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FEM enhanced signal processing approach for pattern recognition in the SQUID based NDE system

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Abstract. An efficient Non-Destructive Evaluation algorithm has been developed in order to extract the required information for pattern recognition of defects in the conductive samples. Using high-Tc gradiometer RF-SQUIDs in unshielded environments and incorporating an automated two dimensional non-magnetic scanning robot, samples with different intentional defects have been tested. We have used a developed noise cancellation approach for the improvement of the effectiveness of the used inverse-problem technique. In this approach we have used a well examined Finite Element Method (FEM) to apply a noise reduction filtering on the obtained raw magnetic image data before incorporating the signal processing analysis. By applying this noise cancellation filter and incorporating three different signal processing algorithms and comparing the results of the predicted images by the pattern of the intentionally made defects, we have investigated the ability of these methods for pattern recognition of unknown defects.

1. Introduction

Magnetic inverse problem is an essential issue in different electromagnetic approaches for non-destructive evaluation such as eddy current SQUID NDE. Various works are devoted to develop signal analysis approaches for solving different cases with special geometries [1]. Furthermore there are many different numerical modelling methods for magnetic modelling of such problems. These modelling tools are being used for optimization of NDE systems [2] and also for yielding expected signal from different flaw types [3]. In ref [2], we have reported the development of an efficient Finite Element Method for modelling of hole-flaws in metallic samples. The acceptable conformity between the FEM simulation and experimental SQUID NDE results of that work is used here for defining a frequency domain noise cancelation filter in order to enhance the signal processing algorithms for the image restoration. Three different signal processing algorithms have been incorporated and their results are being compared. These algorithms include direct inverse filtering, 2-D cross correlation template matching, and minimum mean square error filtering which is also known as Wiener filtering. In this work our focus is on those defects which are constructed by the distribution of a few identical holes on an aluminium plate. We have obtained different image signals by preparing samples with intentional defects on them and incorporating a specially designed low noise RF SQUID Based NDE

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system [4]. These images are then analysed for the identification of the distribution of the holes using different signal processing algorithms along with using FEM based noise cancellation filters for an enhancement in their performance.

2. Experimental Setup

The block diagram of our SQUID based NDE system for 2-D magnetic imaging of the samples is shown in Fig.1. This system include a High-T_C first order RF SQUID Gradiometer, an associated SQUID electronics operating at 750MHz, a planar double-D excitation coil, a completely nonmagnetic scanning Robot with special EMC considerations which can be used for scanning of samples with maximum dimensions of 70cm$\times$72cm, a liquid nitrogen dewar, a lock-in amplifier for phase sensitive amplification and also the conventional electronic systems for excitation and data acquisition [4].

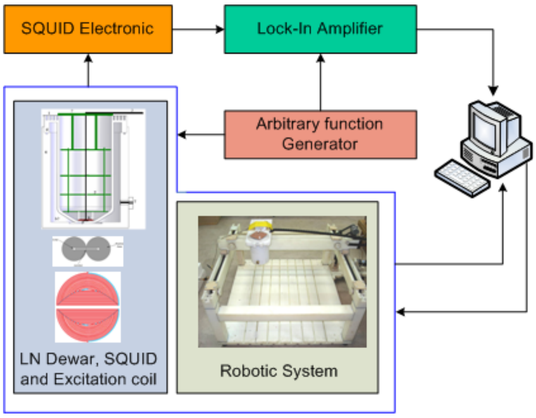

Figure 1. Block diagram of our SQUD based NDE system

3. Numerical Finite Element Simulation

Finite Element method for numerical modelling is one of the most feasible tools in Eddy current NDE simulations. But in FEM based analysis, the number of finite elements for modelling increases remarkably as the size of the flaw becomes narrow and its shape becomes complex, [5],[6]. Therefore, it is difficult to make an accurate finite element model for such flaws and a large amount of computer resources is also necessary to compute the Eddy current distributions [6],[7]. Accordingly the accurate 3D simulation of the whole system as a single problem is not practical. Hence, we divide the problem into two phases, in which as the first step, the planar double-D coil is modelled as a solid object with a special current distribution, where the different components of the induced current in the sample are found. In the second step of the simulation, we model the perturbation in current distribution caused by the defect as a new source of current, and then find its associated magnetic field at the sensor position [8]. In the case of flaw defects, depending on the shape and the depths of the flaw, the Eddy current perturbation acts approximately like a localized magnetic dipole type of current source. It is evident that the magnitude of these sources depends on the current distribution which is found in the first step. The result of our FEM simulation for this configuration is shown in Fig.2.

4. Signal Processing Approaches

As in all other NDE fields, imaging techniques are essential tools for interpretation of SQUID NDE measurement data. Because of that a great deal of work has been devoted to develop different signal processing algorithms for different cases [3],[9],[10]. As also stated before, in this work we are focusing on the problems in which knowing the 2-D scanning result of a single hole, the result of other scans over samples with different distribution of such holes are going to be identified.

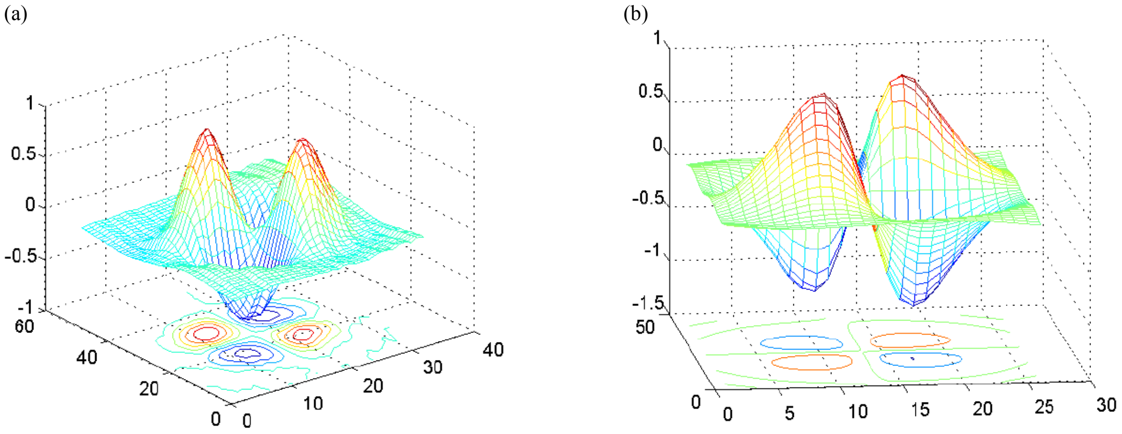

Figure 2. Two dimensional magnetic scanning result of a single hole in an aluminum plate, (a) Experimental result using the SQUID scanning system. (b) FEM simulation result.

These kinds of problems are mostly inferred as image restoration problems in the context of signal processing. Three signal processing algorithms are being used and compared which are: 1) inverse filtering approach, 2) Two dimensional cross correlation template matching, 3) Minimum mean square error filtering (Wiener filtering). In the absence of any additional noise in the scanned result, the best and easiest way for solving such problems is using the inverse filtering. In this approach, assuming that a function $Y(\bar{r})$ is the result of a convolving filter function $G(\bar{r}-\bar{r}')$ with an unknown function $X(\bar{r}')$,

$$Y(\bar{r}) = G(\bar{r}-\bar{r}') \otimes X(\bar{r}'), \tag{1}$$

Then by using the inverse filtering in the frequency domain the unknown function could be found [10],[11]. In our case, the resulted scan of the sample is assumed to be the convolution of a single hole response as the convolving filter with the unknown arbitrary distribution of impulses. The most advantage of this approach is its ability for the identification of the distribution of the holes in the samples when they are very close to each other or their individual signals have large overlaps. But as the important effect of the noise degradation is taken into account, the inverse filtering approach could be found absolutely week. On the other hand using Wiener filtering noise considerations as a modification of inverse filtering approach could be helpful when there is enough information both about the noise characteristics and the original undegraded scanning signal. Although the required information for incorporating Wiener filtering is not available in our problem, in this work we have used the approximated version of this filtering which uses the estimated noise to signal power ratio as its basic parameter for minimum mean square error filtering [11]. In this approach the estimated pattern could be found using equ.2.

$$\hat{F}(u,v) = \left[\frac{1}{H(u,v)} \frac{|H(u,v)|^2}{|H(u,v)|^2 + k}\right] G(u,v) \tag{2}$$

where $H(u,v)$ is a single hole response, $G(u,v)$ is the resulted scan of the sample and $\hat{F}(u,v)$ is the estimated pattern for the distribution of the holes. In equ.2 the parameter k is an approximation for the ratio of the power spectrum of the noise to the power spectrum of the undegraded image.
Another approach we have used for such image restoration problem is incorporating the two dimensional cross correlation template matching algorithm for identification of the known template pattern of the single holes in the considered scanning signal [12]. Beside these two signal processing

algorithms, we have used a major tool for enhancing their ability for identification of the patterns. As discussed in the last session, we have developed a FEM simulator for investigation of the properties of different defects. Using this simulator for obtaining the original two dimensional pattern of a hole signal before addition of any noise, we have made a frequency domain filter as an efficient noise cancellation tool. Incorporating the 2-D Fourier Transform, the frequency contents of the obtained signal illustrated in Fig.2b has been shown in Fig.3. In Fig.4 the used mask for definition of the filter has been shown. For a basic evaluation of the designed filter in noise cancellation, its operation on a noisy signal has been shown in Fig.5. The added noise which degrades the original signal has a white spectrum and its power is nearly 25 times of the power of the original signal. The filtered signal using the mentioned mask is shown in Fig.6.

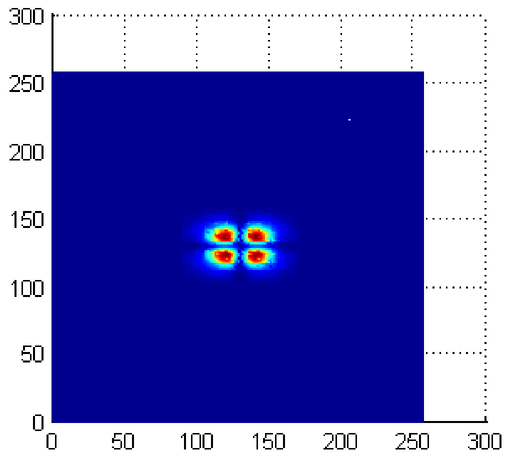

Figure 3. The Fourier Transform of the FEM simulated signal in Fig.2b

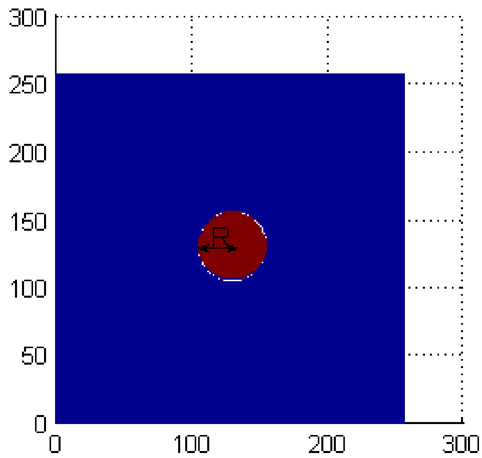

Figure 4. The used mask for definition of the Filter

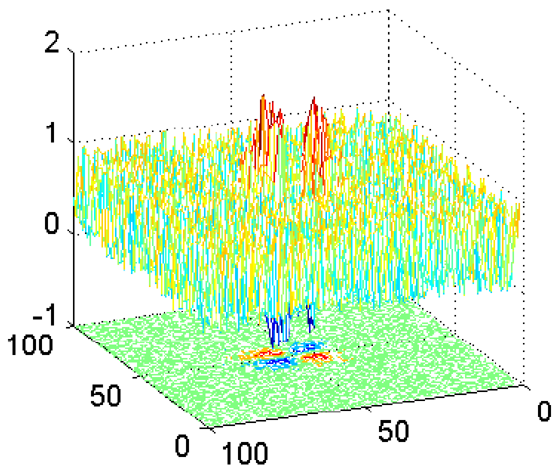

Figure 5. Degraded signal with white spectrum noise

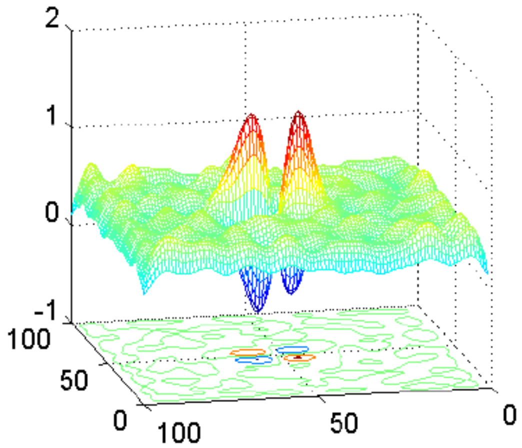

Figure 6. Filtered signal using the mask shown in Fig.4

5. Results and Discussions

Here we are using three signal processing algorithm for identification of the distribution of a few holes in an aluminium plate. For the comparison between the considered algorithms and the effect of noise cancellation, we have made both some simulated patterns with various overlap and noise characteristics, and also many physical samples with different patterns of distribution of holes to be used for SQUID NDE scanning. Fig.4 shows the result of an experimental SQUID magnetic scanning over an aluminium sample with 8 identical holes, which form the character “A”. As it is evident in Fig.4, scanning system parameters like the used double-D excitation coil with its 3cm diameter have made assurance that the individual signals from different holes have enough overlap with each other which is required for the evaluation of the different signal processing algorithms.

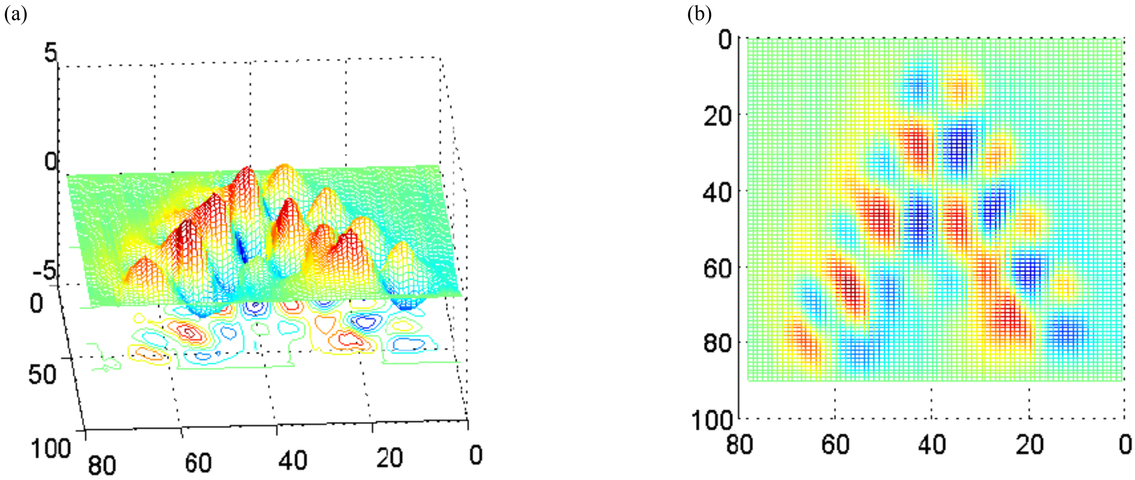

Figure 7. Experimental result for a magnetic scanning of a distribution of holes in an aluminum plate forming the character “A”, (a) 3-D graph, (b) 2-D graph.

We have processed the obtained image using three different image restoration approaches. The results of applying inverse filtering have been shown in Fig.8. In different parts of this figure, the applications of mask filters with different radius are presented. According to each mask radius there is a reduction in the power of the initial signal. The relative image power for a single hole image has been shown in Table.1. It should be noted that for each running of the algorithm, the threshold value for approving a point as a possible hole has been set to a different value to select just the few points with most high probability. Also as shown in Fig.3 we have used 256×256 point Fourier transform and the variable radius mask filter has been placed at the centre of the frequency plane. It is obvious from Fig.8 that the selection of the mask radius of the noise cancellation filter has a great effect on the ability of the inverse filtering method for image restoration. Among the four illustrated cases in Fig.8 for the selection of this radius, the optimized choice is the one which is shown in Fig.8c. Although there is just one estimation error in the result illustrated in Fig.8c, but the noise cancellation filter has improved the inverse filtering method to identify all 8 holes of the sample.

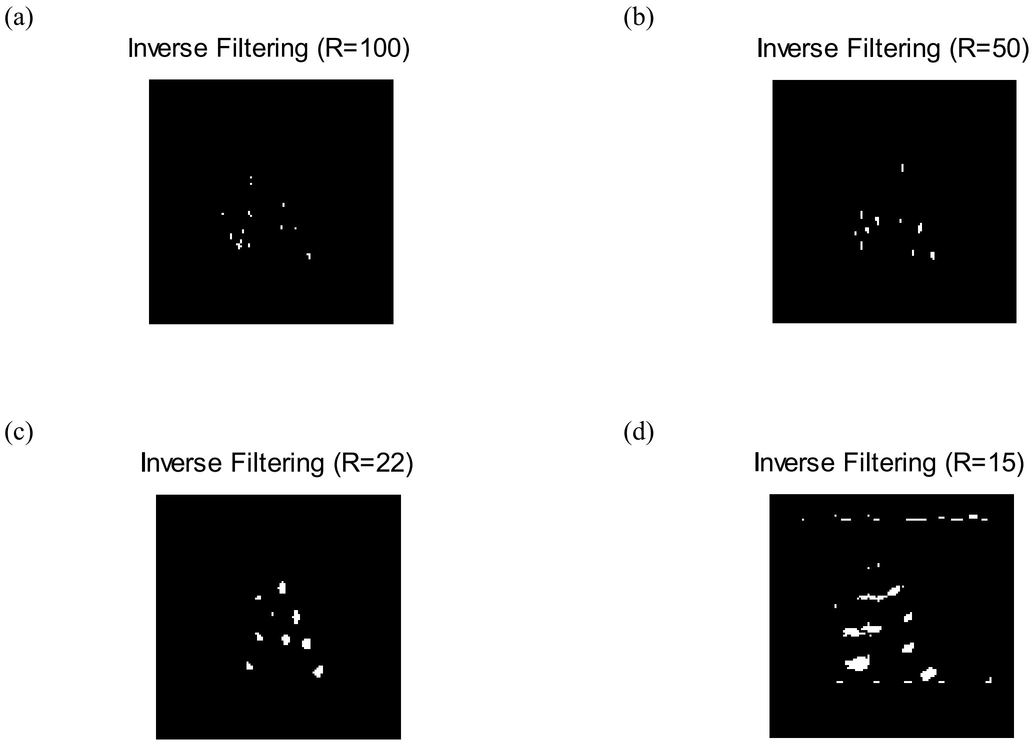

Figure 8. Results of applying noise cancellation filters with different radius of the mask and then inverse filtering algorithm on the experimental SQUID imaging result of Fig.7. (a) R=100, (b) R=50, (c) R=22, (d) R=15

Table.1. Relative filtered image power according to different masks

Mask radius (points)	Relative Power (Filtered image power/initial image power)
R=100	1.0000
R=50	0.9997
R=22	0.9421
R=15	0.6004

Fig.9 and Fig.10 show the results of applying 2-D cross correlation template matching and minimum mean square error filtering algorithms on the experimental SQUID imaging result of Fig.7. It can be found that the Wiener filtering algorithm has identified all the 8 holes without any wrong estimation for the other points of the sample. This is while just 7 holes of the sample are being found by incorporating the template matching method.

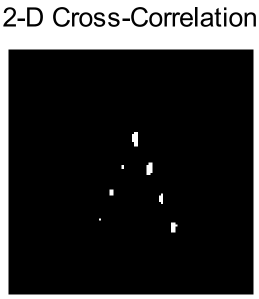

Figure 9. Results of applying 2-D cross correlation template matching algorithm on the experimental SQUID imaging result of Fig.7.

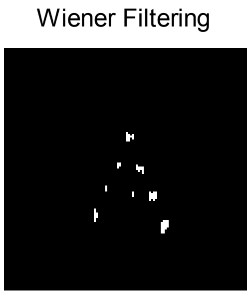

Figure 10. Results of applying minimum mean square error filtering (Wiener filtering) algorithm on the experimental SQUID imaging result of Fig.7.

In contrast to the great effect of the noise cancellation on the performance of the inverse filtering approach, the noise cancellation has substantially lower effect on the two other methods. As the improvements in these two cases are just like more concentrating the predicted points around the single ones, the improved images are not shown here. Comparing the results, it is also found that the ability of template matching approach in extracting the required data from the additional noise is far better than the inverse filtering but it has problems with the overlapped signals of different holes close to each other.

6. Conclusion

An investigation on applying a noise cancellation filter based on the results of FEM modelling to the magnetic images obtained by SQUID NDE scanning system, has been presented. Incorporating this noise cancellation filter along with using three different signal processing algorithms, we have shown that by proper selection of the filter characteristics, substantial improvement can be obtained for direct inverse filtering approach. This is while the improvement for the template matching and the Wiener filtering approaches are not as much as that for inverse filtering. Based on our obtained results illustrated in this work, the Wiener filtering with the suitable noise to signal power (NSR) parameter has the best performance in our considered image restoration problem. The next good performance is found to be for using inverse filtering approach accompanied by the application of the noise cancelation filter and the 2-D cross correlation template matching is found to have weakest performance.

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