DEVELOPMENT AND TESTING OF PROTOTYPE GIANT MAGNETORESISTIVE (GMR) ROTATING PROBE SYSTEM

Buzz Wincheski\textsuperscript{1}, John Simpson\textsuperscript{2}, Min Namkung\textsuperscript{1}, Dan Perey\textsuperscript{1}, and John Callahan\textsuperscript{2}

\textsuperscript{1}NASA LaRC, MS 231, Hampton, VA 23681
\textsuperscript{2}Lockheed Martin Engineering and Sciences Corporation, 1237 South Marvin Street, Hampton, VA 23681

ABSTRACT. Continued development of the giant magnetoresistive based rotating probe system has resulted in the fabrication of a fieldable prototype instrument. The system, designed for the detection of deeply buried flaws under installed fasteners, utilizes a giant magnetoresistive sensor within the self-nulling probe design for improved low frequency capabilities. The prototype unit incorporates a new probe design for deep penetration and reduced edge effects along with new electronics and system software. Testing of the prototype system has been performed at SANDIA National Laboratories Aging Aircraft NDI Validation Center. The complete system configuration along with field testing results are presented.

INTRODUCTION

Detection of fatigue cracks at airframe fasteners has been the focus of a considerable research effort in the aging aircraft and nondestructive evaluation communities \cite{1}. Previous research in this area at NASA LaRC has resulted in the development of the Self-Nulling Probe Based Rotating Probe System, which has been shown to have excellent fatigue crack detection capabilities for near surface damage \cite{1-3}, and has been commercialized by Foerster Instruments Inc \cite{4}. Continued development activities at NASA have focused on improving the deep flaw detection capabilities of the system. To this end, giant magnetoresistive (GMR) sensors were studied for improved low frequency system response \cite{5,6}. Positive initial results led to continued development of GMR based electromagnetic nondestructive evaluation probes and the GMR based Rotating Probe System \cite{7,8}. In this work, the configuration and test results of a prototype GMR based Rotating Probe System are presented. Both laboratory and field test results are discussed, highlighting the system capabilities for detection of inner layer flaws in airframe lap-splice joint samples.
GIANT MAGNETORESISTIVE BASED ROTATING PROBE SYSTEM

The GMR based Rotating Probe System builds upon the capabilities and design of previously developed NASA systems for crack detection. The sensor incorporates the Self-Nulling Probe design in order to provide an easy to interpret signal response. In the Self-Nulling Probe design, the sensor output voltage provides all the necessary information of the material condition. The presence of a fatigue crack under the probe yields an increased output voltage proportional to the crack length. Retention of these features at low frequencies can be performed through the use of a GMR sensor and internal bias coil. The bias coil is used to reduce flux linkage around the probe lens, while the GMR sensor provides enhanced sensitivity to low frequency magnetic fields [6]. Other probe modifications include increasing the width of the flux focusing lens for improved depth penetration of the electromagnetic field and the addition of an external shield to decrease edge effects. The rotating probe mechanism for the GMR based system was achieved by modifying a probe head from a pickup coil based system. Extra signal connectors were added to the probe head in order to provide feedthroughs for the bias coil source, GMR bridge supply voltage, and differential signal sources [7,8]. After these modifications were completed the pickup coil based Self-Nulling Probe could be exchanged for an equivalently sized GMR probe in the rotating probe head. Figure 1 displays the modified Rotating Probe head incorporating the GMR Self-Nulling Probe.

The system electronics for the GMR Rotating Probe System were completely redesigned for the GMR based unit. Two sources, one each for the drive and bias coils, and a new detector were needed. The GMR based Rotating Probe amplifies the output of dual direct digital synthesis (DDS) chips to meet supply signal requirements, with the gain of the amplifier supplying the drive coil set to twice that of the feedback coil. The DDS chips enable complete control of the amplitude and relative phase difference between the sources and are completely configurable through the laptop computer control. The demands of the detector electronics are also greater for the GMR based system as opposed to previous versions of the rotating probe system. The low frequency sensitivity of the sensor, although necessary for deep flaw detection, allows significant motor noise to be introduced into the detector electronics. In order to detect the small magnetic field changes caused by deeply buried fatigue cracks, this motor noise needed to be eliminated. This was accomplished through the use of a high Q notch filter centered at the stepper motor.

FIGURE 1. Rotating probe head incorporating GMR Self-Nulling Probe and added signal connectors.
magnetic field oscillation frequency. As described in previous work, this occurs at 12x(rotation frequency) of the motor [7]. Figure 2 shows the complete GMR Rotating Probe System along with the internal circuitry of the system electronics.

EXPERIMENTAL RESULTS

Laboratory Testing

The flaw detection capabilities of the prototype GMR Rotating Probe System were studied through both laboratory and field test experiments. Laboratory tests were performed on a previously fabricated sample containing electric discharge machine (EDM) notches with lengths of 0.060", 0.100" and 0.150" in the third layer of the aluminum 2024 lap-splice specimen. A more detailed description of the sample geometry is available in Figure 2. Complete GMR Rotating Probe System and internal circuitry of system electronics.
the literature [7]. The system response was examined at 2.0, 2.5, 3.0, and 5.0 kHz. For each frequency, the amplitude of the drive and feedback signals as well as the phase difference between the sources was optimized. This was accomplished by measuring the signal level for each of the inner layer flaws and an unflawed fastener and systematically varying the parameters discussed above to provide the highest signal level ratio for flawed/unflawed fastener. It was found that the signal optimization required a higher feedback level and phase angle at lower frequencies. At 5.0 kHz the system responded well with the feedback source turned off. The best ratio of signal level for flawed/unflawed fasteners on the laboratory samples was found at 3.0 kHz. At this frequency, a drive of 5.6 volts and feedback of 1.4 volts with 85 degree phase shift were used.

Figure 3 displays the instrument front panel for the detection of a 0.060” long 3rd layer EDM notch using a 3.0 kHz drive frequency and the setting described above. The left hand side of the display contains a polar plot of the raw data while the right hand plot shows the processed amplitude (mV) versus angular position (radian). The flaw is clearly indicated in the processed data, identified as a peak in the output at -1.5 radians. The peak amplitude of the processed data, 11.1 mV, is displayed above the plot to aid in flaw detection. This amplitude is compared to with a threshold value, set at 4 mV, to trigger the flaw LED indicator.

All the controls necessary to run the system are software selectable and available on the front panel. Above the polar plot of the raw data are the signal driver settings, including the relative drive and bias signal amplitudes, operating frequency, and phase shift. The spatial and sliding filter controls are located above the processed data plot in the right hand side of the control panel. These include the low and high frequency cutoff of the pass band (in multiples of the rotation frequency) an offset control to remove any DC shift left by the band pass filter, and the expected flaw frequency (used as input to the sliding filter routine). The function of each of these settings has been described in previous work and thus will not be elaborated upon here [8]. The two other operating controls on the front panel are for alignment and probe rotation frequency. The alignment
knob, located above the processed data plot, is adjusted to synchronize the angular position of the probe with the displayed data. The angular position of the probe is calculated based upon the rotation frequency and a timing signal generated as a permanent magnet rotating with the probe passes a hall sensor. Since the angle between the permanent magnet and the probe changes with rotation radius, the alignment control needs to be adjusted when the rotation radius is changed. Beneath the processed data plot is a control to adjust the motor rotation frequency. During testing it was found that fine control over the rotation frequency was required to match the notch filter in the electronics with the stepper motor noise. Pulling the rotation frequency control to the front panel enables the user to optimize this frequency in order to minimize this noise source.

Figure 4 shows the processed data results for inspection of an unflawed fastener along with the results of the 0.060", 0.100", and 0.150" third layer EDM notches. Each set of processed data contains two plots, corresponding to the band pass filter and band pass plus sliding filter results. The application of the sliding filter increases the output amplitude from each of the flawed fasteners while having minimal effect on the unflawed rivet joint such that in this plot the two graphs overlay each other. The peak amplitudes for the data processed with both the band pass and sliding filters are 1.1, 11.1, 22.2, and 39.3 mV for the unflawed, 0.060", 0.100", and 0.150" 3rd layer flaws respectively. It is clear from these values as well as the data plots shown in figure 4 that the system performed very well in the laboratory, with a signal to noise ratio of 10 for a 0.060" third layer flaw. Based upon these laboratory results, field testing of the system was explored to more fully define the functionality of the system for airframe inspections.

FIGURE 4. Processed data output for inspection of laboratory sample with third layer electric discharge machine notches.
Field Testing

Field testing of GMR-based Rotating Probe System was performed at Sandia National Laboratories NDI Validation Center in coordination with the Federal Aviation Administration. The FAA has developed a set of inner layer fatigue crack standards to provide a testing platform for reliability studies on new and existing nondestructive evaluation techniques. The sample set consists of eighteen panels with twenty rivet sites per panel. Fatigue cracks were grown in the inner layer of the panels and the location and length of the flaws recorded prior to panel assembly. The assembled panels contain an outer and doubler layer, each 1 mm thick, above the flawed layer such that the fatigue cracks are hidden under 2 mm of unflawed material. The field testing of the GMR based Rotating Probe System consisted of inspecting these eighteen panels. For every fastener the raw and processed probe output voltages were recorded as a function of angular position. In addition, the operator call for each fastener was noted. As the sample set contained rivets with fatigue cracks emanating from either or both sides of the fastener, 720 independent calls were recorded. The data were also analyzed by extracting the maximum signal level in the processed data from each side of the fasteners, again resulting in 720 inspections. The blind testing proceeded smoothly, and was completed in slightly over two hours.

Two separate Probability of Detection (POD) curves were generated by the Sandia National Laboratories staff corresponding to the operator call data and the system output level versus flaw length data respectively. In the first case, the analysis found a 90% probability of detections for fatigue cracks 0.070" long [9]. Detection of fatigue cracks of this size in the third layer of the lap-splice joint is well below what is achievable with current technologies. The POD was, however, associated with a relatively high false call rate of roughly 10%. In many cases the false calls appeared to be due at least in part by rivet irregularities including rivet tilt, misfit, and rivet hole ovality. Such rivet irregularities may be common on in-service aircraft but were not systematically studied in optimizing the inspection settings (scan radius and Fourier filter parameters). Follow on testing has focused on minimizing these false calls. Preliminary results have found that increasing both the rivet scan radius and high pass filter parameter in the data analysis decrease the system response due to rivet variations while not significantly effecting the flaw signal or the edge sensitivity of the system.

In the second analysis method the processed data saved from the inspection of each rivet was analyzed [10]. As the data files contain the probe output voltage versus angular position, the peak output voltage from each side of the fastener could be extracted. 20 points were removed from the resulting 720 inspection sites due to factors including inability to inspect fastener (4 sites at 2 fasteners), signal saturation (2 largest fatigue cracks), outlying behavior (3 fatigue cracks), and high signal level from unflawed fastener (11 sites at 7 fasteners). The remaining 700 inspection sites were analyzed to produce a family of POD curves based upon the threshold level used for the inspection. Using a threshold of 4 mV, this analysis found the 90% POD for 0.113" long fatigue cracks with an 8% false call rate. As noted above, follow on testing has focused on minimizing this false call rate through optimization of the scan radius and high pass filter parameter. In addition, signal averaging is being incorporated into the data display, Fourier filtering, and data archival to increase signal to noise and remove aberrant data. While operator calls naturally averaged the displayed data, updated several times a second, only a single unaveraged data set was saved to mass storage. It is believed that this factor contributed to the lower performance of the system using the system response data as compared to operator call data.
SUMMARY

A new prototype system for the detection of deeply buried flaws under airframe fasteners has been presented. The system is based upon the Self-Nulling Probe based Rotating Probe System previously developed at NASA LaRC. The incorporation of a magnetoresistive sensor within the Self-Nulling Probe design has been performed to enhance the low frequency and deep penetration capabilities of the technique. The fieldable prototype system incorporates a laptop computer for system control as well as data display, processing and archival. The system configuration has been presented along with laboratory and field test results. Probability of detection experiments performed at Sandia National Laboratories NDI Validation Center have been presented and show the device to be very sensitive to third layer flaws in the airframe lap-splice joint. The field tests also discovered a relatively high sensitivity of the system to surface anomalies at the rivet joint. Follow on testing has shown promise in reducing this effect in order to lower the false call rate on the system for inner layer fatigue crack detection.

ACKNOWLEDGEMENTS

The authors wish to thank Dave Galella of the FAA William J. Hughes Technical Center for support of the probability of detection field tests as well as Mike Bode of Sandia National Laboratories NDI Validation Center for assistance during testing and analysis of the results.

REFERENCES