High-Resolution Magnetometry based on Unshielded SQUID System

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When testing material or machined parts for cracks, inclusions and further non-tolerable inhomogeneities, a non-destructive testing (NDT) often is preferred or even necessary compared with a destructive testing method. Eddy current testing and ultrasonic testing are two such NDT methods which are very powerful and therefore often used. Both, however, have their limitations. Standard eddy current tests only allow for inspections into a quite limited depth under a metal surface. And, for example, if iron inclusions have to be detected within a non-ferrous metal alloy, ultrasonic testing fails because the inclusions have ultrasonic properties similar to that of the surrounding material. Then the ultrasonic contrast is not high enough to be detected.

Both limitations can be overcome with a magnetometer of high sensitivity, especially at low frequencies. The **HMT Magnetometer System** which is described in this SPOT BEAM has such properties. Provided that the ambient noise is not extremely high, the system furthermore does not need any magnetic shielding. Therefore it is capable of testing abitrarily large objects.

Beyond applications in NDT, the HMT can be used for magnetic microscopy. The magnetic image of an object can be generated without special treatment of the surface. Furthermore the HMT can measure to a high resolution the magnetic fields which are generated by human heart activities.

Summarizing, example applications of the HMT are:

- Non-destructive testing NDT
    - localized ferromagnetic inclusions, i.e. Fe, Co or Ni, in nonmagnetic metal matrix
    - distributed ferromagnetic impurities in non-magnetic material
    - eddy current test for large depths

- Magnetic Microscopy
- Magnetocardiography MCG

Fig. 1: HMT Magnetometer System

System Outline

The HMT is based on SQUIDs made from high-temperature superconductors and are cooled with liquid nitrogen (LN2) for operation. **Fig. 1** shows the HMT system, in this case supplemented with a turntable, on which round disks are rotated when testing them. The crane of the HMT holds the cryogenic part of the system and a part of the electronics.

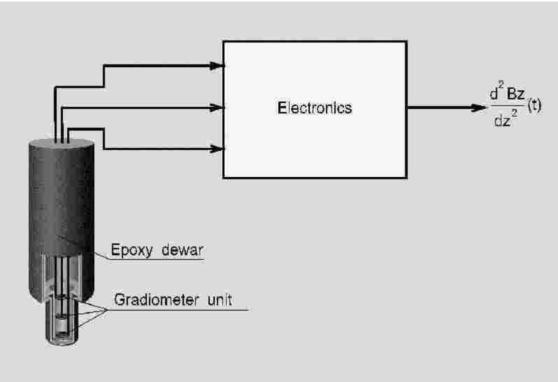

Fig. 2: Principle view of second-order gradiometer

The cryogenic part consists of a non-magnetic fibreglass-reinforced epoxy dewar (thermos) and three identical RF SQUIDs with flux concentrators inside a balancing fixture. The SQUID magnetometers are electronically connected such that they make up a second order gradiometer.

The electronics also suppresses the hum frequency of 50 Hz and its harmonics. The ouput of the system is not the magnetic field itself but its second order gradient, see **Fig. 2.** Working similar as an electronic bridge circuit, this second order gradiometer essentially suppresses environmental noise because the output signal is proportional to $1/R^5$, where R is the distance of the gradiometer unit to the magnetic field source. The device under test (DUT) is usually placed directly below the HMT (R small) and thus a signal from the DUT is practically not suppressed. The noise sources, however, are usually far away enough (R large) to ensure that the magnetic noise is considerably suppressed. Main system parameters are shown in **Table 1.**

Table 1: Performance of HMT Magnetometer System in unshielded space

Parameter	**Value**
Gradiometer Base-line	2 x 60 mm
Spectral field resolution	130 fT × $Hz^{-1/2}$
Dynamic range	150 dB
Slew rate	$10^5\ \Phi_0$ / sec
Field/flux coefficient	5×10^{-10} T / Φ_0
Common-mode rejection	4000
Gradient rejection	200

Fig. 3 shows the noise spectrum, which is white down to 1 Hz at a level of 130 fT × Hz $^{-1/2}$

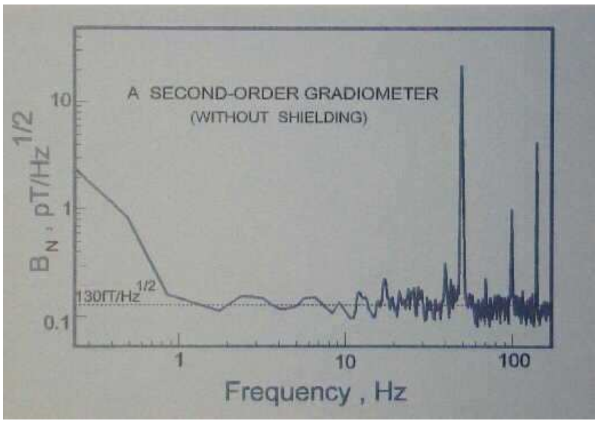

Fig. 3: Magnetic field noise B_N of HMT Magnetometer System

An important application of the HMT is the test for ferrous inclusions in high pressure turbine discs made from a non-magnetic metal alloy. On principle, such ferrous inclusions can be introduced during the manufacturing process and, if present, they can be the origin of cracks in these most critical parts. Therefore such tests are stringent necessary.

In these tests it is to be determined if iron inclusions with a mass greater than a minimum value are present and, if yes, at what location within the disk. The large thickness of the disc is a special challenge.

According to the shape of device under test, in this case a turntable is used to support and move the disc during measurements.

Fig. 4 shows an example measurement for artifical inclusions with masses of 1mg, 10mg, and 15 mg at a depth of 70mm. It is seen that in the present version of the HMT the resolution limit for an inclusion at 70 mm depth is much below a mass of 1 mg.

A measurement procedure has been developed that allows to determine the mass of the inclusion as well as its location with respect to radius, angle, and depth.

The aero engine manufacturer BMW Rolls - Royce is using this technology to asses the cleanliness of certain materials. For this, F.I.T. Messtechnik is doing the HMT-based measurements. Based on this NDT technology, high performance materials with improved reliability can be used for optimum design.

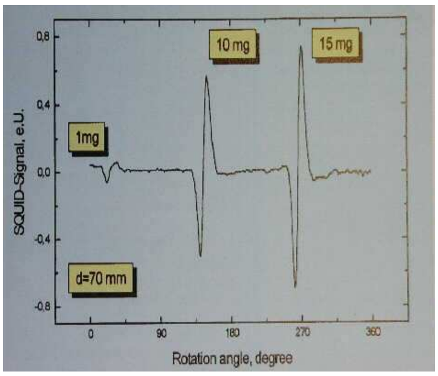

Fig.4: SQUID-Signals of Defects with Different Masses

Further Example Measurements

The activity of the human heart is connected with electrical currents and potentials. Medical doctors and patients are used to electrocardiography, where the potentials are monitored by attaching electrodes to the human body. A contactless method is the magnetocardiography (MCG) where the magnetic field is monitored which stems from the currents. These fields, however, are very small and normally hidden amongst environmental magnetic noise. The HMT, on the other hand, is such sensitive and such specific to fields from nearby sources that it is best suited to monitor an MCG with high signal-to-noise-ratio even without any magnetic shielding, see **Fig. 5**.

The HMT can be supplemented with an appropriate holder and scanning arrangement to produce the magnetic image of a device under test. The lateral resolution of the system is a few tens of micrometers, see **Fig. 6.** Therefore the system is called a **magnetic microscope**. It will be of interest to examine the remanence of paleomagnetic samples as well as the current distributions in solar cells and printed circuit boards.

Fig.5: Human heart signal (Magnetocardiogram) measured without magnetic shielding

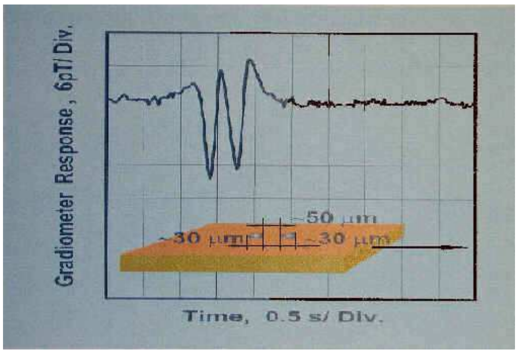

Fig. 6: Gradiometer response measured during the motion of two ferromagnetic particles in real time. The insert represents a schematic view of the experimental setup of both particles

Of high technical importance will be the future application of the HMT for **eddy current testing**. Amongst other applications, this method is used to detect and localize material discontinuities (e.g. cracks, seams or laps) on the surface of and within machined parts made from non-magnetic conducting material, such as alloys of aluminium, copper, brass, and stainless steel. Standard methods are limited in their observation depth, mainly because of the limited senstivity of the used magnetometers at low frequencies. Using the HMT can shift these limits considerably to larger depths.

Fig. 7 shows an example of detecting an artificial crack generated by a slot between two aluminium plates below a 63 mm thick stack of unslotted aluminium plates. The exciting magnetic field had a frequency of about 10 Hz and was generated by a bridge-type coil arrangement.

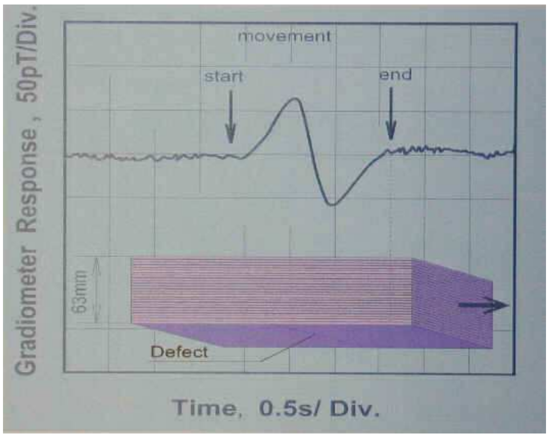

Fig.7: Detection of hidden cracks below layers of aluminium plates

FITM offers:

F.I.T. Messtechnik GmbH (FITM) offers to customers HMT Magnetometer Systems with user-specific supplements. Furthermore we offer to perform tests with the HMT as a service.

References

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