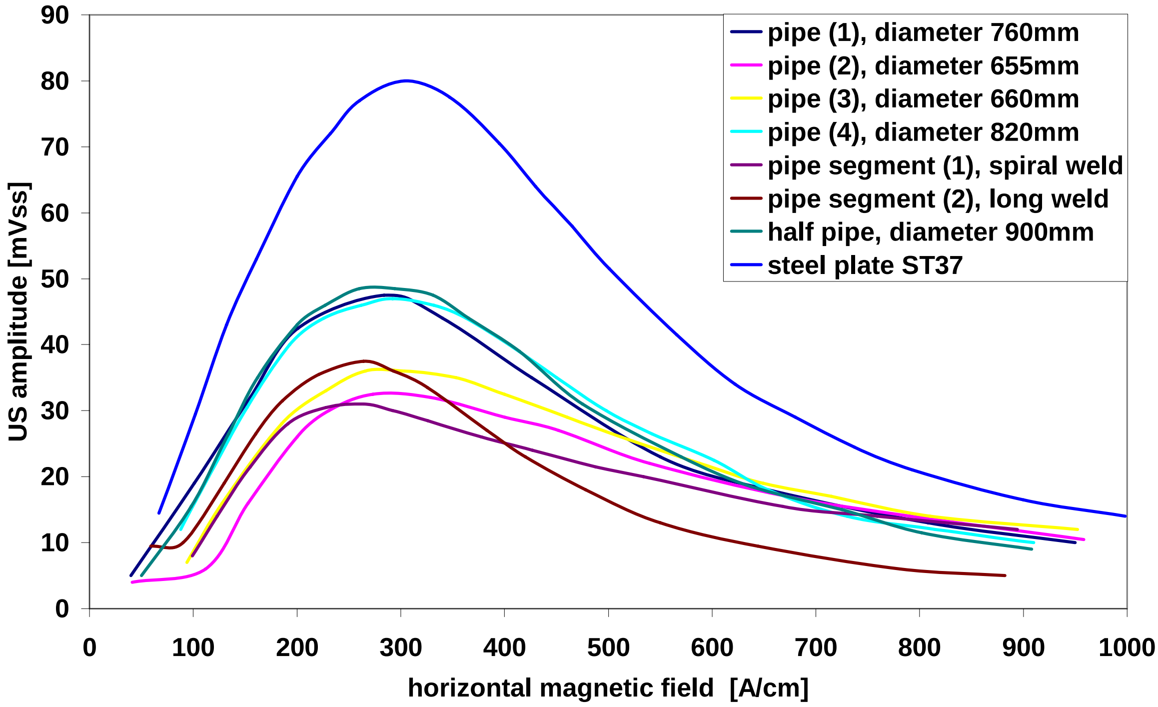

Figure 2: Dependency of the ultrasonic amplitude and the magnetic field strength in case of magnetostrictive coupling for different pipeline steels and ST37

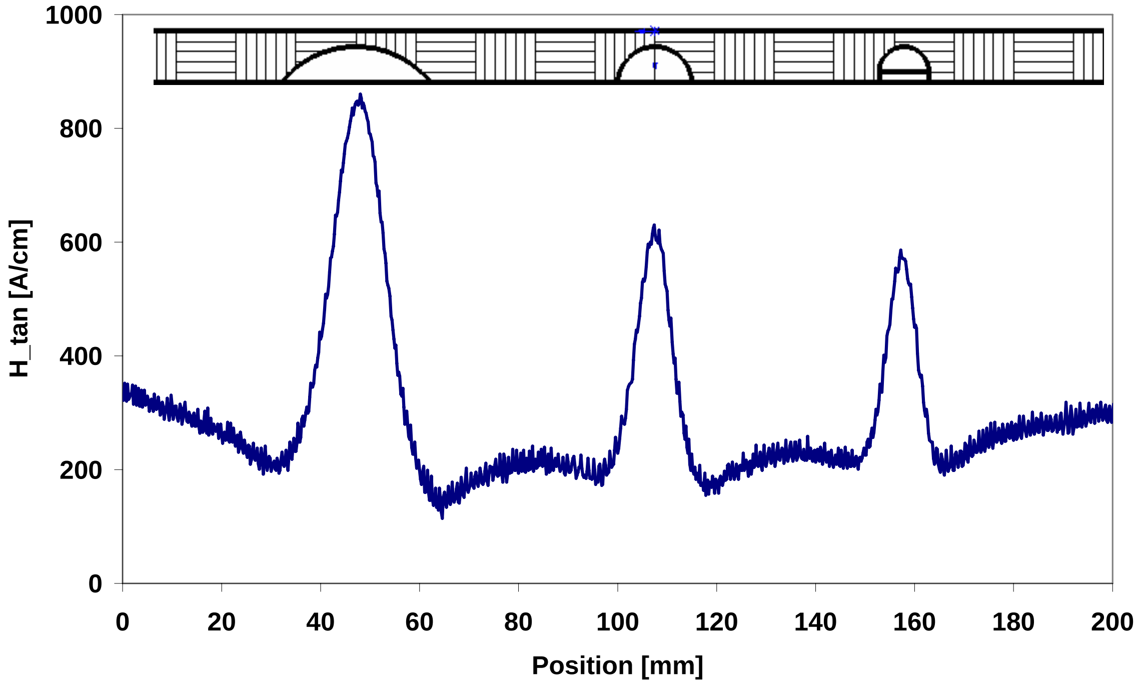

Figure 3: Horizontal magnetic field strength in case of wall thickness reduction. The upper inset shows the shape of the test sample containing three artificial defects.

2.1.2 Sound field

For a precise ultrasonic wall thickness measurement, especially in case of non-parallel and rough surfaces, it is advantageous to have a sound field distribution with a high main lobe

under zero degree and only a low number of side lobes with low amplitudes. Therefore several coil types (see Figure 4, Table 1) have been examined. The best results are obtained using a circular coil with clustered wires and separated transmitter and receiver coils.
A second optimisation criterion is the mode purity of the ultrasonic excitation respectively the selective receiving sensitivity with regard to longitudinal or transversal waves. For a reliable determination of the wall thickness pure modes should be used in order to avoid disturbing signals. The diameters of the circular coils have been varied to optimise the mode purity. The results are shown in Figure 6. The reduction of the coil diameter reduces the longitudinal part of the ultrasonic wave.
Figure 5 shows the combined transmitter and receiver sound fields parallel and normal to the bias magnetisation for the optimised coil design with regard to mode purity and sound field.

Table 1: Investigated coil types

coil type	**amplitude maximum under zero degrees**
oval coil	yes
rectangular coil (1)	yes
spiral or pan cake coil	yes
butterfly coil	no
butterfly coil with angled return paths	no
rectangular coil (2)	no

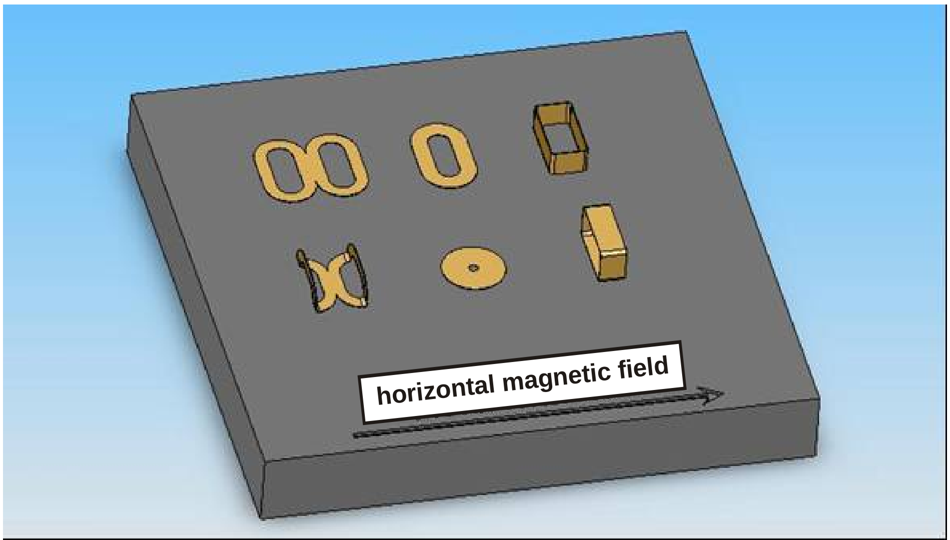

Figure 4: Investigated coil types: upper row, from left to right: butterfly coil, oval coil, rectangular coil (1); lower row: butterfly coil with angled return paths, spiral or pan-cake coil, rectangular coil (2)

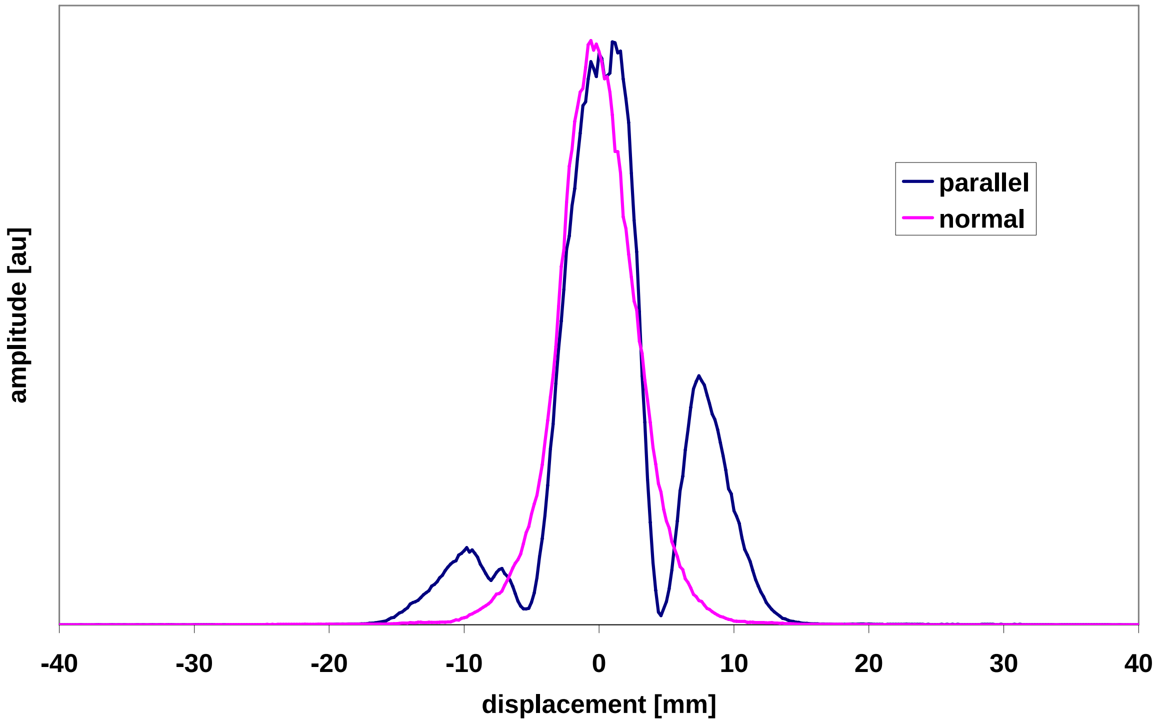

Figure 5: Sound field of the optimised EMAT coil, parallel and normal to the horizontal magnetic field

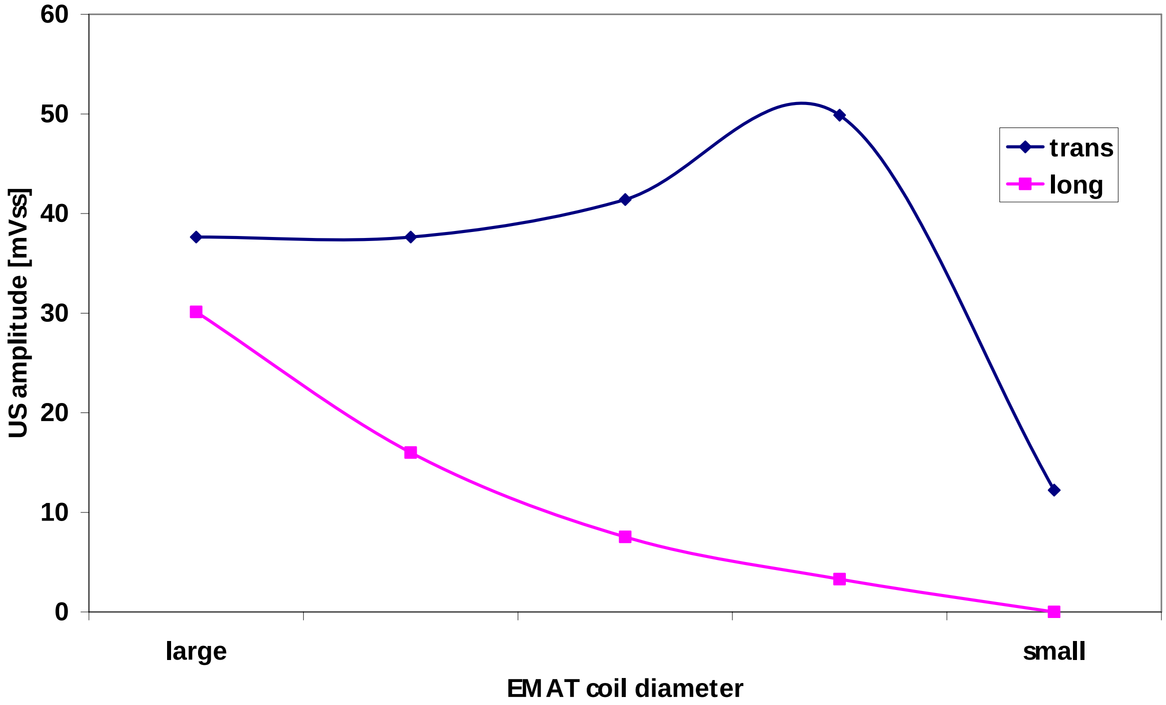

Figure 6: Sound field mode purity for circular coil systems with different coil diameters.

2.2 Combination with Pulsed Eddy Current

If metal loss is present at the transducer-near side, it is not possible to determine the remaining wall thickness because the lift-off of the EMAT sensor caused by the wall thickness reduction may lead to a complete loss of the ultrasonic signal. In order to ensure a reliable measurement for this case, the EMAT technique is combined with the eddy current

(EC) technique. The EC technique is able to detect metal loss at the transducer-near side by measuring the transducer lift-off. The EMAT excitation signal is used as a pulsed EC excitation. Thus both techniques are operated simultaneously. The EC receiving signal can be picked up either by the EMAT receiver coil or by a separate coil. The advantage of using a separate receiving coil is that it can be optimised for EC metal loss detection. The maximum depth that can be resolved depends on the coil diameter: a larger coil diameter leads to a larger depth range.
The evaluation of the received EC signals follows the classical EC signal analysis, separation of amplitude and phase of the signal for the analysis frequencies.
Figure 7 shows the measured amplitude for several sensor lift-offs. With the current configuration, separate EC receiver coil, a determination of the sensor lift-off is possible up to approx. 8mm. At higher depths the signal is saturated.

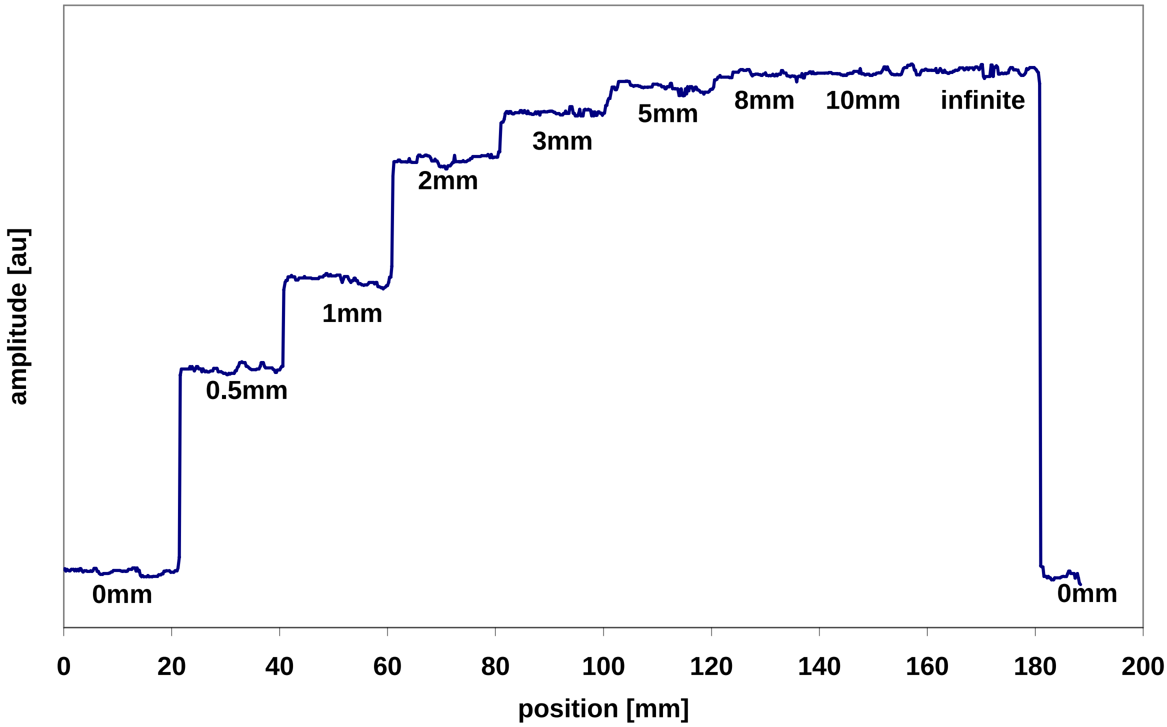

Figure 7: EC amplitude for different sensor lift-off

2.3 Combination with MFL

The EMAT technique is very sensitive to sensor lift-off. In case of internal metal loss the EMAT signal may be completely lost. Then, in addition to the EC signal, also the MFL signal can be used for measuring the depth. Essential hardware components are used simultaneously for both techniques: The magnetiser is used to set the magnetostrictive operation point of the ultrasonic excitation and to magnetise the component for MFL inspection. The EMAT coil is additionally able to detect the MFL component normal to the surface as an induction voltage when moving relative to the component. The integration of the induction voltage yields the value of the MFL signal.
A separation of the receiving signal into an EMAT part and a MFL part is ensured by frequency filtering as the frequency range of the MFL signal is basically different from the range of the ultrasonic signal.

3 Experimental Results

The combined sensor with the optimised coil system has been tested using several specimens with machined corrosion-like defects. The results shown in Figure 8 and Figure 9 are obtained from a 10mm steel plate with calotte-shaped defects. The diameter of the calottes at the surface are 10, 15 and 30mm, the depth is 30% of the wall thickness. The principle set-up is also depicted in the figures. The sensor system is moved along the surface of the specimen, first on the defect-free side and then on the other side containing the defects.
In case of external defects (Figure 8) the wall thickness can be calculated using the time-of-flight of the ultrasonic backwall echo signal. The shape of the artificial defects and the measured wall thickness fit very well. As expected, the EC technique does not show any indication.
Figure 9 shows the results when the defects are located at the internal side. In the defect areas the EMAT signal breaks down, and the ultrasonic thickness measurement is no longer possible. However, the EC technique now detects the inside defects. The depth is determined with the help of the lift-off calibration curve (Figure 7). The measured depths differ somewhat from the real values. This can be explained by the fact that the EC response represents an average value over the sensor and the defect aperture.
In both cases, the MFL signals indicate the defects in the well known manner.

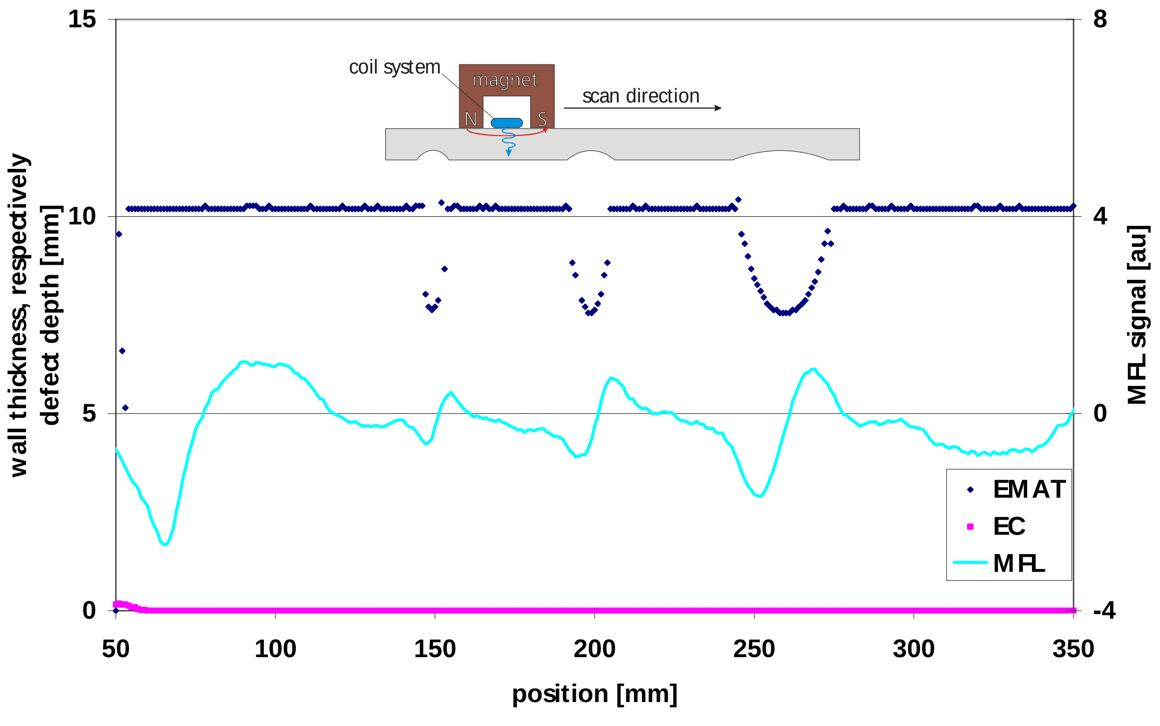

Figure 8: Results of the combined EMAT, EC and MFL inspection of external defects

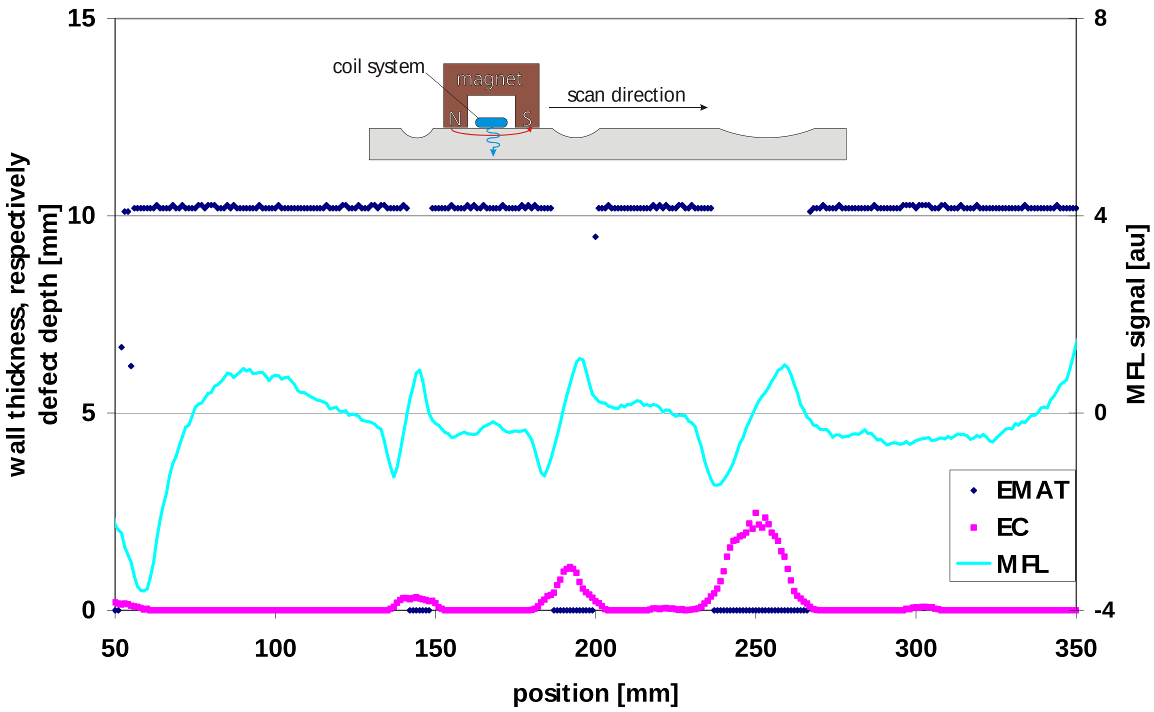

Figure 9: Results of the combined EMAT, EC and MFL inspection of internal defects

4 Conclusions & Summary

An electromagnetic acoustic transducer (EMAT) has been developed and optimised for excitation and detection of linear polarised shear waves at normal incidence with the use of a horizontal magnetisation of the test object. The sound field has been optimised for the measurement of the wall thickness of components such as steel plates or pipe joints. Special focus is on determining the remaining wall thickness in case of metal loss (e.g. general corrosion, pitting corrosion).

The sensor system and the magnetisation unit are mechanical decoupled to reduce the wear of the sensors.

In order to ensure reliable measurement for internal metal loss, the EMAT technique is combined with the eddy current (EC) technique and the magnetic flux leakage (MFL). The EC technique, that uses the EMAT excitation signal as a pulsed EC excitation, is able to detect metal loss at the transducer-near side by measuring the sensor lift-off simultaneously. Additionally, a MFL signal is derived by making use of the horizontal magnetisation and the EMAT receiver coil as a flux leakage sensor. The MFL signal can be separated and analysed by appropriate filtering because it contains mainly low-frequency components as compared to the high frequency EC signal respectively ultrasonic signal.

By combining the different inspection technologies the disadvantages of the individual techniques are eliminated. As a result, a sensor is now available, that allows to redundantly measure the (remaining) wall thickness of a component as well as to determine the location in the wall of a detected metal loss. Table 2 shows an overview on which information is obtained from the individual inspection techniques.

A further advantage of the new sensor conception is that essential hardware components can be used in parallel. In particular, pronounced improvements in the field of metal loss inspections of gas pipelines are expected.

Table 2: Defect information obtained from the individual inspection techniques

	EMAT-Info (US)	EC-Info	MFL-Info
external metal loss: remaining wall thickness	direct measurement	n. a.	indirect measurement (calibration curve)
external metal loss: length	direct measurement	n. a.	(direct) measurement
internal metal loss: remaining wall thickness	n. a.	indirect measurement (calibration curve)	indirect measurement (calibration curve)
internal metal loss: length	direct measurement	direct measurement	(direct) measurement

References

[1] Hirao, M. and Ogi, H. (2003), EMATS for Science and Industry (Kluwer Academic Publishers)

[2] Wilbrand, A. (1990), Theoretische und experimentelle Untersuchungen zu einem quantitativen Modell für elektromagnetische Ultraschallprüfköpfe, Technisch-Wissenschaftlicher Bericht Nr. 900125-TW, IZFP Saarbrücken