Development of Eddy Current Techniques for the Detection of Cracking In Space Shuttle Primary Reaction Control Thrusters

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DEVELOPMENT OF EDDY CURRENT TECHNIQUES FOR THE DETECTION OF CRACKING IN SPACE SHUTTLE PRIMARY REACTION CONTROL THRUSTERS

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ABSTRACT. A recent identification of cracking in the Space Shuttle Primary Reaction Control System (PRCS) thrusters triggered an extensive nondestructive evaluation effort to develop techniques capable of identifying such damage on installed shuttle hardware. As a part of this effort, specially designed eddy current probes inserted into the acoustic cavity were explored for the detection of such flaws and for evaluation of the remaining material between the crack tip and acoustic cavity. The technique utilizes two orthogonal eddy current probes which are scanned under stepper motor control in the acoustic cavity to identify cracks hidden with as much as 0.060" remaining wall thickness to the cavity. As crack growth rates in this area have been determined to be very slow, such an inspection provides a large safety margin for continued operation of the critical shuttle hardware. Testing has been performed on thruster components with both actual and fabricated defects. This paper will review the design and performance of the developed eddy current inspection system. Detection of flaws as a function of remaining wall thickness will be presented along with the proposed system configuration for depot level or on-vehicle inspection capabilities.

INTRODUCTION

The Space Shuttle Reaction Control System (RCS) provides thrust to the vehicle for attitude and translational maneuvers during flight using both forward and aft RCS thrusters. The reusable Primary RCS (PRCS) thrusters are designed for a minimum of 100 missions, with 14 forward and 24 aft PRCS thrusters on the orbiter providing redundancy to the system [1]. The recent discovery of cracking in the PRCS thrusters has been identified as a potential failure mechanism of the critical flight hardware and has triggered an extensive NDE effort to identify techniques capable of detecting potential damage throughout the thruster inventory [2-4]. Over the life of the shuttle program, cracking in the relief radius area of seven thrusters has been isolated. Due to unknown variables including crack growth rates, failure modes, and the population of potentially compromised thrusters within the shuttle fleet, an eddy current technique has been developed for detection of the most hazardous flaws - deep relief radius cracks. The technique incorporates a dual frequency, orthogonally wound eddy current probe mounted on a stepper motor controlled scanning system. The system is designed to inspect for outer surface damage from the interior of the thruster. As the outer surface of the thruster is inaccessible without extensive disassembly, this enables on-vehicle or routine depot level inspection of thrusters for relief radius

cracking. Extensive testing has been performed using both manufactured and naturally occurring damage. Results have shown that flaws extending to within 0.060" of the inner surface can be detected, allowing sufficient margin for safe operation of the hardware.

EDDY CURRENT SYSTEM FOR ORBITER PRCS THRUSTER INSPECTIONS

Figure 1 displays a photograph of the prototype eddy current (EC) sensor and a conceptual diagram of the eddy current inspection technique. Matched eddy current coils are arranged orthogonally to each other and scanned into the acoustic cavity of the thruster. In the conceptual diagram in Figure 1, the inspection coil on the left is arranged with its axis along the circumferential direction. This orientation enables a relatively deep field penetration with the small diameter coil required to fit into the acoustic cavity, and induces current in a direction that will have a strong interaction with cracking originating in the relief radius and growing towards the acoustic cavity. The second coil is arranged with its axis parallel with the axis of the acoustic cavity. This second coil is designed to provide a local reference for the inspection coil while minimally interacting with damage originating at the acoustic cavity.

In order to interrogate beneath the surface of the acoustic cavity toward the relief radius, a low frequency excitation is required. An estimate of the required operating frequency can be found using the skin depth equation,

$$\delta = 1 / \sqrt{\pi f \mu \sigma} \tag{1}$$

with f = excitation frequency, μ = permeability, and σ = electrical conductivity. PRCS thrusters are fabricated from columbium with nominal values of $\sigma \approx 6.7 \times 10^6$ 1/(ohm-m) and μ = permeability of free space = $4\pi \times 10^{-7}$ Weber/(amp-m). A frequency f = 12 kHz then gives a skin depth $\delta \approx 1.8 \times 10^{-3}$ m, or approximately 0.070". The developed inspection procedure incorporates a dual frequency excitation, with the lower frequency enabling deep penetration into the part and the upper frequency helping to mix out responses from surface
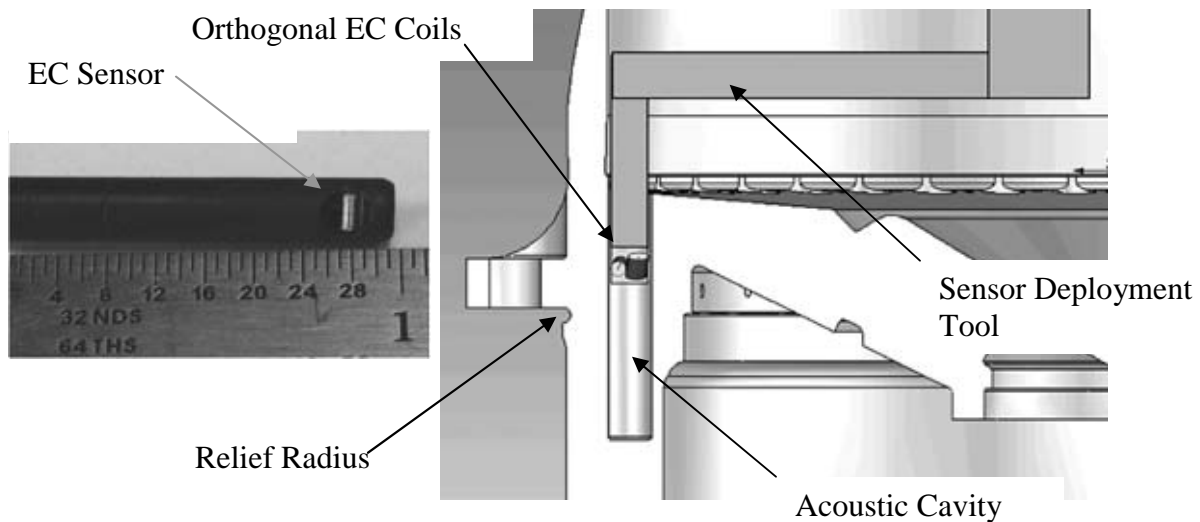

Figure 1. Photograph of prototype eddy current sensor and schematic diagram of eddy current thruster inspection tool.

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features such as lift-off and roughness of the acoustic cavity wall. Based upon the calculated skin depth and experimental data, 12 kHz and 100 kHz where chosen as standard operating frequencies for the inspection.

Initial testing performed with the sensor design shown in Figure 1 found a good sensitivity to nearly through-wall flaws, but damage that had not progressed to within approximately 0.020" – 0.040" of the acoustic cavity was difficult to detect due to the complex geometry of the part. The presence of varying material thickness, fuel passageways, and a potentially rough surface of the acoustic cavities was further complicated by the need to deploy the probe through the injector nozzle, past a narrow throat, and into the acoustic cavity for inspection. To minimize the combined effects of these attributes, a stepper motor controlled scanning system was incorporated into the inspection system. The stepper motor scanning system, designed in conjunction with NASA White Sands Test Facility, is deployed in the reaction chamber and rests on the face of the thruster. Once positioned, a pre-programmed scan of the sensor through the area of interest is performed. The use of the stepper motor scanning system significantly reduces lift-off effects associated with probe tilt and wobble, which are extremely difficult to control under hand scanning. In addition, the stepper motor scanner provides for indexed scanning such that eddy current response data can be plotted directly against location of the probe within the acoustic cavity. Probe responses associated with edge effects and varying wall thickness throughout the scan region can then be directly accounted for and filtered out, greatly enhancing the flaw detectability of the system.

Figure 2 shows a photograph of the eddy current sensor attached to the stepper motor scanner. The eddy current coil pictured in Figure 1 is now mounted in a probe housing that is attached to the stepper motor. In addition to the eddy current sensor, the probe housing holds a second, spare, scanning leg. Two other, fixed legs are attached to the scanning system to provide mechanical stability during scanning. When the scanner is positioned within a thruster, the four legs are spaced to fit into adjacent acoustic cavities. After receiving a trigger signal the stepper motor pulls the probe housing (along with the
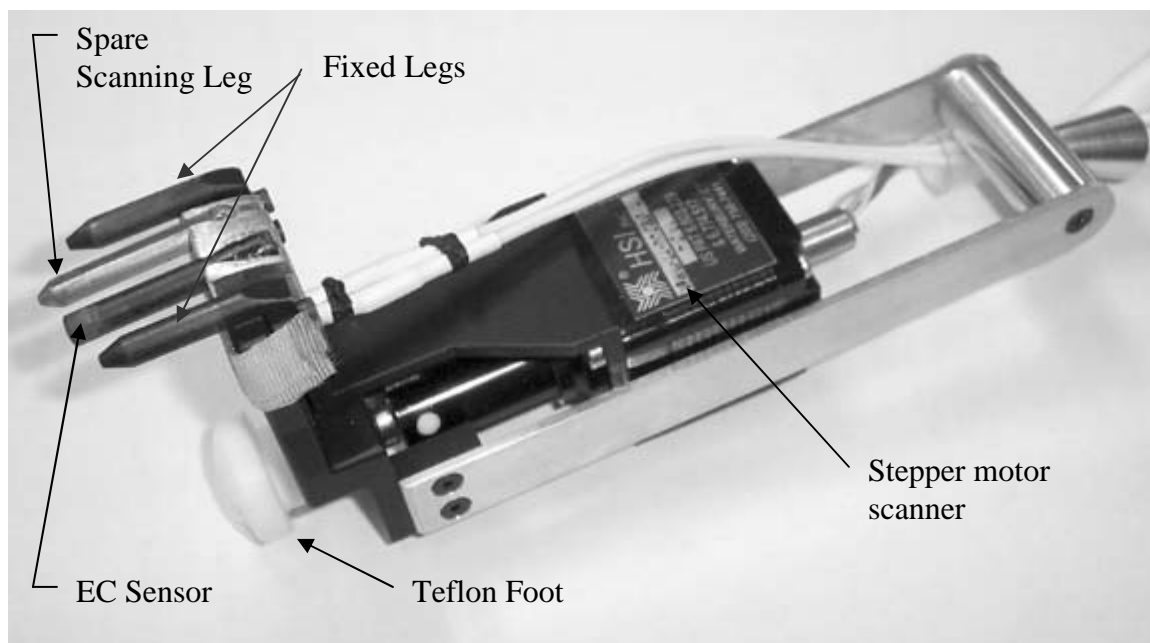

Figure 2. Stepper motor controlled eddy current PRCS thruster scanner.

Figure 3. Complete eddy current PRCS thruster inspection system.

eddy current sensor and spare scanning leg) away from the thruster face, moving the eddy current sensor through the region of interest. Immediately after withdrawing the probe the stepper motor reverses, moving the sensor once more through the region of interest and back to its start position.

The complete eddy current PRCS thruster inspection system is pictured in Figure 3. Along with the eddy current sensor and scanner, the system consists of a dual frequency eddy current instrument, laptop computer, A/D converter, and custom software. The scanner is shown inserted into a thruster mock-up used for setup and calibration.

The system control and data processing software initiates a scan sequence by sending a trigger signal to the stepper motor. Analog output data from the eddy current instrument are then acquired by the computer as the sensor scans partially out of and then back into the acoustic cavity. After the scan completes the acquired data at 12 kHz, 100
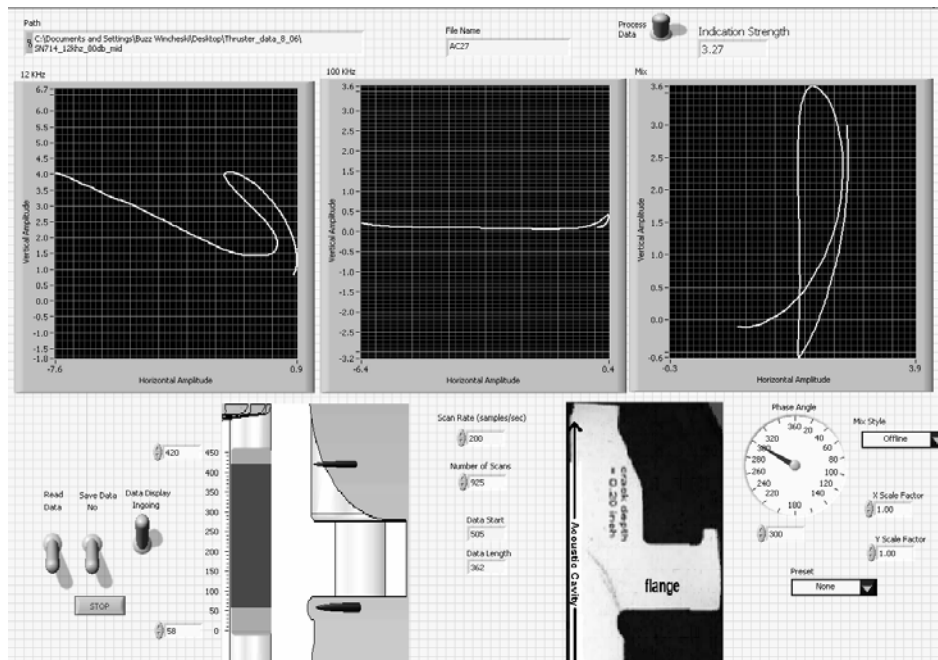

Figure 4. Front panel display of system control and data processing software.

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kHz, and frequency mix (calculated as the difference between the 12 kHz and 100 kHz responses) are displayed. Figure 4 shows a close up view of the front panel of the system software with data acquired during an inspection of a notched reference standard with 0.020" remaining wall thickness between the notch and the acoustic cavity. The three plots from left to right across the screen display the 12 kHz, 100 kHz, and frequency mix results, respectively. The nearly through-wall flaw is clearly detected in the low frequency and mix signals, with a slight indication of the flaw apparent even at 100 kHz. Toggle and slide switches are incorporated to enable the plotting of data over any region within the complete scan range, as well as of data acquired during the outgoing or ingoing scan of the probe. Controls are also present to adjust the mix signal parameters for data analysis on the selected portion of the scan data. The front panel also contains a micrograph of a cracking site dissected from a PRCS thruster. The typical crack profile displayed in the micrograph is useful for interpreting the eddy current response in relationship to potential damage in the hardware.

A final feature to be noted on the front panel is the calculated "Indication Strength", given in the upper right hand corner of the display. This value is calculated by fitting the eddy current response to the anticipated profile for the sensor scanned through an unflawed acoustic cavity region. Due to the edge effect as the probe nears the acoustic cavity opening, a sharp increase in the low frequency signal level is seen in this region. As the sensor moves into the cavity, a minimum in the low frequency vertical response is detected, most likely due to increasing wall thickness in this area. As the probe passes deeper into the cavity an increase followed by a final slight decrease in the probe output is detected. Subtracting the high frequency vertical component from low frequency vertical component helps to remove other artifacts, such that subsequent analysis is performed on this difference signal. Analysis of this signal profile has led to a signal processing technique employing curve fitting to a cosine modulated exponential function. The vertical component of the low frequency probe response minus that of the high frequency is fit to a curve of the form

$$V(x) = \cos(2\pi x/L) \times \exp(-x/A) \qquad (2)$$

with L = the secondary peak location, x = scan position inside the cavity, and A = the curve fit parameter. The fit is also constrained to match the data at each end of the scan. Figure 5 displays the results of applying this curve fitting procedure to an unflawed acoustic cavity (left plot) as well as a region where a notch approaches an acoustic cavity to within 0.040" remaining wall thickness (right plot). The difference between the raw data and the curve fit highlights the flawed region in the plot on the right. This technique is particularly useful for flaws growing at a steep angle, projecting to an intersection of the acoustic cavity near the cavity opening. It has been found that a calculation of the peak amplitude in the plot of the difference between the curve fit and the raw data correlates well with remaining wall thickness between the acoustic cavity and damage originating in the relief radius area. This calculated peak amplitude is the "Indication Strength" displayed on the system software front panel.

Figure 6 displays a plot of the calculated indication strength, as described above, versus remaining wall thickness between the acoustic cavity and relief radius. The data in Figure 6 was acquired on three thruster reference standards fabricated with electric discharge machine (EDM) notches and two non-flight (Class 3) thrusters. The EDM notch standards contained flaws at angles of 30, 45, and 60 degrees with remaining wall thicknesses of 0.020", 0.030', 0.040", and 0.060". There are no known flaws in the two
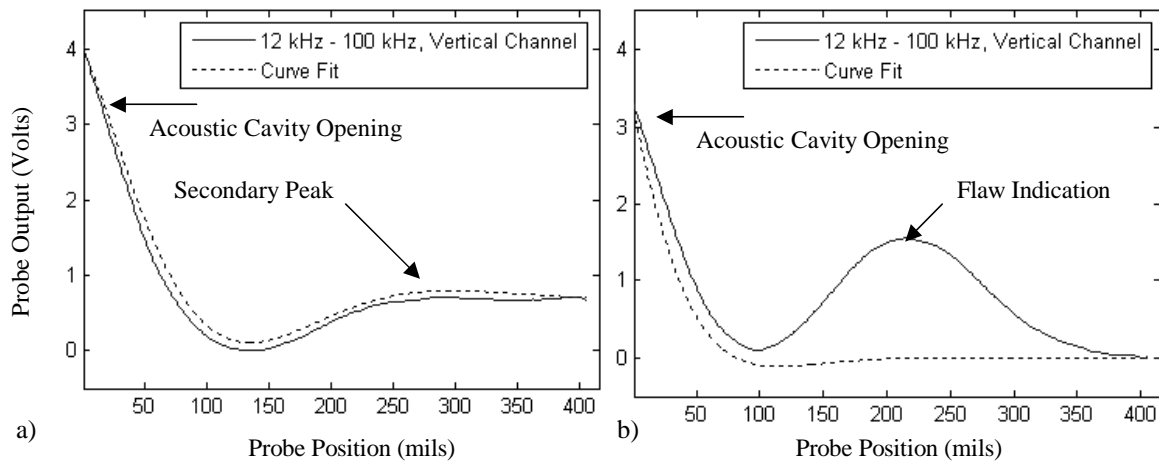
Figure 5. Plot of curve fit results for (a) unflawed cavity and (b) cavity with notch approaching to within 0.040" of the acoustic cavity wall. Error between curve fit and raw data highlights flawed regions near the acoustic cavity.

Class 3 thrusters. The minimum distance between the relief radius and the acoustic cavity in an unflawed thruster is roughly 145 mils, such that the cluster of points at that value in Figure 6 represents all of the inspected unflawed cavities, 170 sites.

Based upon the data depicted in Figure 6, a clear threshold can be established between unflawed thruster regions and areas with notches approaching to within 0.060" of the acoustic cavity wall. It should be noted that the data shown in Figure 6 corresponds to notches originating directly across from the acoustic cavity. As the eddy current coil is aligned in this direction, the sensor has maximum sensitivity for flaws in this orientation. As a part of the reference standard development, flaws originating at an off angle have also
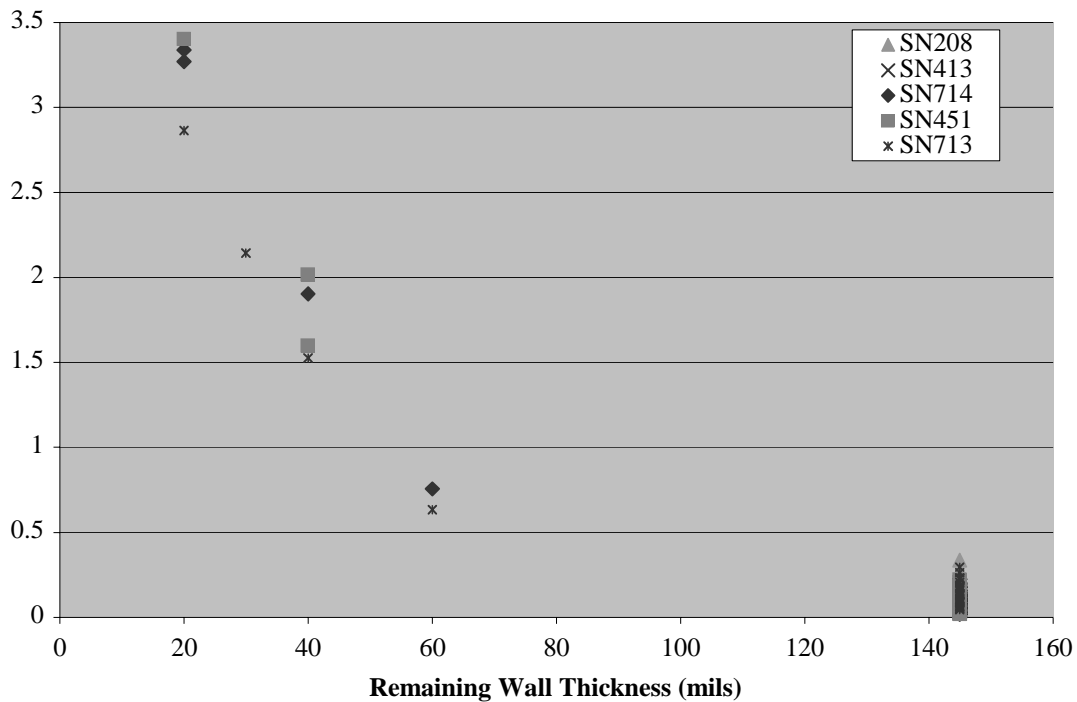

Figure 6. Calculated indication strength for all cavities with calibration notches originating across from the acoustic cavity as well as all unflawed cavities in PRCS thruster serial numbers 208, 413, 714, 451, and 713.

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been fabricated. Test results have shown that the signal response for flaws originating between cavities as opposed to directly across from a cavity does drop, although flaws up to 0.060" away from the acoustic cavity are still detectable.

Naturally occurring cracking in PRCS thrusters has also been studied. A limited number of cracking sites identified in the thruster inventory have been maintained for NDE development and system calibration. The indication levels from this naturally occurring damage have been found to be as high or higher than those for simulated damage using EDM notches. The likely cause for the increased signal levels on naturally occurring damage is the flaw profile. All naturally occurring damage sites identified to date have shown a very high aspect ratio of crack length to crack depth. The notch standards were all fabricated with a two to one aspect ratio, and therefore likely underestimate the crack length at a given remaining wall thickness. The natural crack profile with a long circumferential direction also makes the occurrence of deep cracking between cavities with little damage directly across from the cavity unlikely. It therefore is reasonable to anticipate flaw detection capabilities for naturally occurring cracking to be at least as reliable as those for the calibration data shown in Figure 6.

SUMMARY

As a result of the recent detection of cracking in Space Shuttle Primary Reaction Control System thrusters, an in-depth analysis of potential failure modes and flaw detection capabilities in the hardware was initiated [2-3]. To detect the most probable critical damage, an eddy current technique has been developed to inspect for nearly through-wall cracking originating in the relief radius of the thruster. The technique incorporates orthogonally wound eddy current probes that are scanned within the acoustic cavities under stepper motor control. A dual frequency inspection procedure is used to minimize surface and lift-off effects. Data processing and analysis routines have also been developed and incorporated into the system control software. The system has been extensively tested on both simulated and naturally occurring flaws, showing a signal to noise ratio better than 3 to 1 for flaws as deep as 0.060" away from the acoustic cavities.

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14. ABSTRACT

A recent identification of cracking in the Space Shuttle Primary Reaction Control System (PRCS) thrusters triggered an extensive nondestructive evaluation effort to develop techniques capable of identifying such damage on installed shuttle hardware. As a part of this effort, specially designed eddy current probes inserted into the acoustic cavity were explored for the detection of such flaws and for evaluation of the remaining material between the crack tip and acoustic cavity. The technique utilizes two orthogonal eddy current probes which are scanned under stepper motor control in the acoustic cavity to identify cracks hidden with as much as 0.060" remaining wall thickness to the cavity. As crack growth rates in this area have been determined to be very slow, such an inspection provides a large safety margin for continued operation of the critical shuttle hardware. This report presents flaw detection capabilities along with the proposed system configuration for depot level or on-vehicle inspection capabilities.

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