MEASUREMENTS OF SURFACE-BREAKING FLAWS IN STEEL PIPES USING A SQUID SUSCEPTOMETER IN AN UNSHIELDED ENVIRONMENT

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INTRODUCTION

This paper describes the application of a SQUID susceptometer in nondestructive evaluation of steel pipes used in oil refmeries. Commonly used methods, such as ultrasound and eddy current techniques [1], normally need a very small liftoff distance between the pipe wall and the sensor, which would require removal of the thermal insulation protecting the pipe, thus increasing the costs related to the inspection.

SQUIDs have already proven to be able to perform nondestructive evaluation tasks without the need to remove such thermal insulation, having been successfully applied in electric current injection inspection of planar aluminum samples [2][3], with liftoff distances of up to 9 cm. So, SQUID systems open new frontiers for nondestructive evaluation with large liftoff of electrically conducting and ferromagnetic materials. Also, the development of high temperature SQUIDs, to which superconductivity occurs at liquid nitrogen temperatures, will further reduce the costs associated with the inspection by eliminating the need for cryogenic equipment to operate the SQUIDs with liquid Helium.

The next section describes the experimental setup used and the principle of operation of the SQUID susceptometer, followed by a description of the sample, which contains machined flaws, and the experimental results. Also, a comparison of these results with those from a commercial finite element method software is discussed.

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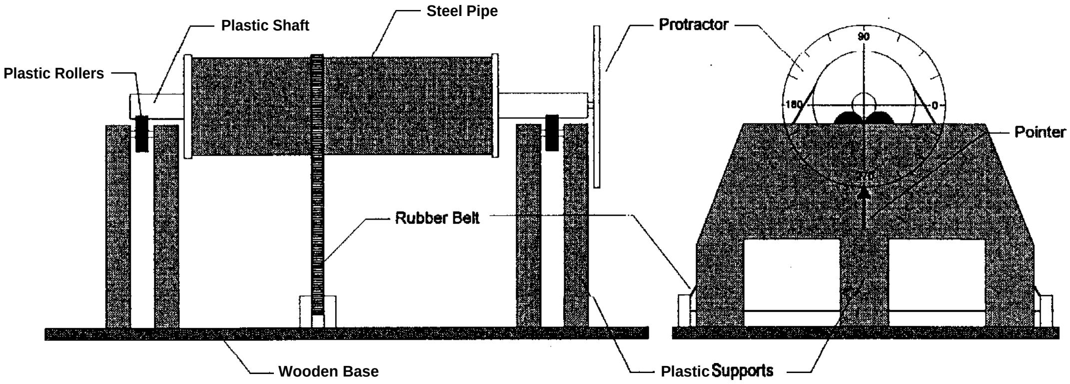

Figure 1. Side and front view of the plastic sample holder built to support and rotate the steel pipe. The angular position is measured with a 360° protractor.

THE EXPERIMENTAL SETUP

In order to overcome the difficulties found in rotating the SQUID sensor around a steel pipe, an assembly to hold the sample and allow its rotation was built. The assembly is depicted in Fig. 1, and was fabricated using only non-magnetic materials, such as plastic and glass. A protractor is connected to the pipe, so that the sample can be accurately rotated in one-degree increments, and a rubber belt is used to hold the sample stationary at each position. The sample used in this work consists of a 5 mm thick pipe with a length of 30 cm and a radius of 4.5 cm, made of 1020 steel.

By using such assembly it was possible to keep the liftoff distance constant, so, for imaging purposes, the surface of the steel cylinder can roughly be regarded as a plane. To make the measurements, a SQUID susceptometer (Conductus, Inc.) was used, whose principle of operation is shown schematically in Fig. 2. The gradiometer coils are positioned in such a way that in normal operation the magnetic flux generated by the dc magnet is not detected by the SQUID. When a superficial flaw in the material is scanned past the SQUID, however, the magnetic flux lines are distorted, and the field difference between the two gradiometer coils leads to a net flux being coupled to the SQUID, so that a peak signal can be observed above the flaw location.

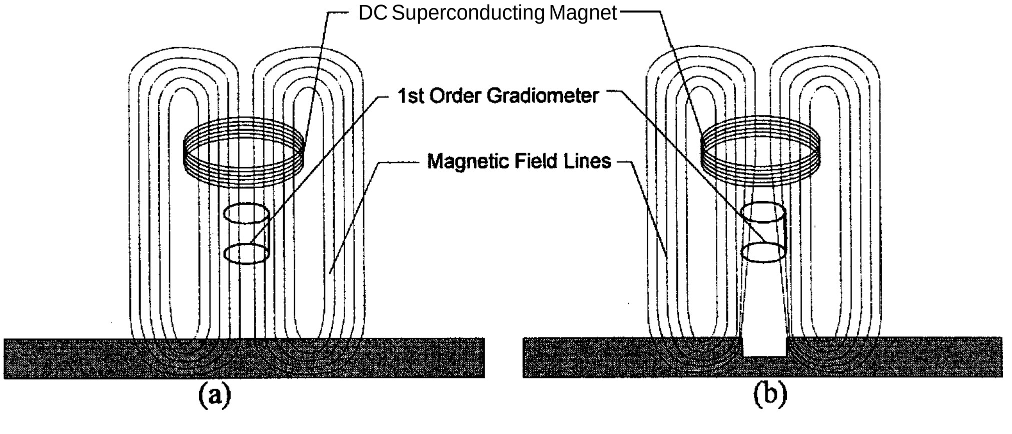

Figure 2. Principle of operation of the SQUID susceptometer: (a) DC magnetic field applied to an unflawed sample. The two oppositely wound gradiometer coils couple zero net flux to the SQUID. (b) Field applied to a flawed sample. The field lines are distorted, and the net flux through the gradiometer and hence the SQUID is no longer zero.

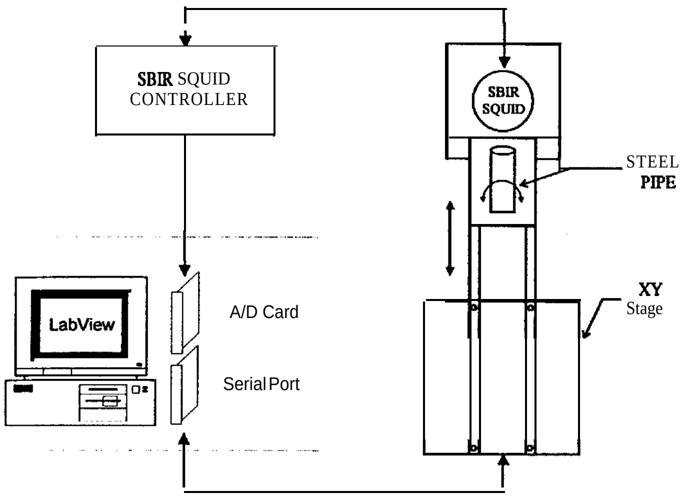

Figure 3. Measurement system used in this work, comprised of a SQUID susceptometer, SQUID controllers, a PC computer equipped with an A/D Card and LabVIEW, an XY scanning stage, and the plastic sample holder shown in Fig. 1.

The superconducting magnet used in this work has a diameter of 2.4 cm, a height of 2.5 cm, and can carry up to 20 A, thereby generating a magnetic flux density of up to 1.5 T at 1 cm from its base. The DC-SQUID is connected to a first order gradiometer with a 5 mm diameter and a 2 cm baseline. The base of the magnet and the gradiometer face coil lie in the same horizontal plane and are coaxial. Figure 3 shows the whole measurement system used in this work. The output signal from the SQUID electronics is read with the aid of a PC-computer, using an A/D converter and an acquisition program implemented in LabVIEW [4]. The program also implements the control of an XY-stage based on stepper motors, used for scanning the sample in the axial direction beneath the SQUID. So, for each angular position, a straight line was scanned, and all such lines were then combined to form two-dimensional images.

SAMPLE MACHINED FLAWS

Three sets of flaws have been machined at different angular positions in one steel pipe using drills and end mills. Figure 4 shows schematically such flaws, which will be further referred to as flaw sets #1, #2 and #3.

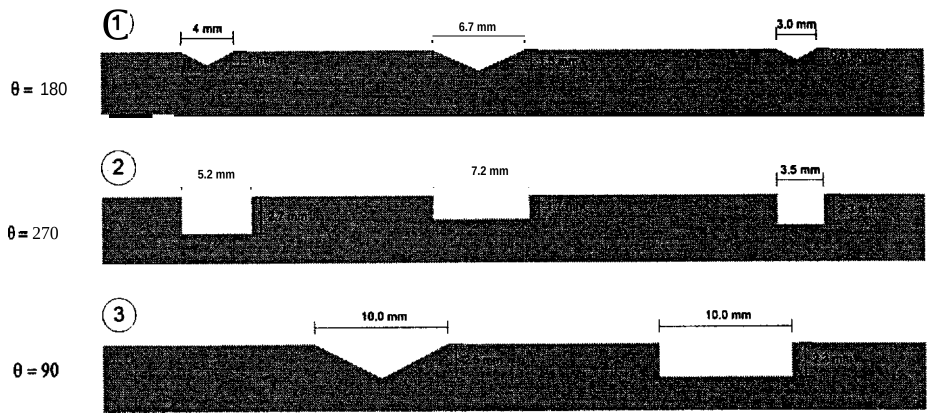

Figure 4. The three sets of flaws machined in the steel pipe.

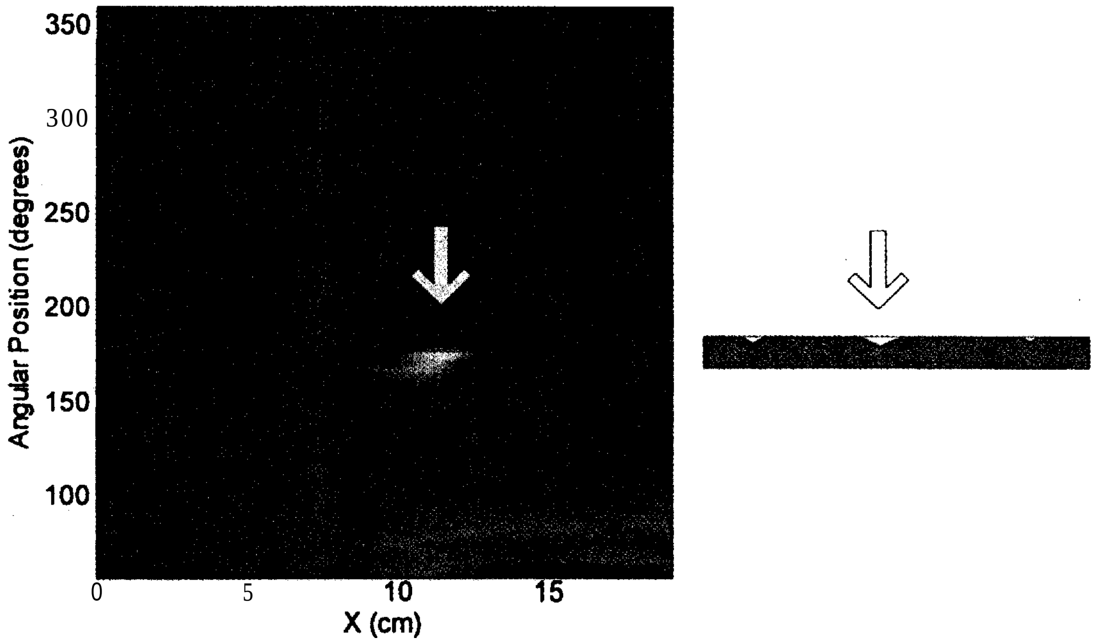

Figure 5. Susceptometer response at 2 cm liftoff, with 20 mT applied field, for flaw set #1.

RESULTS

Figure 5 above presents the image obtained by scanning the susceptometer over a region containing flaw set #l. Figure 6 show the image obtained over a region containing flaw set #2, at a higher liftoff (3.2 cm) and with a higher applied field (40 mT).

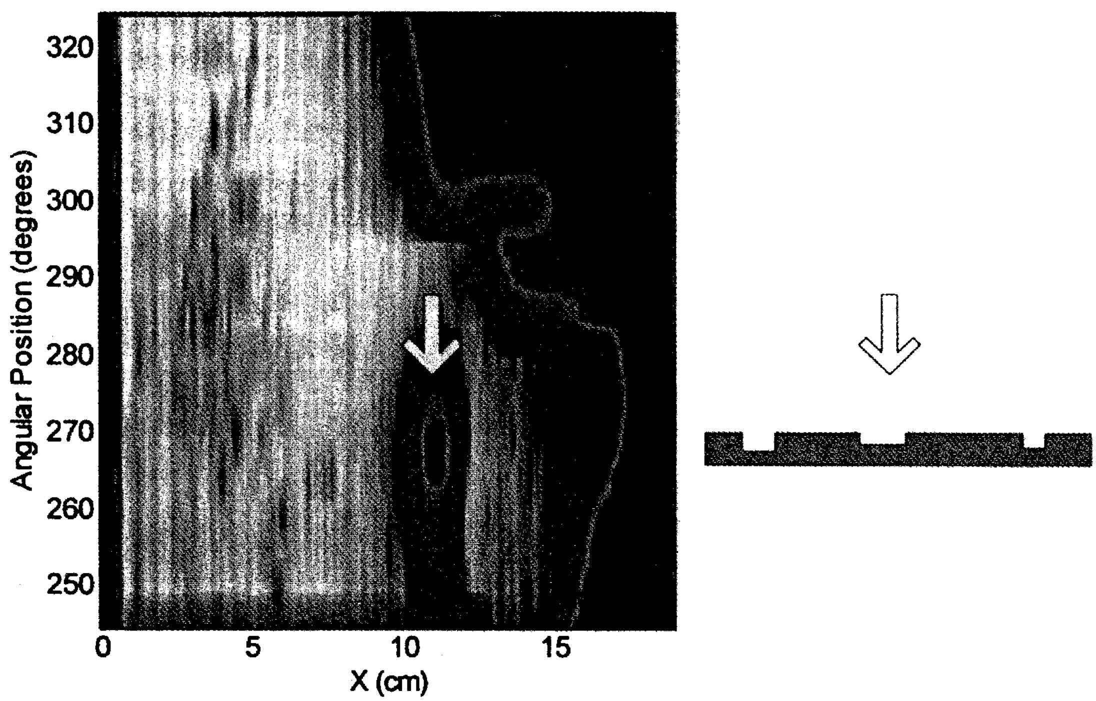

Figure 6. Susceptometer response at 3.2 cm liftoff, with 40 mT applied field, for flaw set #2.

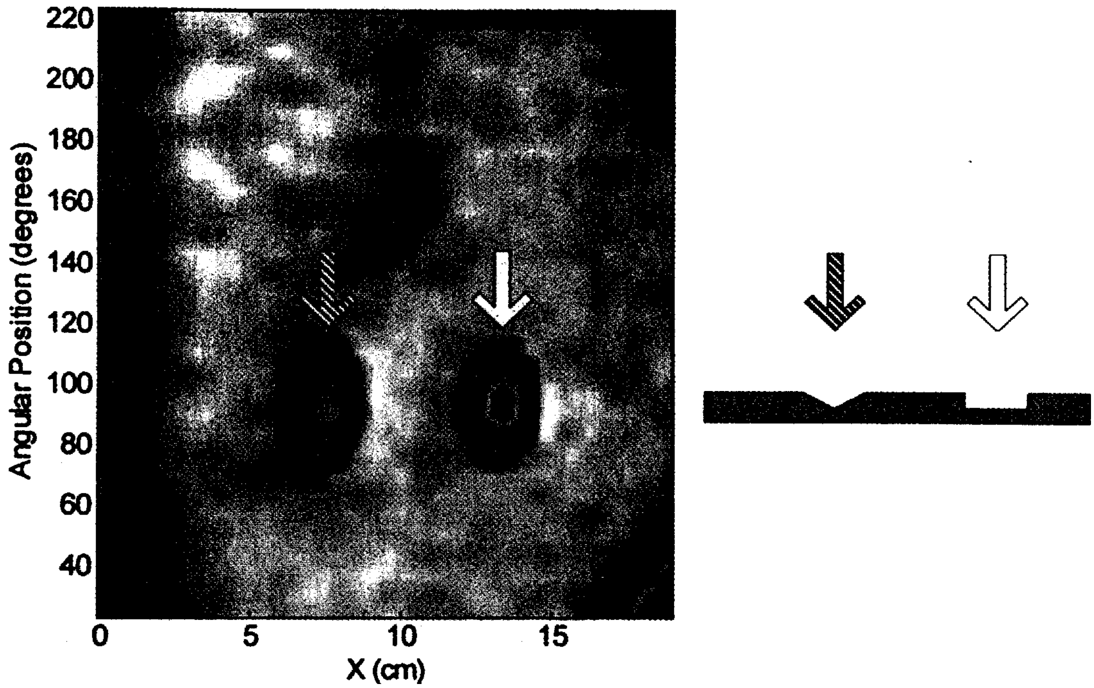

Figure 7. Susceptometer response at 3.2 cm liftoff, with 40 mT applied field, for flaw set #3.

Figure 7 above shows the image obtained over set #3, with the same liftoff (3.2 cm) and applied field (40 mT) used previously on set #2. In Fig. 8 below, the liftoff has been further increased to 3.7 cm, and the applied field has been decreased to 30 mT, and the entire pipe circumference was scanned. Flaw set #3, and one flaw of set #2 are visible. Finally, a different visualization scheme is shown in Fig. 9, in which the image of Fig. 7 is mapped onto the surface of the steel pipe.

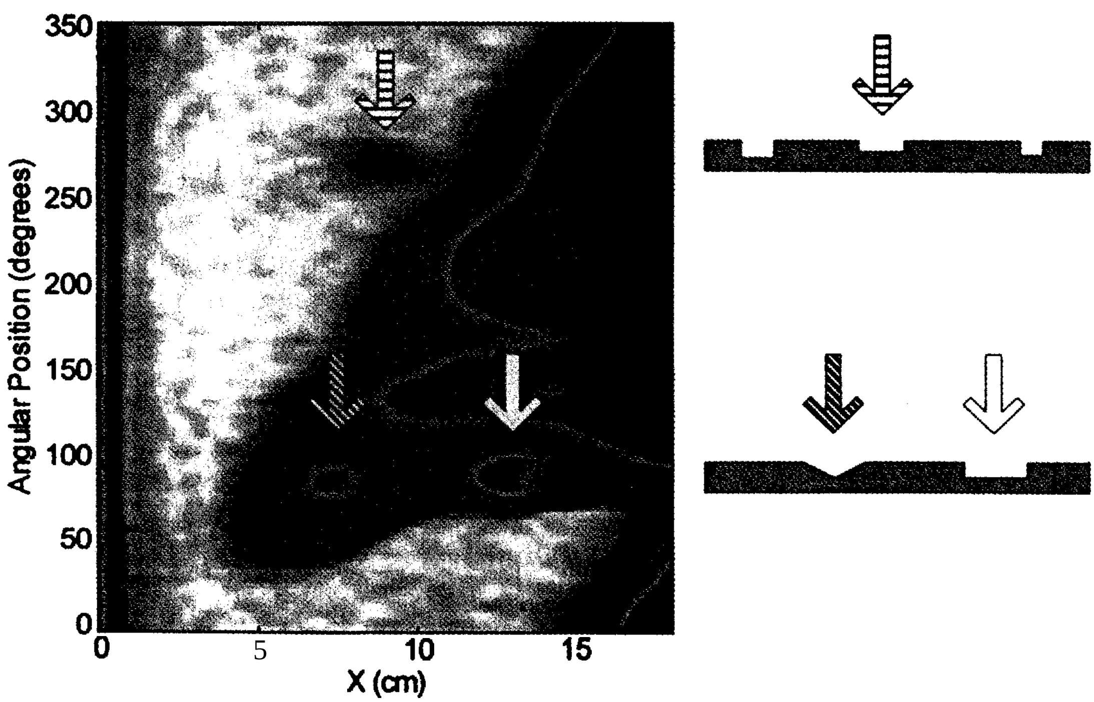

Figure 8. Susceptometer response at 3.7 cm liftoff, with 30 mT applied field, for flaw sets #2 and #3.

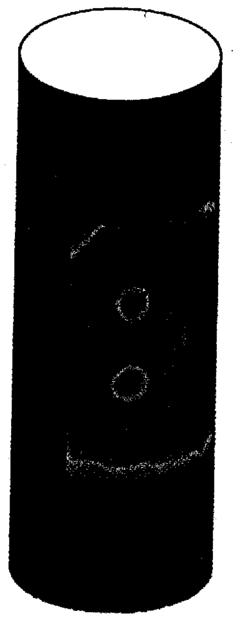

Figure 9. Experimental result shown in Figure 7 mapped on the steel pipe surface

COMPARISON WITH FINITE ELEMENT METHOD SIMULATION

Figure 10 shows a comparison between the experimental result shown in Fig. 7 and the magnetic field simulated using finite element method (FEM) software [5]. The simulated magnetic field is broader than the experimental one because a uniform magnetic field was used as excitation in the FEM model, instead of the actual field generated by the dc magnet. Also, electric currents are induced in pipe radial direction due to the scanning speed, causing distortions in the experimental field, which becomes non-symmetrical [6].

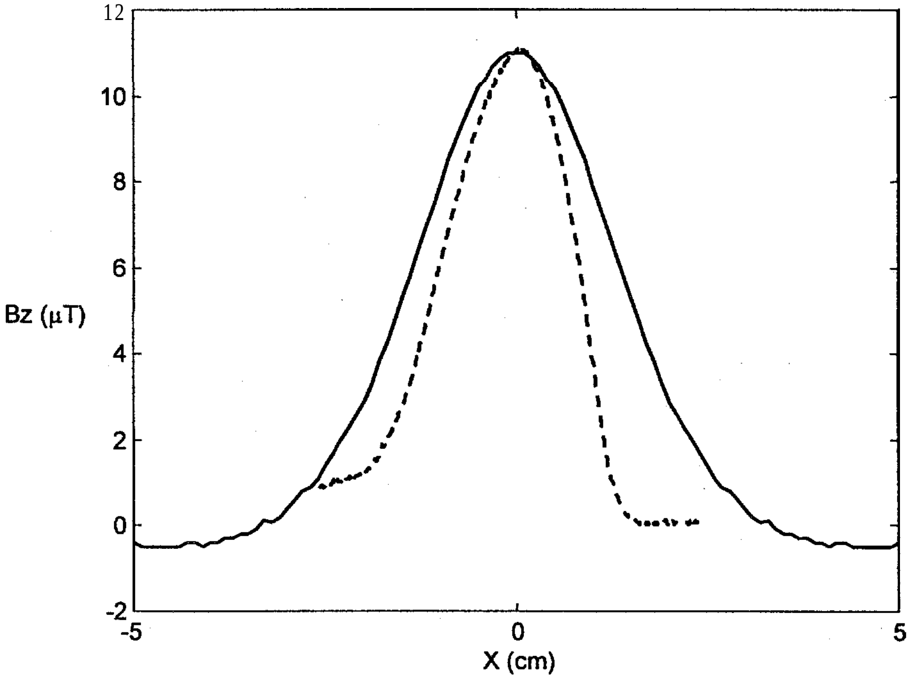

Figure 10. Comparison between FEM simulation (solid line) and experimental result (dashed line), for the case shown in Figure 7.

CONCLUSION

A SQUID susceptometer has been successfully applied in the detection of surface-breaking flaws in steel pipes used in oil refineries, in a magnetically harsh laboratory environment without any shielding. DC magnetic fields with magnitudes ranging from 20 mT to 50 mT have been applied, and the SQUID sensor was coupled to a first order gradiometer with 5 mm diameter and 2 cm baseline. Various flaws were detected, with diameters ranging from 3 mm to 10 mm and depths from 1.5 mm to 2.5 mm. The liftoff distances between the gradiometer base and the steel pipe surface varied from 2 cm to 3.7 cm, far enough to allow the testing of pipes with thermal insulation up to 2.5 cm thick. The high environmental noise present in the measurement site, about 0.5 μT, prevented the detection of' the smaller flaws, in that the magnetic noise was comparable to the magnetic signals, as predicted by the FEM calculations. Also, the 2.0 cm baseline of the gradiometer will have reduced the signature of flaws for liftoffs greater than 2.0 cm.

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