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Title: NON-DESTRUCTIVE EVALUATION WITH A LINEAR
ARRAY OF 11 HTS SQUIDS

Author(s): Michelle A. Espy, Andrei N. Matlachov, and Robert H. Kraus,
Jr., Biophysics Group (P-21)
John C. Mosher, NIS-9

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Non-Destructive Evaluation With a Linear Array of 11 HTS SQUIDS

Michelle A. Espy, Andrei N. Matlashov, John C. Mosher and Robert H. Kraus, Jr.

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Abstract—A linear array of 11 High Temperature Superconducting (HTS) SQUIDS was used for non-destructive evaluation (NDE) applications. The array consists of 11 SQUID magnetometers arranged linearly along a single substrate at 0.75mm spacing. The SQUIDS have $105\text{nT}/\Phi_0$ field sensitivity and $<20\mu\Phi_0/\text{Hz}$ noise values at 1kHz with DC bias current. We used an eddy current NDE technique. The eddy current induction coils were arranged such that there was a null in the induction field at the SQUIDS. Single frequency and multi-frequency induction schemes were used. Both SQUIDS and induction coils were placed at the bottom of a liquid nitrogen dewar with a 4mm hot-to-cold distance. Flawed and unflawed samples were scanned beneath the array. The phase and amplitude of the SQUID's response relative to the induction signal were acquired. This paper presents experimental results and their interpretation.

Index Terms—High-Temperature Superconductor, SQUIDS, Non-destructive testing, eddy currents

I. INTRODUCTION

The linear array of 11 HTS SQUIDS discussed in this paper has been developed into a non-destructive evaluation (NDE) tool we refer to as the SQUID array microscope (SAMi). The SAMi is a second-generation device, developed after we built and successfully deployed a single-SQUID NDE instrument [1]. Both the SAMi and its single SQUID predecessor were designed for stockpile stewardship applications at Los Alamos National Laboratory.

The stockpile stewardship application is well suited to SQUID NDE techniques. The features of interest are in conductive material, typically small in spatial extent, generally deeply buried ($>1\text{cm}$), and the cost of destructively evaluating a sample is sufficiently high to render the overhead of a SQUID system negligible.

II. INSTRUMENT DESIGN

A. Dewar

The SAMi dewar is made of fiberglass and has a hot-cold

Fig. 1. Schematic drawing of the SAMi dewar (left) and probe (right). The SQUID array is located at the bottom of the probe.

distance of $\sim 4\text{mm}$. The SQUIDS as well as the induction coil are in the liquid nitrogen bath. The dewar was custom built by Cryogenic Electronic Systems¹. A schematic drawing of the dewar and the insert are shown in Fig. 1. Samples are scanned by two axes of stepper motors.

B. Array

The array consists of 11 HTS SQUID magnetometers designed and manufactured the Institut Für Physikalische Hochtechnologie, Jena. The SQUIDS are arranged linearly on a single substrate. Field sensitivity is $105\text{nT}/\Phi_0$ field sensitivity and noise values are less than $20\mu\Phi_0/\text{Hz}$ at 1kHz with DC bias. The inter-SQUID spacing is 0.75mm. Cross-talk, primarily caused by stray field from the SQUID circuit coupling to neighboring sensors, was less than $3\text{m}\Phi_0/\text{Hz}$ for nearest neighbor SQUIDS for a $1\Phi_0$ signal at 20kHz.

C. Induction Schemes

The induction coils were designed to produce a null field at the SQUIDS. All data presented in this paper was taken with a $15\text{cm} \times 20\text{cm}$ rectangular coil placed as shown in Fig. 1. The induction coil was designed to approximate the field seen from an infinitely long wire. The magnetic field from such a source falls off slowly as $1/r$ where r is the distance to the wire (compared to $\sim 1/r^3$ fall off from a circular coil). The idea of such a coil was to maximize the amount of power delivered to the deeper layers of the sample. The field from the vertical return leads cancels out.

Two different induction schemes were used. The first was a

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M. A. Espy is with the Los Alamos National Laboratory, Los Alamos, NM 87545 USA (telephone: 505-665-6218, e-mail: espy@lanl.gov).

A. N. Matlashov is with Los Alamos National Laboratory, Los Alamos, NM 87545 USA (telephone: 505-665-6183, e-mail: matlashov@lanl.gov).

R. H. Kraus, Jr., is with Los Alamos National Laboratory, Los Alamos, NM 87545 USA (telephone: 505-665-1938, e-mail: rkraus@lanl.gov).

J. C. Mosher is with the Los Alamos National Laboratory, Los Alamos, NM 87545 USA (telephone: 505-665-2175, e-mail: mosher@lanl.gov).

¹ Springfield, MA 01104, USA (413)7342034

conventional single frequency method where a function generator drove the induction coils at a discrete frequency. The phase and amplitude of each SQUID's response with respect to a reference signal was recorded at each point in the scan.

The second method involved using a white noise signal. The power spectrum is flat out to 800 Hz before rolling off due to anti-aliasing filters. The random input and output sequences were processed in MATLAB (The Mathworks, Inc) for their linear coherence and transfer function. Such analyses follow classical correlation and spectral analysis techniques [2].

The data were collected for one second at each step, then processed and averaged to yield ~1Hz resolution throughout the frequency span. In this manner, SQUID response at multiple skin depths (frequencies) could be effectively simultaneously acquired and analyzed. The skin depth at a specific frequency for the material being examined could then be used to try and extract information the depth of the features

III. PRELIMINARY RESULTS

A. Spatial Resolution

The spatial resolution of the instrument was tested using 150 mm × 150 mm fiberglass plate coated with 100 μm of copper. Pairs of scratches, separated by various distances, were carved through the 100 μm copper layer. The scratches were each ~100 μm wide and 75 mm long. We define spatial resolution as our ability to tell the difference between a single scratch and two scratches. The results are shown in Fig. 2. The chain-dashed curve is for a plate with a single scratch. The solid curves are for pairs of scratches with distances as labeled. Deviations from the single scratch pair begin appearing around 20mm.

The spatial resolution of the instrument was also tested for localized current sources. Wires at varying separations were wound on a 12cm×15cm×3.2mm piece of plexiglass placed

Fig. 2. Spatial resolution test using scratch pairs in 100 μm copper plated fiberglass. The chain-dashed line is for a single scratch. The solid lines are as labeled.

Fig. 3. Upper: Cartoon of the wire phantoms used to test SQUID resolution. Lower: Fits of magnetic field as a function of wire position for each SQUID.

Fig. 4. Plot of amplitude for wires wound in the shape of "P-21".

on edge such that the $L=3.2$ mm-long current elements were below the SQUID array as shown in the upper panel of Fig. 3.

The SQUID array was centered over the 3.2mm wire elements. The lift-off was $z=4$ mm. Wires were activated individually and the magnetic field recorded by 7 SQUIDs. The data were fit to the analytic expression for a straight wire element of finite length

$$B_z = \frac{\mu_0 I x}{4\pi\rho^2} \left[\frac{L_2}{\sqrt{\rho^2 + L_2^2}} + \frac{L_1}{\sqrt{\rho^2 + L_1^2}} \right], \quad (1)$$

where $L=L_1+L_2$, $\rho=\sqrt{(x^2+z^2)}$, and $y=0$ ($L_1=L_2$). The current I was allowed to vary. Small corrections to x , z , L_1 and L_2 were also allowed to vary. The results of the fitting are shown in the lower panel of Fig. 3. The differences in the fit of x between SQUIDs corresponds the inter-SQUID spacing

Fig. 5. Upper panel: scans of laser welds made with different laser energies. Lower panel: scan of welds in same position on three different samples. The weld labeled "10J-df" was done with the laser defocused by 25%.

on the array. The fit was accurate to ± 0.2 mm.

Spatial resolution should be considered distinct from the ability to detect the presence of a feature. The instrument is sensitive to features that are much smaller in spatial extent.

Fig. 4. shows the scan of a wire that was wound in the shape of "P-21". A 680Hz signal was applied. The letters were ~ 3.8 cm high and ~ 2 cm wide.

B. Examining welds

One quality control issue important to both stockpile stewardship and industrial applications is the inspection of the quality of laser welds. We inspected welds in samples of incoloy 825 (a nickel-iron-chromium alloy). The samples consisted of two 20mm $\times$ 76mm plates of ~ 3 mm thickness. The plates were laser welded in 3 places along their length. The energy of the welding laser was varied for each of the three welds and between samples. The data for several scans at 750Hz are shown in Fig. 5. The upper panel shows scans of three welds on the same sample. The lower panel shows scans of welds in the same position for three different samples. The data indicate that welds are generally places of higher resistivity, resulting in a large SQUID response at the weld. These results also indicate that the more energy is used in the weld the lower the resistivity, reducing the amplitude of the SQUID's response. The weld labeled "10J-df" in the lower panel of Fig. 5 was made with the welding laser defocused by 25% and appears to resemble the lower energy welds. It should be noted that the samples have not yet been destructively tested to verify the weld quality and our results are preliminary at this time.

C. Buried Features in Aluminum: White Noise Induction

The ability of the white noise induction scheme to provide depth information was tested with plates of aluminum that were 15cm $\times$ 15cm and 1.5mm thick. Fig. 6 shows the SQUID response at frequencies from 200Hz to 800Hz for a stack of three plates. The bottom plate had a 5mm diameter hole located at $x=10$. The middle plate was blank. The top plate had a similar hole located at $x=40$. The distance between the

Fig. 6. Plots of amplitude vs. x for different frequencies. The sample was a stack of three 1.5mm thick aluminum plates. The top plate had a 5mm diameter hole at $x=40$. The middle plate was blank. The lower plate had a hole at $x=10$.

Fig. 7. Plots of amplitude vs. x for different frequencies. The sample was a stack of four 1.5mm thick aluminum plates. The top plate had a 5mm diameter hole at $x=40$. The middle two plates were blank. The lower plate had a hole at $x=10$.

top plate and the bottom of the dewar was ~ 2 mm. Holes appear as a two-lobed feature in the data. The bottom hole (4.5mm deep) is visible at frequencies < 700 Hz where the skin-depth is > 3 mm. As the frequency increases, the skin depth decreases and the sensitivity to the buried feature also decreases. The hole on the top becomes more visible as frequency is increased. The images in Fig. 6 were all acquired simultaneously and the different frequency components separated during the data analysis.

Fig. 7 shows similar data at different frequencies for a stack of four aluminum plates. The bottom plate has a hole at $x=10$. The two middle plates are blank. The top plate has a hole at $x=40$. The bottom hole (6mm deep) is only visible at

frequencies < 300 Hz where the skin-depth is > 4.8 mm. It is worth noting that the difference in the skin depths at which we lose sensitivity to the buried hole is ~ 1.8 mm, approximately the same value as the 1.5mm difference in the depth of the hole. In addition the frequencies were all acquired simultaneously, significantly reducing the data acquisition time.

Fig. 8 shows the amplitude of two holes (where amplitude is defined as the difference between the maximum and minimum amplitude of the lobes) plotted as a function of frequency for the same data as shown in Fig. 6. As the frequency is increased the amplitude of the hole on the surface continues to increase. The amplitude of the buried hole decreases as the frequency increases and the skin depth is reduced.

IV. DISCUSSION

We have developed an instrument that uses a linear array of 11 HTS SQUIDs for a robust NDE tool. The use of the array enables us to reduce the scan time. Eventually we hope to further use the array information to do true imaging of samples. The spatial resolution of the instrument to point sources is sub-millimeter, but for distributed sources is ~ 10 -20mm. However, the instrument is sensitive to defects orders of magnitude smaller. We used this instrument to inspect laser welds and preliminary data indicates that we are able to discriminate between welds of different laser energy. The development of a multi-frequency induction technique using white noise has enabled us to scan over many frequencies simultaneously and use the skin-depth information to try and gain insight into the depth at which features are located.

REFERENCES

- [1] M. A. Espy, L. Atencio, E.R. Flynn, R. H. Kraus, Jr., A. N. Matlashov, "Design and preliminary results from a high temperature superconducting SQUID microscope used for non-destructive evaluation," *IEEE Trans. Appl. Supercond.*, vol. 9, No. 2, pp 3692-3695, June 1999.
- [2] J. S. Bendat, A. G. Piersol, *Engineering applications of correlation and spectral analysis*, New York: Wiley, c1980.