Detection of deep-lying subsurface cracks by SQUID-based low frequency eddy current techniques

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Abstract

The application of standard eddy current techniques is limited to surface breaking defects or subsurface defects which are located extremely near to the surface. In order to increase the inspection depth, extremely low frequencies have to be used and magnetometers which are most sensitive at these frequencies. This paper describes a SQUID-based low frequency eddy current system with the special challenge of the inspection within bore holes. It is shown that the system is such sensitive that it can detect defects down to 1.5 mm radius being located 5 mm below the surface.

1. Introduction

The subject of this paper is a non-destructive testing method to detect small deep-lying subsurface cracks in non-magnetic metal parts. A prominent example are aero engine turbine discs made of a nickel-based alloy. In this application a special variety of the NDT problems is the detection of deep-lying subsurface cracks within bore holes. In this case the probe has to fit into the holes. This paper describes a work using a low frequency eddy current (LFEC) approach.

Often an eddy current (EC) sensor consists of only one coil combining the functions of magnetic field generator and magnetic field detector. Due to the skin effect extremely deep-lying subsurface cracks can only be detected using very low signal frequencies. Then a coil as magnetic field detector can not be used because of its vanishing sensitivity at low frequencies. Instead, a separation of generator and detector is necessary. We use furtheron as magnetic field generator a coil system and as magnetic field sensor the most sensitive which is available. This is a so-called Superconducting Quantum Interference Device (SQUID). It can be used directly [1] or together with an adapter which plays the role of an AC magnetic flux transformer. We describe below our results with both kinds of the SQUID application in a LFEC system.

2. Cracks under a flat surface

2.1. Measurement system

The basics of the measurement system are described in [2], the principal view is shown in figure 1. It consists of three SQUID sensors which make up a so-called SQUID gradiometer unit. This is used to suppress parasitic magnetic background signals, e. g. variations of the earth magnetic field and man-made magnetic noise. Figure 1 also shows the principle of the device under test. It is a disc with two layers. At the border of the two layers artificial cracks 1 to 4 are located. The magnetic field generator is realized by two eddy current coils which are operated in opposite phase. The SQUID gradiometer detects the resulting magnetic field at a constant radius above the disc when it is rotated on a turntable

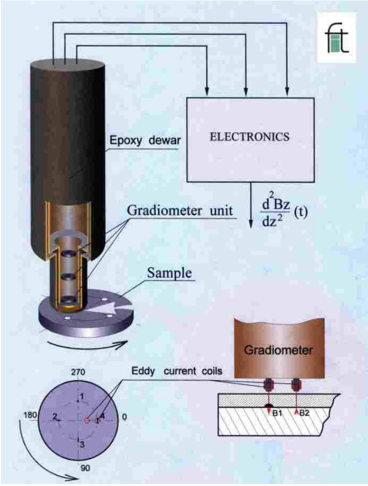

Figure 1. Principal view of the measurement system *(please click on image to enlarge)*

2.2 . Measurement results

Measurements were performed with both the upper part of the disc being 3 mm thick and being 5 mm thick. Here only the more challenging situation of 5 mm thickness is described. Results are shown in figure 2. The horizontal axis is the rotation angle extending from 0 o to 360 o between the two trigger signals. The vertical axis shows the rectified signal of the SQUID gradiometer. The defects are made as segment-shaped cut-outs. Their view and positions are shown on the right-hand side of figure 2. The defect width is d = 0.3 mm. Length l and height h for the defects 1 to 4 are given in the rectangular frames on top of the main part of figure 2.

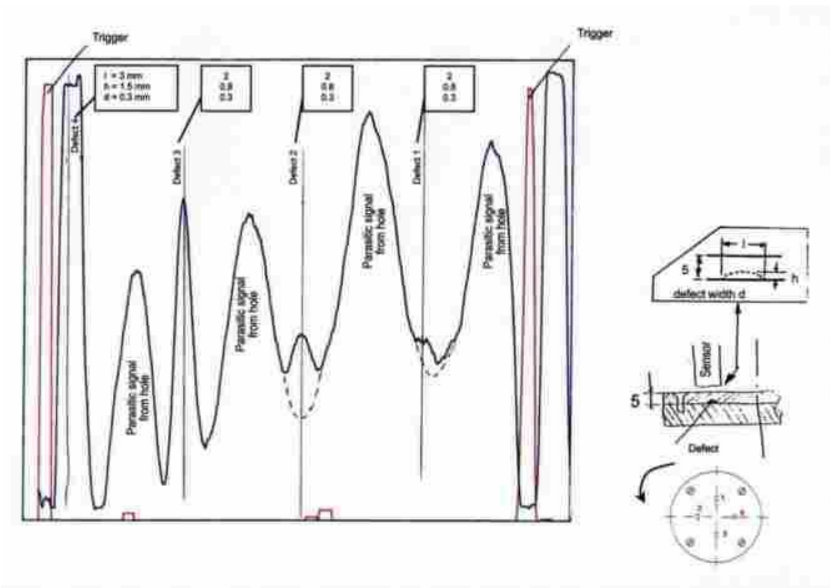

Figure 2. Measurement results:artificial cracks under a flat surface *(please click on image to enlarge)*

The two slices of a sample are hold together by four screws as it is shown in the lower right corner of figure 2. These screws and the holes generate considerable background signals, marked as “parasitic signal from the hole in the diagram. Only the large artificial defects #4 and #3 produce signals which are not affected by this back ground signal. The smaller defects #2 an #1 are affected by the background signal; the output amplitudes belonging to these two defects may be estimated when taking the dashed lines as the base line. It can be concluded that even the smallest artificial defect, being 0.5 mm long, 0.3 mm high and 0.25 mm wide and lying 5 mm below the sample surface, can be detected. The enlarged defects correspondingly produce larger signals.

3. Cracks under the surface of a borehole

In most practical situations such screws will not be present and disturb the measurements. Taking this into account and the challenge of testing inside a borehole, further samples have been prepared: samples with artificial defects and samples with natural defects. In the following the measurement system and measuring results will be described.

3.1. Measurement system

The goal of the work is to test within boreholes with diameters of approximately 40 mm. The SQUID gradiometer unit is too large and does not fit into such a hole. For this reason and to increase the spatial resolution, an adapter is added to the SQUID gradiometer which consists of two coils and acts as an AC magnetic flux transformer. Figure 3 shows the block diagram of the complete SQUID-based eddy current system of this type. Figure 4 shows a photograph of a specimen and the sensor part of the adapter, the specimen being placed on an turntable. When measuring, the sensor part of the adapter is moved down into the hole, so scanning the wall at a constant sensor depth below the upper plane of the specimen.

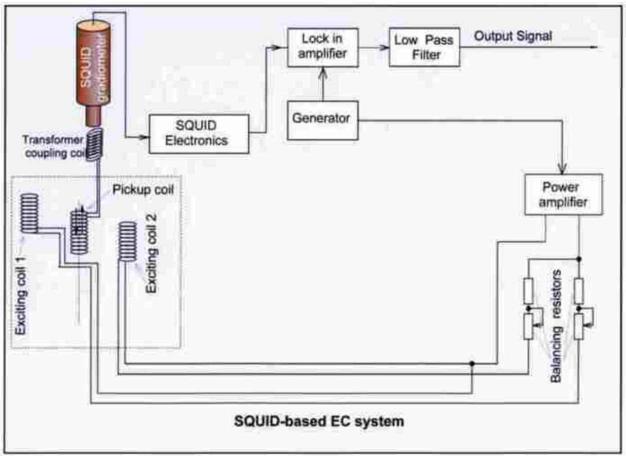

Figure 3 . Block diagram of SQUID-based EC system *(please click on image to enlarge)*.

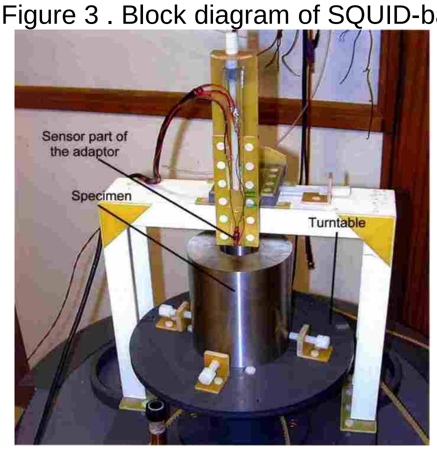

Figure 4. Photograph of a specimen and the sensor part of the adapter *(please click on image to enlarge)*.

3.2 . Measurement results

3.2.1. Artificial defects

Figure 5 shows a drawing of the samples with the artificial defects. Their width is about 0.2 mm, their radii R1 and R2 vary from 0.35 mm to 3.0 mm. The wall thickness t of the inserted metal tube varies between 1 mm and 10 mm. This thickness t is also the depth of the defect under the surface. Not all of the results are shown here, but only a part of them. Figure 6 shows the signal of an artificial defect of radius 0.35 mm and lying 1 mm below the surface. This signal is more than an order of magnitude larger than any of the background signals. Figure 7 shows a defect of radius 1.5 mm being 5 mm below the surface. Also in this case the defect can clearly be recognized. In addition to the A-scans, as shown in figures 6 and 7, also C-scan type of diagrams were generated. Figure 8 shows an example. The wall thickness of the inserted tube is 5 mm. The left-hand side of figure 8 shows the measurement result stemming from a defect with a radius of 3 mm and the right-hand side shows the result of a defect with the radius of 1.5 mm. The C-scans are to be understood such that the inner radius of the displayed ring corresponds to a sensor depth of 30 mm and the outer radius of the ring corresponds to a sensor depth of 60 mm for the right-hand side of figure 8. Similar holds for the left-hand side of figure 8. The magnetic fields range from red to deep violet. In both examples the signals of the defects can clearly be seen.

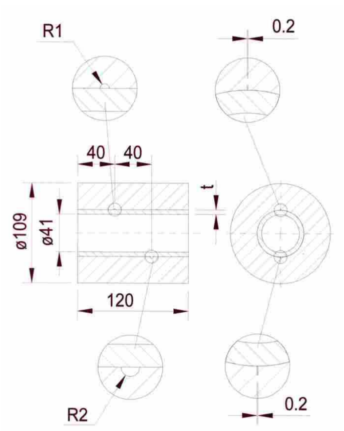

Figure 5. Drawing of the samples with artificial defects *(please click on image to enlarge)*.

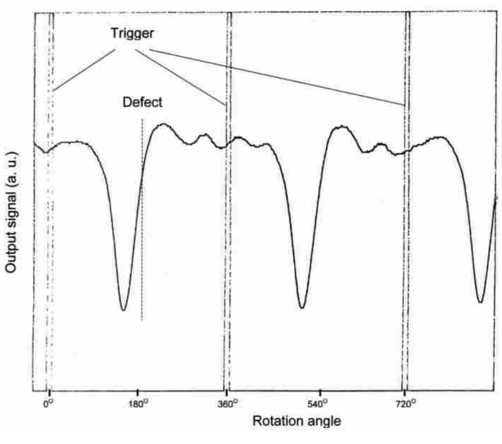

Figure 6. Output signal versus rotation angle for a defect of radius 0.35 mm lying 1 mm below the surface *(please click on image to enlarge)*.

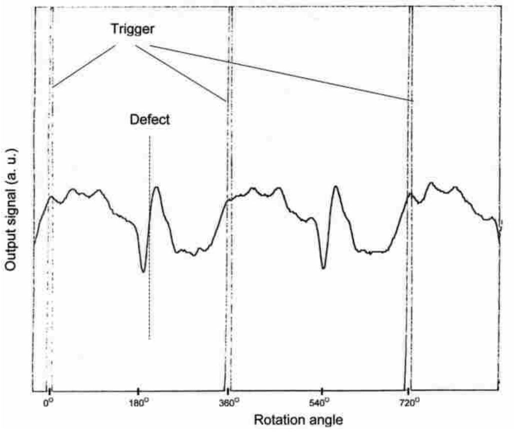

Figure 7. Output signal versus rotation angle for a defect of radius 1.5 mm and 5 mm below the surface *(please click on image to enlarge)*.

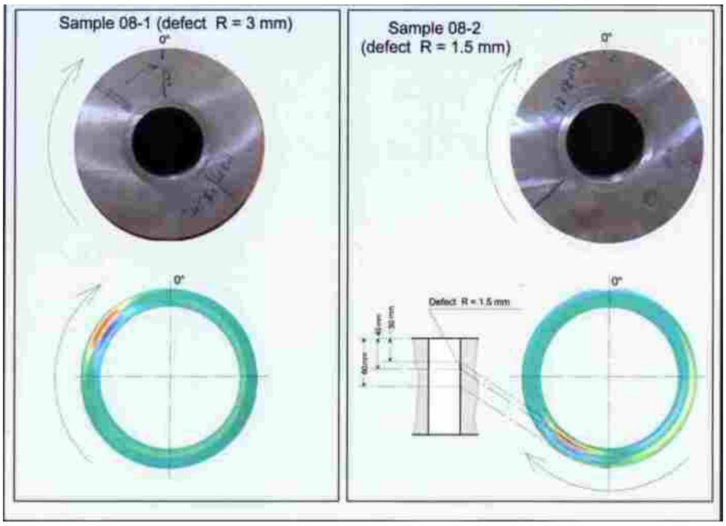

Figure 8. C-Scan diagrams of sample with artificial defects inspected with the LFEC technique. Spacing is 5 mm. Left: defect radius 3 mm. Right: defect radius is 1.5 mm *(please click on image to enlarge)*.

3.2.2. Natural defects

Natural defects were prepared in the following way. During the maintenance of turbines, surface breaking cracks in boreholes of turbine discs are detected by standard methods. A couple of them were selected and the discs were machined into proper dimensions around these cracks in boreholes. Figure 9 shows such a sample. On the inner surface of the bore hole #2 there is a natural crack, being 5 mm long and of unknown depth but anyway less or equal to 2.5 mm. Similar as described in section 3.2.1, tube sections were inserted into this hole, such realizing different spacing. The measurement results of the sample of figure 9 are shown in figure 10. The material was Udimet 710. It can be seen from figure 10 that even with a spacing of 5 mm the defect can be recognized in the signal.

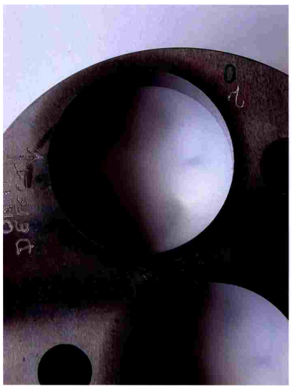

Figure 9. Sample with bore hole #2 and natural defect. The angular position of the defect is marked by an arrow *(please click on image to enlarge)*.

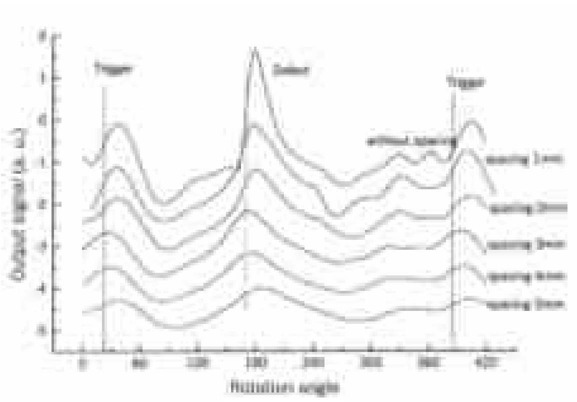

Figure 10. Output signal versus rotation angle for the natural defect. Spacing ranging from 0 mm („without spacing“) to 5 mm *(please click on image to enlarge)*.

4. Conclusions

We have built a setup to inspect non-magnetic metal parts within bore holes for cracks which lie deep below the surface. For example, within a bore hole of 40 mm diameter cracks of 1.5 mm radius could be detected lying 5 mm below the surface. Also natural defects in the same position could be detected. This system is a promising tool for improving the deep detection of defects which may be dangerous for the airworthiness of aerospace engines critical components.

5. References:

[1] Y. Tavrin, H.-J. Krause, W. Wolf, V. Glyantsev, J. Schubert, W. Zander, and H. Bousack:, Cryogenics, 26 (1996), No. 2, 83.

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