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Low noise SQUID Based NDE with Non-magnetic scanning system in unshielded environment

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Abstract. A Non-magnetic scanning Robotic system with special EMC considerations has been designed for SQUID-Based NDE of room temperature stationary samples in unshielded environment. Considerable efforts have been made to cancel out noise of the system which resulted in detection of two major noise sources. Characterizing the noise contribution of the involved parts, a minor noise component was found to be due to the robot and the other due to liquid nitrogen bubbling in some frequencies which could be avoided by choosing proper excitation frequency. Using our NDE system we performed a NDE scan of hidden cracks in aluminum plates with white noise level of 50 $\mu\Phi_0/Hz^{-1/2}$.

1. Introduction

Nondestructive evaluation systems have found applications far beyond accessing damages and cracks in industrial products and structures. There is tremendous potential in employing a high-Tc Superconducting Quantum Interference Device (SQUID) for non-destructive evaluation (NDE) of metallic structures. For eddy current NDE, SQUIDs can be used with an excitation magnetic field to image cracks or material erosion deep in conducting structures.

Demand for practical nondestructive evaluation of large-scale objects has prompted systems with freely movable SQUID sensors against them. However because of the sensitivity of the SQUID to rotation in an external magnetic field or translation in an external field gradient, the signal-to-noise ratio of the SQUID sensor is adversely affected in a portable system. To suppress the frequent spurious signals, in most conventional SQUID-NDE systems the object is moved under a rigidly fixed SQUID sensor in a stationary cryogenic dewar, while the sensor is covered by magnetic shielding. Independent groups have worked on the realization of SQUID sensor that can freely move in ambient environment. Isawa et al reported a traveling SQUID-NDE for low-Tc sensor in [1]. Our experimental results have shown that SQUID signal is affected by commercial scanning systems because of their materials and high capability for electromagnetic noise induction. Recently we developed a practical NDE system with portable high-Tc rf-SQUID for inspection of stationary targets based on a designed nonmagnetic low noise robot [2].

In this paper, we present the performance of the scanning stage and the designed liquid nitrogen dewar as two major parts of our NDE system. The evaluation is performed by measuring the contribution of them in the noise characteristics of the system. The sources of noise in our system are also investigated and analyzed here. Also the NDE result of a stationary room temperature sample with hidden crack is presented.

2. System setup and Experimental details

Our experimental system consists of a RF-SQUID gradiometer and its relevant electronic system, a x-y scanning stage, a dewar with isolating stages, a lock-in amplifier and a function generator as external excitation source. A *LabVIEW* program running on a personal computer is developed to control the system and to collect and save data. Figure 1 shows the block diagram of the system setup. To eliminate the background magnetic field and noise, A 3 mm wide step-edge junction, high-Tc RF-SQUID, 1st order gradiometer with 1.5 mm base-line and 1.5 mm diameter washer area was used in combination with conventional LC resonators at 750MHz [3],[4]. We also used a 3 Cm diameter double-D excitation coil to induce eddy currents in the sample. For fine adjustment of the excitation coil and the Gradiometer a precise X,Y,Θ micro positioner was designed and placed under the dewar. While the SQUID gradiometer was not perfectly balanced due to the imperfection of the device, using a single turn compensation coil installed at one of the washer areas of the SQUID, we compensated the balance imperfection of the sensor to sense as minimum signal as possible from excitation coil. This improved the sensitivity of the sensor by two orders of magnitude to the ultimate performance of the system.

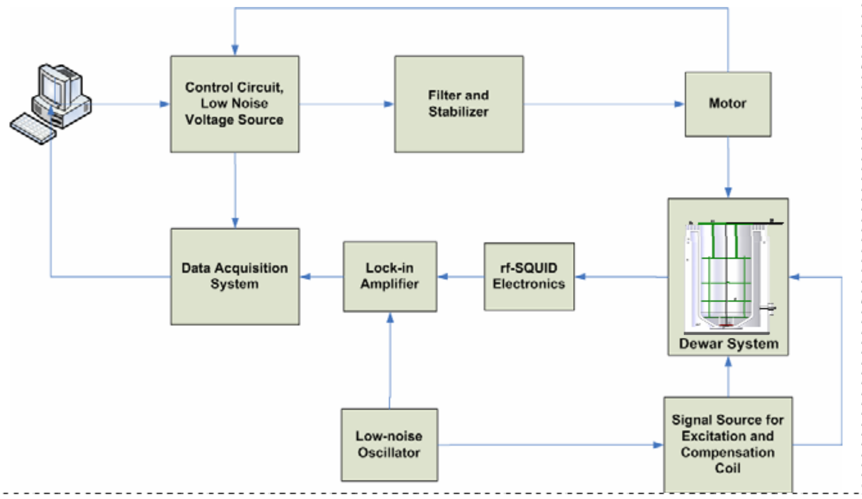

Figure 1. System setup and block diagram of the NDE System

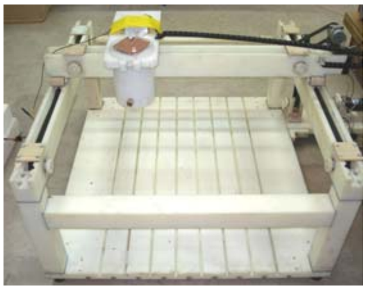

Figure 2. The implemented robot system carrying the LN dewar

3. Construction of Robotic & Cryogenic Systems

Our robotic system is a 2D x-y scanner made from polymeric materials (figure 2). The developed robotic system is based on support sliders and guide columns. The structure of the robot is made from Polyamides, which show proper quasi-isotropic and high strength characteristics further improving the rigidity of the system. Poly Carbonates, as a nominee for shaft and bearings, showed lower resistance to lateral forces and impacts, especially on cantilever sides and were avoided. The robot scans 2D surface samples with dimensions of 70cm by 72cm with 1mm resolution in a continuous and ultra low vibration motion mode. A polymeric table with micrometer resolution is constructed to adjust the placement of the sample and vertical distance of the sample and SQUID.

The translation in the x-y stage is performed by a DC motor and a stepper motor. The system is designed so that only the DC motor runs during the sampling. The stepper motor runs at the edges of the scan area while sampling is paused. This procedure facilitates the placement of the DC motor with maximum possible distance to the SQUID. Because of the SQUID's high sensitivity, we applied EMC techniques such as electronic shielding, proper grounding system, avoiding pulsed currents in control and filtering the unwanted noise from motor brushes to eliminate the electromagnetic interferences from robot.

Measured lateral vibration in the system is in the order of 1/10th of the resolution of the scanner, which is between 100µm to 1 mm depending on the used shaft encoder. The vibration increases at low and very high scan speeds, while shows a decrease at normal scan speeds of about 10cm/sec. By using low pass filtering at the edges of the scan area to reduce the scanning speed we could control the vibration well below the resolution of the system.
A liquid Nitrogen dewar is designed using ANSYS software. The dewar consists of two polymeric solid parts and is designed to be durable against the special stress and temperature variations of the system. Using few layers of radiation shields around inner part of the dewar and making a robust SQUID holder with separated parallel plates for damping of L.N. motion, resulted in a considerable reduction in L.N bubbling during the scan [5]. The distance between the SQUID sensor and sample could be adjusted by the holder, while a minimum distance of about 7mm was enforced by the dewar head.

4. System noise analysis and considerations

As mentioned above, two remarkable systematic noise sources in our NDE setup are the noise resulted from the bubbling of the liquid nitrogen in the dewar and the noise resulted from the scanning robot. We used noise spectra of the system to investigate the effect of different noise sources of the system. The noise spectrum of the device in an unshielded environment is measured as shown in figure 3. The flux noise of the SQUID sensor was measured to be about $50\times10^{-6}\,\Phi_0\,\mathrm{Hz}^{-1/2}$ at 500 Hz in unshielded environment.

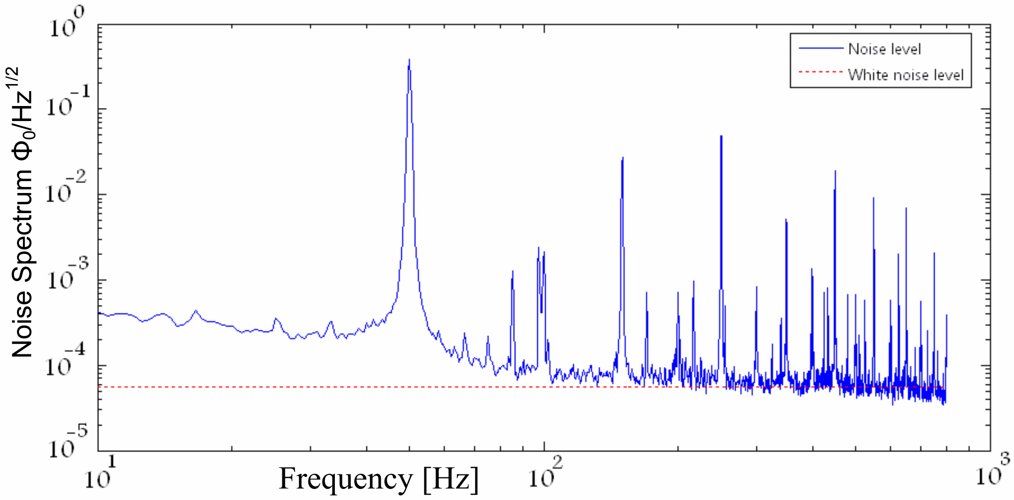

Figure 3. Noise Spectrum of system

To study the effect of the noise resulted from the bubblings, noise spectrum of the SQUID's output signal is measured within one hour in equal time intervals. Figure 4 shows the result of noise spectrum measurements and the inner part of figure 4 shows variations of 217Hz frequency component of the noise spectrum during the measurement time.
As is observed in the figures 4, system's white noise level increases with time especially for some frequency components such as 217Hz and its harmonics. We also see that the frequency of the peak of noise around 217Hz increases with time. This is interpreted to be due to the fact that as time passes air molecules leak into the dewar vacuum chamber decreasing the vacuum between internal and external walls of the dewar. This in turn increases convection heat transfer of the dewar and the evaporation rate of the L.N. and therefore increasing the L.N. bubbling.

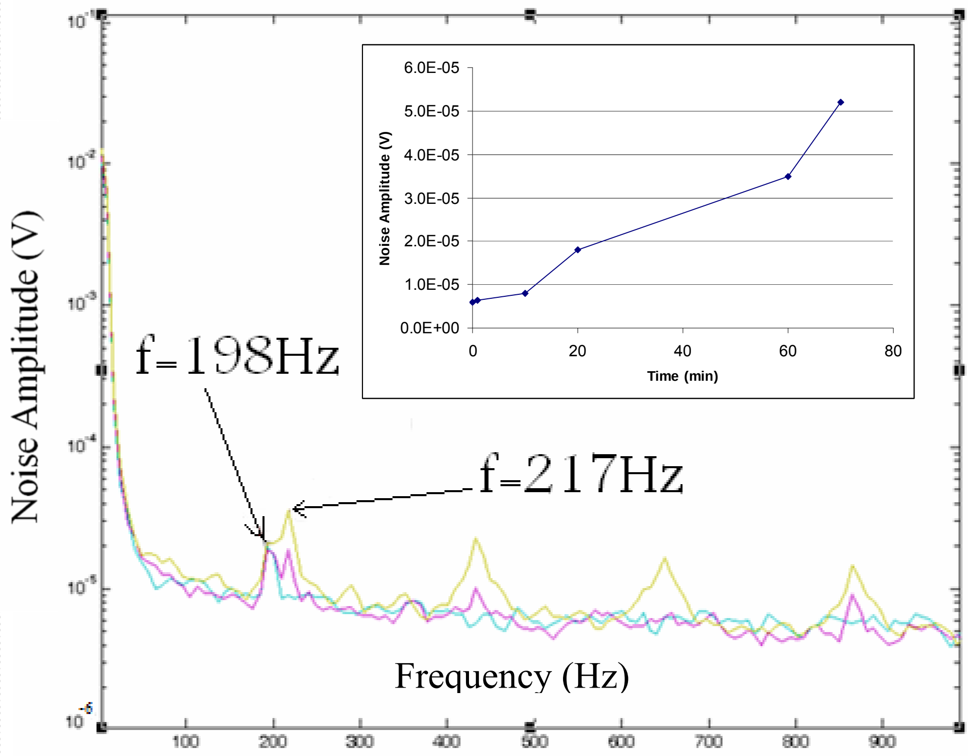

Figure 4. Noise spectrum of RF SQUID system in different times. The inner figure: Noise Amplitude of the 217Hz Component of SQUID Noise Spectrum in 70min

The Bubbles formed at the bottom of the dewar produce tremors in liquid nitrogen. The transferred tremors to the SQUID sensor cause vibrations with a frequency proportional to the bubble formation rate, which can result in further noise in the system.

As bubble formation rate increases in time, the momentum transferred from bubbles to SQUID also increases and so the vibration of the SQUID, which results in an increase in the amplitude of the white noise level of the system. In addition, it is interpreted that the increase of the bubble formation rate directly increases the frequency of dominant component in the noise spectrum.

Figure 5 shows the noise characteristics of the system when robot is working. All the presented data here was obtained without any magnetic shielding. The noise level of the system was measured at three points, the start, middle, and the end of the scan line, the average of which is shown in figure 5(a). This data is compared to the noise characteristics obtained during scanning. From figure 5(b) it could be seen that the robotic system's effect on the noise level is more detectable at frequencies below 200 Hz. This perturbation is very small in comparison to the noise level of the system in Figure 5(a). A large portion of the influence is found to be related to the DC motor. At 110Hz a noise component is added to the spectra when the robot is working. Further investigation of the system with a typical pickup coil, while the control circuit's filters are removed, shows that motor brushes produce this noise component. The interpretation is confirmed by putting the dewar in a stationary position to remove mechanical vibrations and running the robot. Such a noise component is detected at shifted frequencies for different motor speeds. To investigate the effect of the control circuit, we measured the noise spectra while the robot was stationary and control circuit was on, and compared it to the noise spectra of figure 5(a). No clear distinction could be made between the two characteristics. Noise levels of the system in figure 5 were almost the same for frequencies higher than ~200 Hz. Mechanical vibration of the robot introduced negligible noise fluctuations at frequencies below 20 Hz.

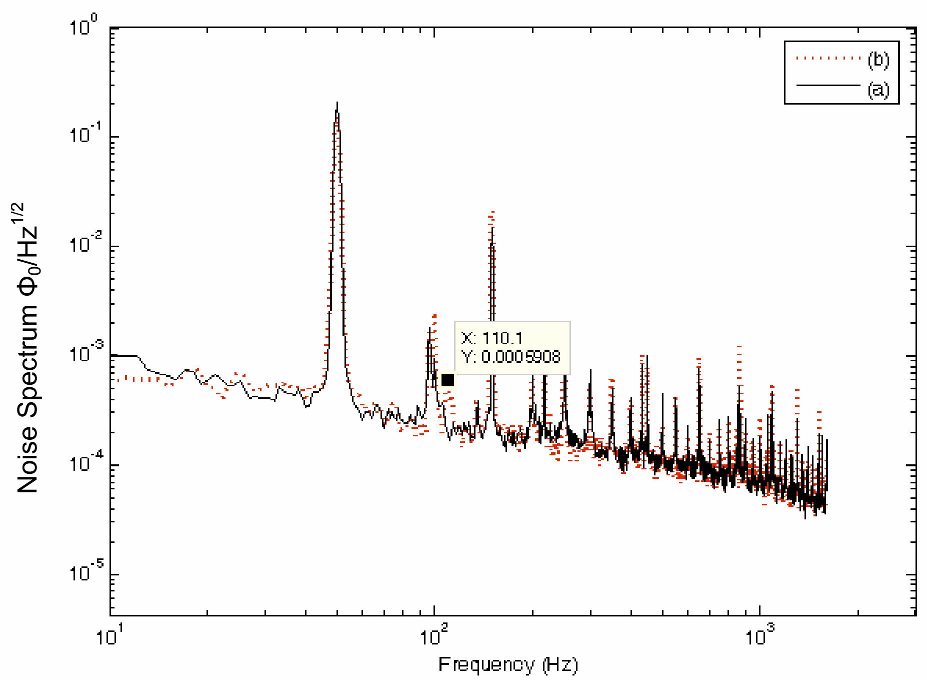

Figure 5. Noise spectrum of NDE system (a) Robot is off (b) Robot is on

Using this setup we scanned different samples with artificial cracks in them. Figure 6 illustrates a 70μm crack between two aluminum plates (according to [6]), which is taken by an optical microscope. We also put another 5mm aluminum plate on the crack to make a hidden crack. Figure 7 shows the resulting NDE for 4cm distance between the sample and the SQUID. We have tested 1-D and 2-D scans of different crack patterns and hidden holes. Also a signal processing program is developed for pattern recognition of the cracks by processing the amplitude and the phase components of the collected data. Further studies of the phase behavior and noise effect on phase data are under study.

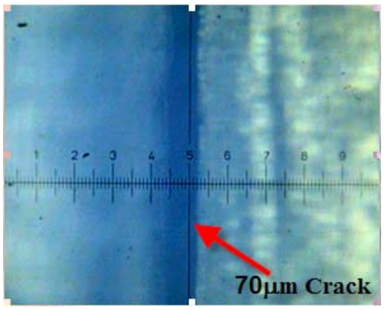

Figure 6. a 70um crack between two aluminum plate

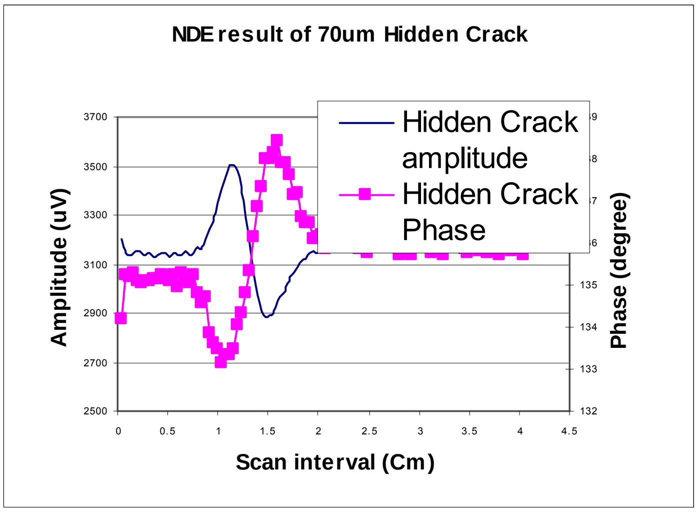

Figure 7. NDE result of a 70um crack from a 4cm distance

5. Conclusion

Two major noise sources of our SQUID Based NDE system were detected as the robot and the cryogenic dewar of the system. It is shown that these noise sources add negligible noise components to the total noise floor of the system. But each of them contributes to minor noise components at predictable frequencies. The noise frequencies of dewar L.N bubbling depends on the vacuum quality and the rate of bubble production. The Noise of the robotic system which is limited to DC motor's interference is at fixed frequency which is determined by speed of the robot. As the undesired frequency components of these two noise sources are predictable, we could choose the excitation frequency of the system in a clean area of frequency spectrum for the best performance. Using our NDE setup with measured flux noise of about 50×10^{-6} Φ_0 $Hz^{-1/2}$ at 500Hz in unshielded environment, the system is able to scan the aluminum plates and detect hidden cracks smaller that 70µm.

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