FINAL REPORT

Low Temperature SQUID for NDE Applications

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SUMMARY
We have developed a low temperature SQUID measurement system for detection of defects deep under the surface of aluminum structures using eddy current techniques. The system uses a two dimensional planar inducer with two different excitation frequencies to induce a current in the sample. We have developed a data analysis software program that enabled us to distinguish between round defects (holes), straight defects (slots) and slots close to holes simulating cracks starting from rivets in aluminum structures. We were able to detect defects that are 8mm below the surface. We have also measured the change in phase of the detected signal as a function of depth of the defect. This relationship can be used to determine the depth of hidden flaws. Using this analysis software with the high temperature SQUID system at NASA Langley we were able to detect slots close to holes in layered aluminum sample.

INTRODUCTION:
The use of SQUID sensors in nondestructive evaluation especially for detecting defects in metals has been documented for some time [1]. In particular, eddy current techniques have been used in SQUID systems to image defects deep under the surface using relatively low frequencies. One of the challenges facing researchers in nondestructive evaluation is to detect cracks adjacent to rivets in layered aircraft structures. It was suggested that by using an orthogonal current inducer [2], one could enhance and differentiate the signal produced by a crack propagating from a rivet. In this research effort we have developed such a system and developed software analysis programs to enhance the ability of detecting such cracks that are close to rivets. In addition we developed data analysis software that makes it possible to determine the shape of the defect as part of the effort to distinguish between the signature of rivets with cracks and those without.

Another important aspect of this research study is to find the correlation between the phase of the detected signal at the defect and the depth of such a defect. The relationship between the phase of the measured signal and the depth of the defect can be used to measure how deep is an unknown defect.

EXPERIMENTAL SETUP:

The DC Low Temperature SQUID system was built by Tristan Technologies (San Diego, CA.). It includes a 1-channel LTS gradiometer probe, a nonmagnetic liquid He dewar and a Quantum Design SQUID controller model 5000. The DC SQUID sensor provided by Quantum Design has 1/f corner frequency of < 0.6 Hz and no load noise of 5×10^{-31} J/Hz at 100 Hz. The pick up coil is configured as dB_z/dz gradiometer to cancel the effect of uniform magnetic fields. The signal detected by the SQUID is due to the net flux threading the pick up coil caused by the non-uniform magnetic field generated by the eddy current near the defect. In this set up, the gradiometer pick up coil has a diameter of 1.2 cm, and as a result of its relatively large area, the spatial resolution of this system is not high enough to detect defects that are smaller than the pick up coil surface area. The overall sensitivity of the LTS system is 3×10^{-9} T/V when using the most sensitive scale of the SQUID controller and its slew rate is $2 \times 10^{4}\ \Phi_\circ$ /s. The resolution of the system is in the order of 10^{-11} T and is capable of working in unshielded environment.

We designed a planar, two-dimensional current inducer (see figure 1) with two orthogonal copper sheets (each is 5.6 cm wide x 8.4 cm long) excited by two SRS-DS345 Function Generators at two different frequencies that are usually 10% apart in value.

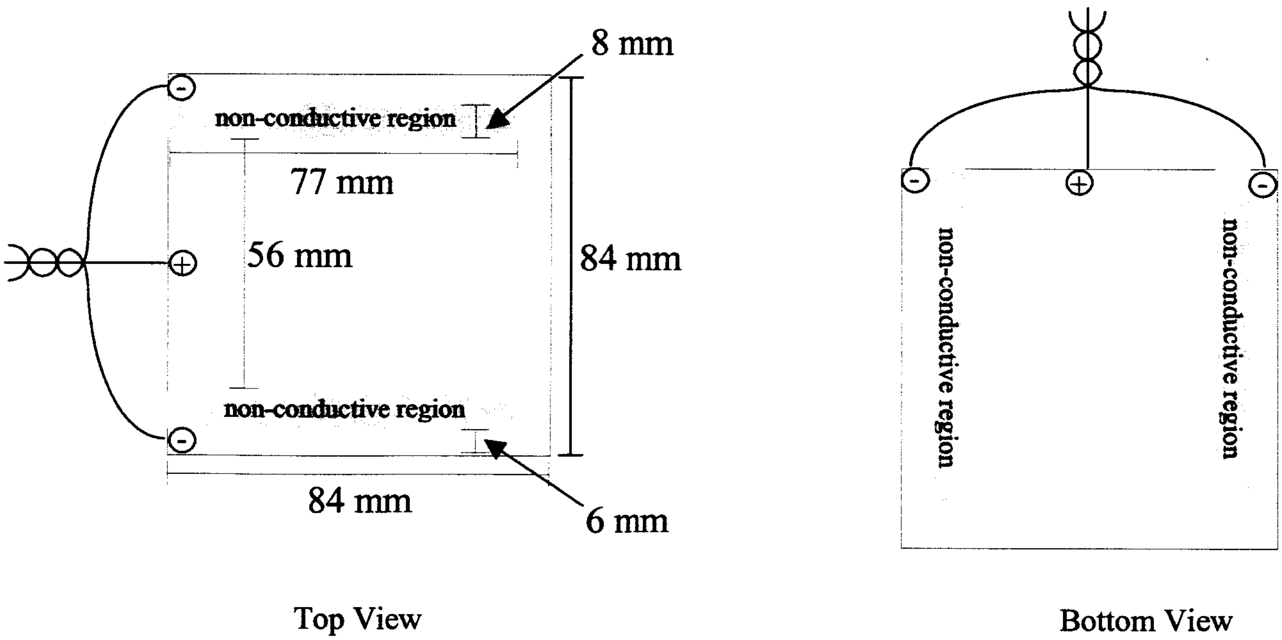

Figure 1: Planar two-dimensional current inducer.

The SQUID output is connected to two EG&G 5302 lock-in amplifiers to isolate the two signals produced from the two orthogonal currents. A data acquisition system was developed which allows a computer to interface a Parker Compumotor 4000 Motion Controller, which controls a two-dimensional scanning table. A schematic diagram of the system is shown in fig. 2. Each file produced in scanning a sample contains four sets of data: in-phase x-inducer data, X (0); quadrature x- inducer data, X (90); and similarly the y-inducer data, Y (0); and the y-quadrature data Y (90). For convenience we chose the x-direction of the scanning table to be the same as the x-direction of the current inducer.

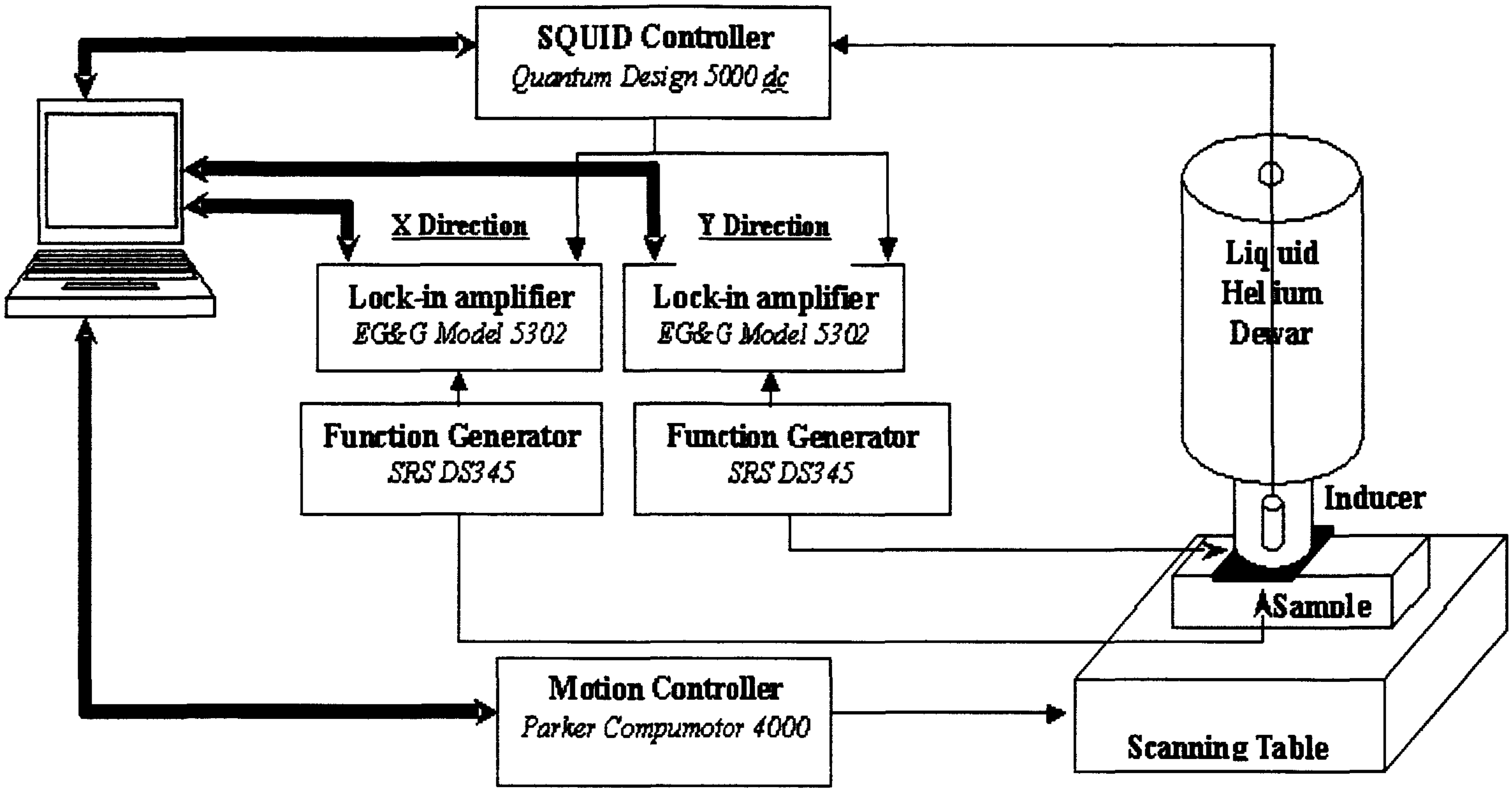

Figure 2: Schematic diagram of data acquisition system for Low Temperature Squid System

A High Temperature SQUID (HTS) system designed and built by MagneSensors, Inc. (San Diego, CA) was used to accomplish the same goal, namely the ability to detect cracks close to rivets. It is a portable system that is in essence similar to the Low Temperature System (LTS) described above and has the potential for use outside the laboratory (fig. 3). The pick up coil is a planar gradiometer for cancellation of uniform magnetic fields and has an area of 0.3 cm x 0.3 cm. In general the set up and the data acquisition system is similar to that of the LTS system.

Figure 3: High Temperature Squid System Developed by MagneSensors, Inc.

Software Development:

Analysis of the results was done using custom LabVIEW software that was developed specifically for these SQUID systems. The collected data in the x direction X (0) and X (90) as well as the data for the Y direction Y (0) and Y (90) were flattened and made symmetrical in order to remove any linear drift in the signal due to an uneven gap between the inducer and the sample. Figure 4 shows a line scan for X (0) and X (90) before processing, and after leveling and subtracting a linear term resulting in more symmetrical signals. The effects of such processing on the amplitude and phase of the x direction data are also shown. Finally the intensity chart is shown to be more symmetrical as a result of this process. Figure 5 shows the front end of this part of the LabVIEW software with one set of data (the x direction) optimized.

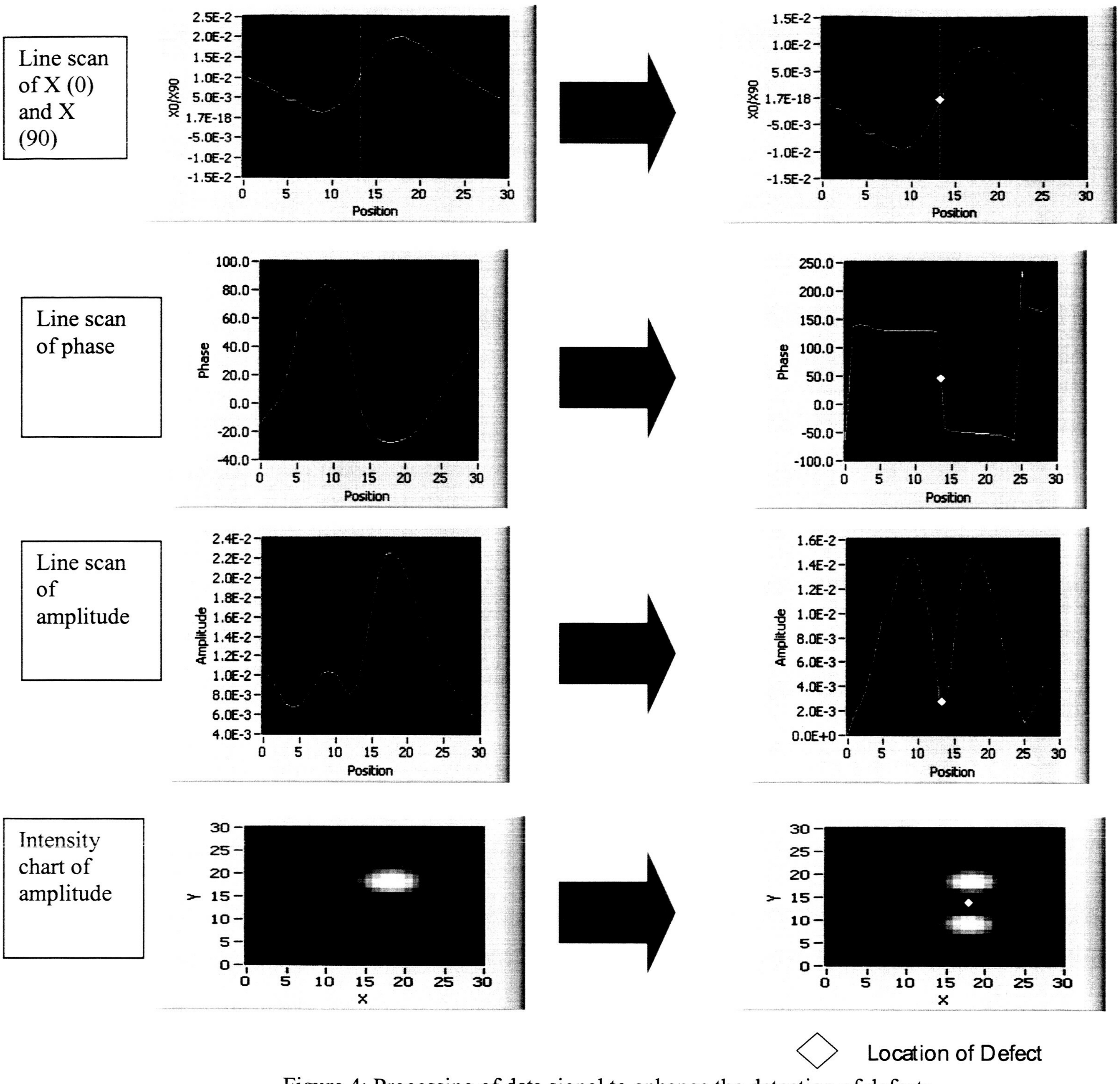

Figure 4: Processing of data signal to enhance the detection of defects.

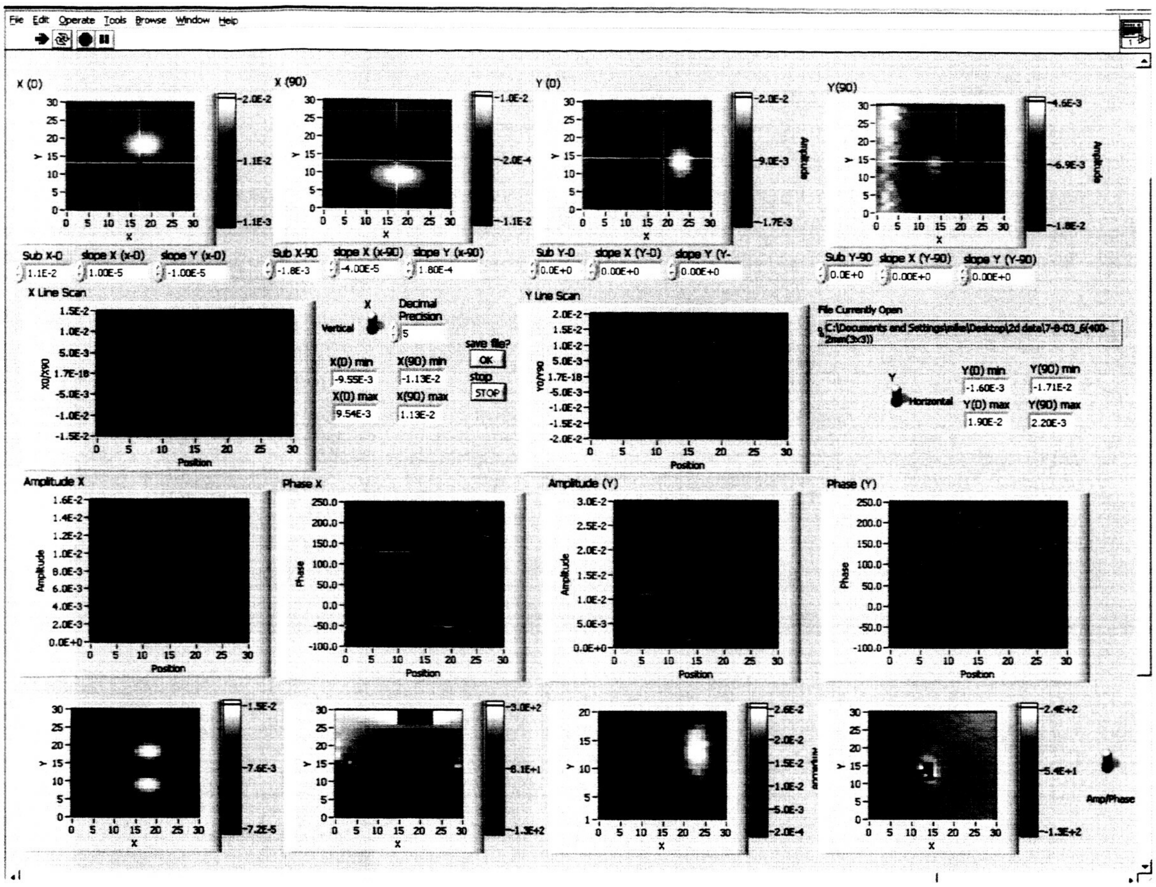

Figure 5: Front end of software developed to level the signal

We have also developed a software program using LabVIEW that allows for combining the four data sets of each file and producing a data set for the intensity at a certain current angle and at a certain phase angle i. e. we can vary the current angle to any direction from 0 ° (x direction) to 180 ° (-x direction) allowing us to see how the signal changes with the current angle and help in determining the direction of the defect (see figure 6). Similarly the program allows for changing the phase to a certain phase angle allowing us to optimize the signal for a defect at certain depth.

In addition the program generates the maximum- minimum (Max - Min) intensity signal at each current angle (at a specific phase angle) and graphs this difference in arbitrary units (volts) and as a percentage. These graphs are very useful in determining the shape of the scanned object. A round object will produce a relatively small change in the amplitude of the signal as one changes the current angle from the x direction to the -x direction using this data analysis software. A crack or a slot will produce a large change in the amplitude of the signal as one changes the current angle in a similar fashion. One would observe that the amplitude of the signal peaks at a certain angle of current indicating that a slot or a crack exists perpendicular to this current direction. A slot (crack) close to a hole (rivet) will have a distinctive signature on such a chart as one changes the current angle.

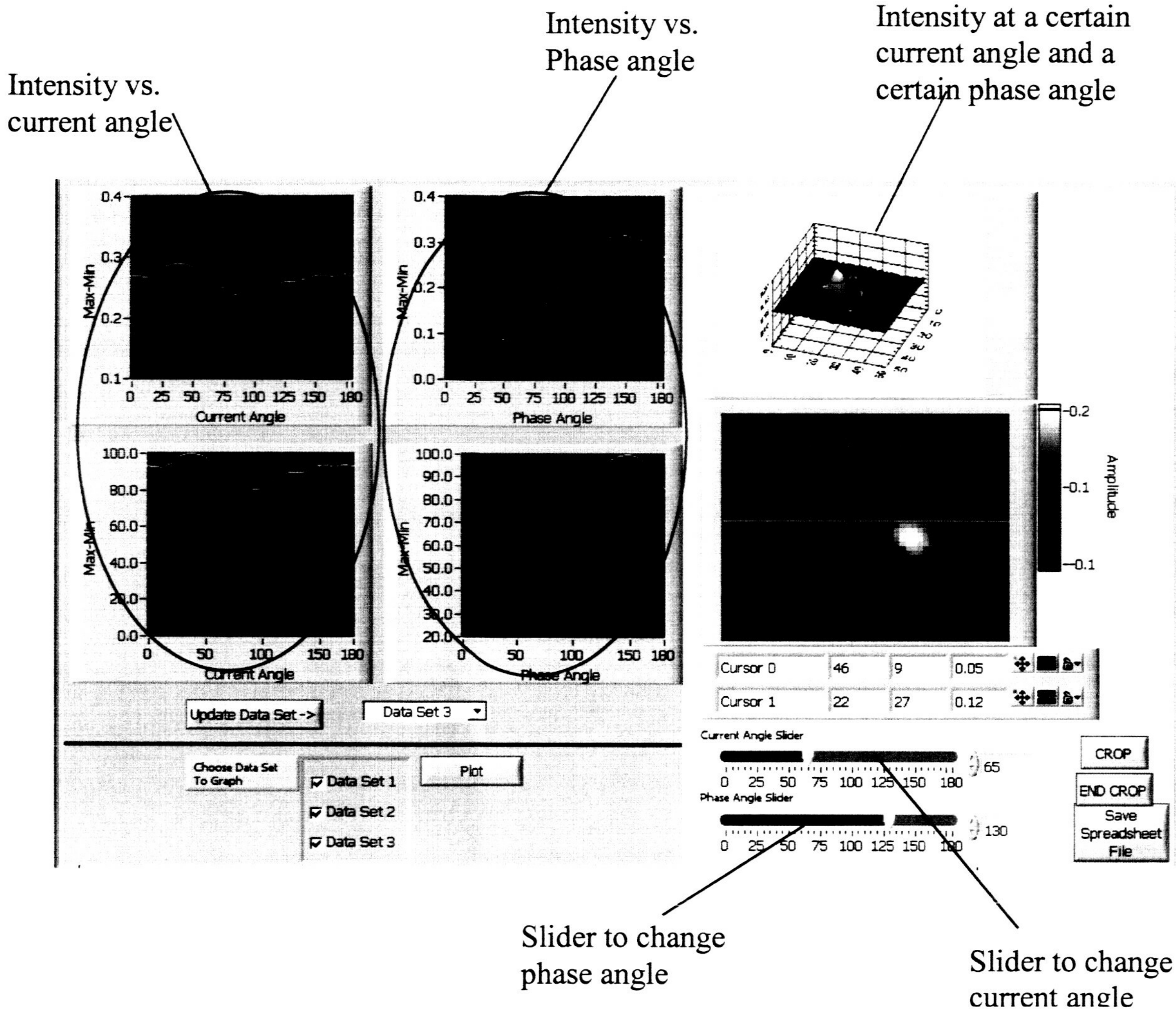

Figure 6: Front end panel of data analysis program

A small change in the intensity as one changes the current angle indicates a fairly round object while a large value at a certain current angle would indicate a flaw perpendicular to this current angle. Figure 6 shows the front-end panel of the data analysis software with three charts for three holes. The change in amplitude (maximum – minimum) is plotted at each current angle in volts and also as a percentage. Similarly the program allows one to change the phase angle from 0 ° (in phase) to 180 ° (out of phase) at certain current angle. As a result one can find out the phase angle at which the signal is maximized, which can be thought of as maximizing the signal of a defect at a certain depth.

In addition to the above capabilities, one can toggle from this mode of displaying data to a different mode that displays the amplitude and phase in each direction i.e. one can display A_x, ϕ_x for the x direction signal as well as A_y and ϕ_y for the y direction signal.

EXPERIMENTAL RESULTS:

1) Low Temperature Squid System:

A) Shape detection:

The following results show how one can use the analysis software to distinguish between a hole (rivet), a slot (crack) in the horizontal direction, a slot (crack) in the y direction or a slot close to a hole resembling a crack near a rivet.

Fig. 7 a, shows a scan of an aluminum sample with a 1/4 inch diameter hole at the surface. The change in intensity (as % of maximum- minimum) is presented versus the current angle, which is varied from 0 (x direction) to 180 (-x direction). One notices that the % change in amplitude as the current angle changes is usually small. In the majority of round defects that we measured the % amplitude does not fall below ~ 75% of its normalized peak value. One can use this value as a cutoff parameter for detecting holes (rivets) with no cracks in close proximity.

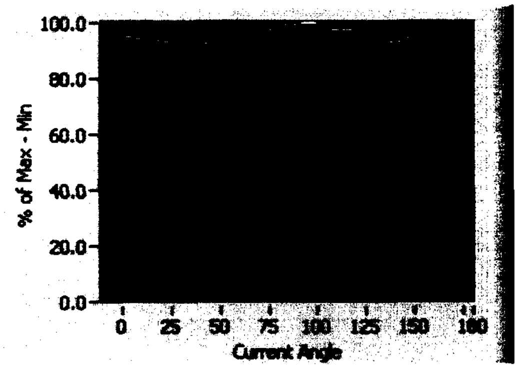

Fig. 7 a

Fig. 7 b shows a graph for a surface 14mm slot in the x direction. The % of change in intensity is quite large and the difference in the % change drops to below 20% from its normalized peak value. The maximum intensity at current angle of 90 degrees (y direction) indicates that the slot is in the x direction. A change in this % intensity to values below 30% usually indicates that the flaw is a slot or long crack.

Figure 7 b

Figure 7c shows a 1 KHz surface scan of a ¼ inch hole with a slot 1/8 inch long in the x direction. The % change in the signal is down to ~ 40 % with the maximum at a current angle 90 degrees.

Using this normalized chart of % change in intensity, one can determine the type of defect present in the sample. Percentage change above 75% indicates a hole with no cracks close to it. Samples with % changes drop to below 30 % indicate the presence of a crack or a slot. For samples with % of changes drop to the ~ 40-70 %, indicate a crack close to a hole. Our experience indicates that this parameter, the % change of intensity as one changes the current, is a fairly reliable prediction of the shape of the defect. In addition, the shape of this chart is distinctively different for each type of defect.

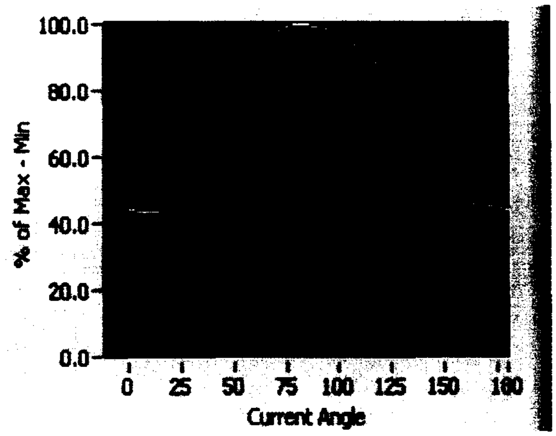

Figure 7 c

B) Depth limit of detection:

Using the low temperature Squid system we were able to detect a 1/2 inch long slot located 8mm below the surface using 165 Hz and 135 Hz frequencies for the excitation current of the 2D inducer. The sample was placed below 3 layered aluminum plates (one 1/2" thick plate and two 1 mm thick plates). Figure 8 shows how the % change in intensity drops to ~25% indicating a slot, and the maximum value is at a current angle ~90 degrees indicating that the slot is in the X direction. We have repeated the measurement with the sample below 8 1-mm aluminum sheets and obtained similar results.

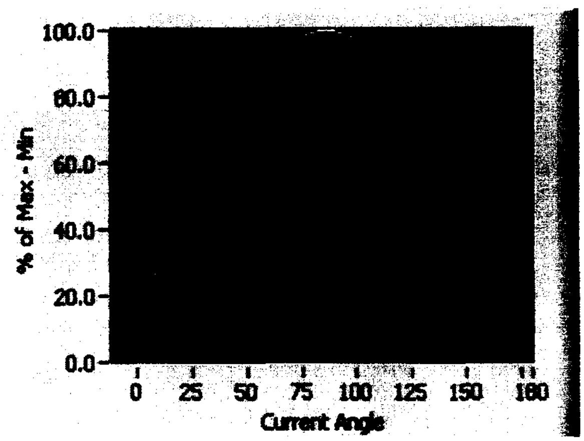

Figure 8

C) Determining depth of defects using phase

We have calculated the phase of the signal to be equal to $\tan^{-1} X(90)/X(0)$ for the x direction signal. Similarly a phase for the y direction signal is defined as $\tan^{-1} Y(90)/Y(0)$. After processing the results to flatten the data as previously described, we used the line scan of phase to calculate the change in phase produced by the presence of the defect (see figure 4). We graphed this change in phase versus the depth of the defect. Figure 9 shows how the phase of a slot that is ½ inch long varies with depth. We varied the depth of the slot from 0 mm (surface defect) to 6 mm deep below the surface and used scanning frequencies of 400, 500 and 800 Hz. The defect is under a number of aluminum sheets equivalent to its depth (e.g. 4mm depth is accomplished by placing four 1-mm aluminum sheets between the sample and the inducer). In this case, the quoted frequency is the average value of the two actual frequencies used for the two orthogonal currents.

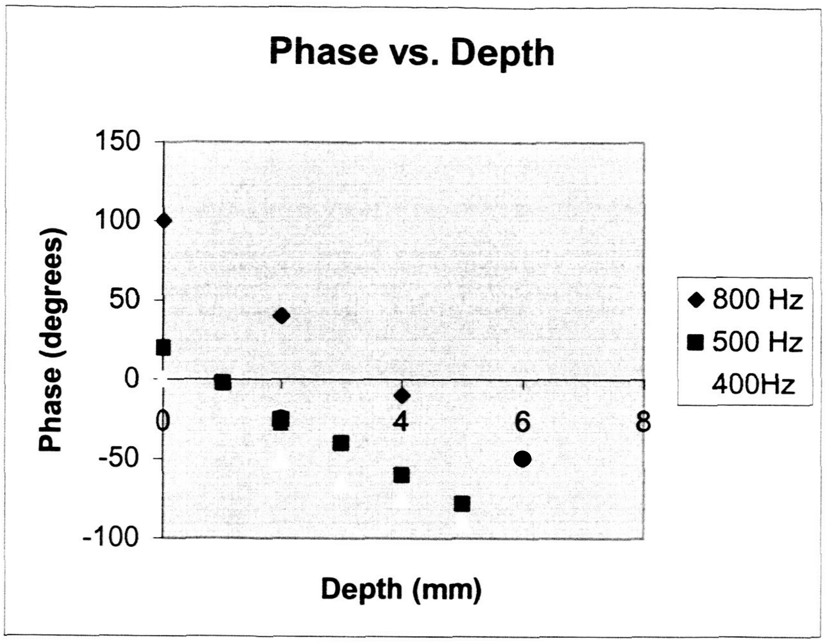

Figure 9

In figure 9 one observes that the slope of the phase versus depth data at each frequency is dependent on the scanning frequency. For the 400 Hz set of data, the slope is ~ -13 °/mm, for the 500 Hz frequency the slope is ~ -16 °/mm and for the higher 800 Hz set, the slope is ~ - 25 °/mm. We found that these slope values are consistent and reproducible in our measurements. One can determine the depth of an unknown defect by measuring the change in phase produced by such a defect and using these charts or these slope values. The graph also indicates that slope is proportional to the $\sqrt{f}$, but we don't have enough data to confirm such relationship. We have also found that if the inducer goes out of alignment and needs to be realigned to null the signal, the phase value changes, but the slope of such a phase does not change. As a result it is crucial to keep the same inducer alignment to produce such a chart or to use the resulting phase values in determining the depth of an unknown defect. We found that in our setup, it was challenging to keep the inducer from being bumped and going out of alignment as a result of the small gap between the moving sample and the inducer mounted at the bottom of the tail end of the helium dewar. But the important finding in this case is that once one aligns the inducer and calibrates the set up for a surface defect at certain frequency, one can calculate the depth of an unknown defect by measuring the change in phase of the signal by the defect then use the corresponding slope for that frequency to determine the depth of this defect.

2) High Temperature Squid System:
Shape detection:

As in the case of the low temperature Squid system, we were interested in samples that contain a defect that has a slot (crack) close to a hole (rivet). Figure 10 shows such an example where a 1mm thick aluminum plate with a 14 mm slot is placed on top of an aluminum plate with a ¼ inch diameter hole. The results of a 1 KHz scan show that largest intensity is when the current is flowing perpendicular to the crack, or in the y - direction (~ 90 degrees). The graph indicate that the % change in intensity drops to ~ 45 %, which is in the range of 40-70%, consistent with the signature of a slot (crack) close to a hole.

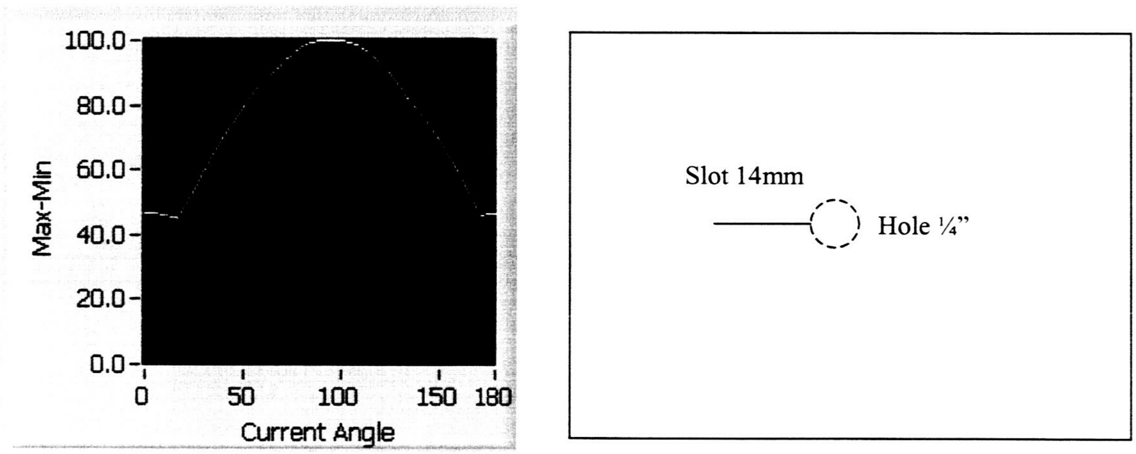

Figure 10: 14 mm long slot in x-direction on top of a 1/4 inch hole.

A more realistic sample was made by using rivets to form a layered sample made of 3 aluminum plates each is 1 mm thick. This sample had 3.75 mm (0.150 inch) diameter holes that are 1 inch apart. The middle aluminum plate contained two slots radiating from the holes as shown in figure 11. Slot D is 2.5 mm long and slot E is 3.75 mm long. The results of the scan are also shown in figure 11. The larger of the two slots at rivet E produced the larger % change in intensity, with % change in intensity down to 50%. The slot at rivet D produced a smaller change in the % of intensity down to 70% indicating a smaller size slot while the rivet between D and E produced a signature consistent with a hole.

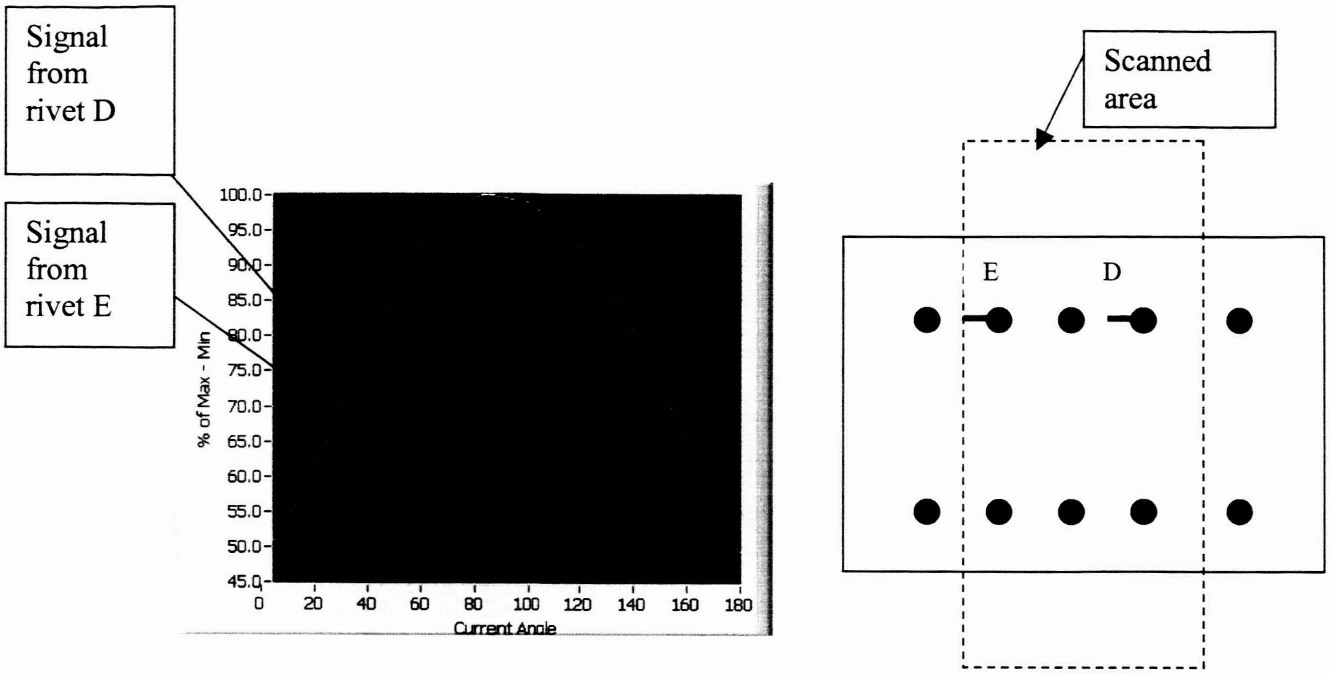

Figure 11: 3-layered sample with results of scan for slots near holes D and E.

These results show that using the high Tc SQUID system with its planar gradiometer and its smaller size pick up coil, we were able to detect smaller cracks that are starting close to rivets. Also, these results show that the % intensity at multiple current angles can be used to differentiate between rivets with cracks and those without cracks.

CONCLUSION:

We have developed a data acquisition system for a 2 dimensional eddy current measurement for a low temperature SQUID system and a software analysis package that can be used for both the high temperature and the low temperature SQUID systems. Using this 2-dimensional eddy current technique, we were able to detect cracks forming close to rivets. In addition, using this set up we have demonstrated that the depth of an unknown defect can be determined by measuring the change in the phase produced by such defect.

Acknowledgements:

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References:

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2. Ma Y. P. and Wikswo J. P. Jr.; Rev. Prog. QNDE Volume 17 (1997)