Validation Test Results for Orthogonal Probe Eddy Current Thruster Inspection System

Russell A. Wincheski
Langley Research Center, Hampton, Virginia

November 2007
Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) Program Office plays a key part in helping NASA maintain this important role.

The NASA STI Program Office is operated by Langley Research Center, the lead center for NASA’s scientific and technical information. The NASA STI Program Office provides access to the NASA STI Database, the largest collection of aeronautical and space science STI in the world. The Program Office is also NASA’s institutional mechanism for disseminating the results of its research and development activities. These results are published by NASA in the NASA STI Report Series, which includes the following report types:

- **TECHNICAL PUBLICATION.** Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counterpart of peer-reviewed formal professional papers, but having less stringent limitations on manuscript length and extent of graphic presentations.

- **TECHNICAL MEMORANDUM.** Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- **CONTRACTOR REPORT.** Scientific and technical findings by NASA-sponsored contractors and grantees.

- **CONFERENCE PUBLICATION.** Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or co-sponsored by NASA.

- **SPECIAL PUBLICATION.** Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- **TECHNICAL TRANSLATION.** English-language translations of foreign scientific and technical material pertinent to NASA’s mission.

Specialized services that complement the STI Program Office’s diverse offerings include creating custom thesauri, building customized databases, organizing and publishing research results ... even providing videos.

For more information about the NASA STI Program Office, see the following:

- E-mail your question via the Internet to help@sti.nasa.gov
- Fax your question to the NASA STI Help Desk at (301) 621-0134
- Phone the NASA STI Help Desk at (301) 621-0390
- Write to: NASA STI Help Desk NASA Center for AeroSpace Information 7115 Standard Drive Hanover, MD 21076-1320
Validation Test Results for Orthogonal Probe Eddy Current Thruster Inspection System

Russell A. Wincheski
Langley Research Center, Hampton, Virginia

November 2007
Background

Recent nondestructive evaluation efforts within NASA have focused on an inspection system for the detection of intergranular cracking originating in the relief radius of Primary Reaction Control System (PCRS) Thrusters [1-3]. Of particular concern is deep cracking in this area which could lead to combustion leakage in the event of through wall cracking from the relief radius into an acoustic cavity of the combustion chamber. In order to reliably detect such defects while ensuring minimal false positives during inspection, the Orthogonal Probe Eddy Current (OPEC) system has been developed. 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 intergranular cracking. A more detailed description of the OPEC technique is contained in a previous report [1].

System Validation

In order to verify the reliability of the OPEC system an extensive validation including blind inspection of over 1500 acoustic cavities was performed. Validation testing was conducted at United Space Alliance (USA) facilities in Cape Canaveral Air Force Station by USA eddy current level II NDE inspectors. Prior to the beginning of the inspections, two days of training consisting of a system overview, demonstration, and hands on practice was provided to the inspectors by the system developer. Demonstration and hands on work was performed on a sample set consisting of an oil-bronze thruster replica with fabricated flaws as well acoustic cavities 25 – 29 of PRCS thruster serial number 713. Following training, three United Space Alliance (USA) eddy current level II NDE inspectors were tasked to inspect the validation sample set. These inspections were performed in accordance with written procedures documented in the validation plan [4,5]. Flaw calls were made immediately by the inspectors and documented on inspection reports. All raw data were also saved for further analysis.

Validation Sample Set

Four PRCS thrusters, three of which contained fabricated electric discharge machine (EDM) notches, were used for this validation study. Table 1 reports the location, remaining wall thickness, and angle of the flaw with respect to mounting flange for each of the fabricated EDM notches. The first 11 notches were placed directly across from the indicated acoustic cavity while the final 7 notches were placed between the two adjacent cavities identified in the table. The resulting flaw population contains 18 independent flaws approaching 25 acoustic cavities. The fourth thruster used in the validation study contained no flaws. As each thruster contains 42 acoustic cavities, the sample set of four thrusters contained 143 unflawed inspection sites. The complete validation sample set was inspected three times by each of the three level II NDE inspectors for a total of nine

1
inspection cycles. The complete validation inspections therefore resulting in 225 scans of cavities with approaching flaws and 1287 scans of unflawed cavities. Neglecting the 5 inspection sites used for training and calibration, the condition of the thrusters was not known to the inspectors.

### Table 1. Manufactured Flaws in Validation Standards

<table>
<thead>
<tr>
<th>Thruster S/N</th>
<th>Acoustic Cavity</th>
<th>Remaining Wall Thickness (in)</th>
<th>Flaw Angle (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>714</td>
<td>16</td>
<td>0.02</td>
<td>30</td>
</tr>
<tr>
<td>451</td>
<td>27</td>
<td>0.02</td>
<td>45</td>
</tr>
<tr>
<td>713</td>
<td>37</td>
<td>0.02</td>
<td>60</td>
</tr>
<tr>
<td>451</td>
<td>32</td>
<td>0.04</td>
<td>30</td>
</tr>
<tr>
<td>714</td>
<td>32</td>
<td>0.04</td>
<td>45</td>
</tr>
<tr>
<td>451</td>
<td>37</td>
<td>0.04</td>
<td>60</td>
</tr>
<tr>
<td>714</td>
<td>27</td>
<td>0.02</td>
<td>45</td>
</tr>
<tr>
<td>714</td>
<td>37</td>
<td>0.06</td>
<td>45</td>
</tr>
<tr>
<td>713</td>
<td>27</td>
<td>0.03</td>
<td>45</td>
</tr>
<tr>
<td>713</td>
<td>32</td>
<td>0.06</td>
<td>45</td>
</tr>
<tr>
<td>713</td>
<td>16</td>
<td>0.04</td>
<td>45</td>
</tr>
<tr>
<td>714</td>
<td>10/11</td>
<td>0.02</td>
<td>30</td>
</tr>
<tr>
<td>451</td>
<td>42/1</td>
<td>0.02</td>
<td>45</td>
</tr>
<tr>
<td>713</td>
<td>42/1</td>
<td>0.02</td>
<td>60</td>
</tr>
<tr>
<td>713</td>
<td>5/6</td>
<td>0.04</td>
<td>30</td>
</tr>
<tr>
<td>714</td>
<td>5/6</td>
<td>0.04</td>
<td>45</td>
</tr>
<tr>
<td>713</td>
<td>10/11</td>
<td>0.04</td>
<td>60</td>
</tr>
<tr>
<td>451</td>
<td>5/6</td>
<td>0.06</td>
<td>45</td>
</tr>
</tbody>
</table>

**Inspection Results**

Flaw calls were reported by the inspectors immediately following the scan of a given cavity. This call data along with specific inspection criteria and all raw data were then recorded before the next cavity was inspected. Figure 1 displays a plot of the flaw call results. In this plot the hit ratio for flaws at each remaining wall thickness is calculated as the number of flaw calls divided by the number of opportunities to detect flaws of that remaining wall thickness. All unflawed cavities are plotted at a thickness of 0.145”, the approximate minimum wall thickness between the relief radius and acoustic cavity in the absence of any flaws. All inspections at sites with 0.020” and 0.030” remaining wall thicknesses were called along with 89/90 0.040” remaining wall thickness sites and 18/36 0.060” flaw sites. No false positives were reported from any of the unflawed cavities.
A closer look at the data reveals additional information concerning the undetected flaws. Strong evidence exists that the one missed call at 0.040” remaining wall thickness is due to a missed inspection site rather than a missed call at the site with 0.040” remaining wall thickness. It appears a duplicate inspection was performed on the cavity prior to the cavity in question (S/N 713, AC16) which was then skipped over on the next inspection. All other inspections of S/N 713 AC 16 produced strong flaw response. The remaining missed calls all occurred at the sites corresponding to the 0.060” remaining wall thickness flaw originating between adjacent acoustic cavities (S/N451 AC5-AC6). The two flaws with 0.060” remaining wall thickness which originate directly across from the acoustic cavity (S/N 713, AC32 and S/N 714 AC37) were detected in every inspection cycle.

Another method for examining the validation test results is to plot the system response versus remaining wall thickness. The data fall into two main clusters depending upon the orientation of the flaws. Figure 2 displays the results for all flaws originating across from an acoustic cavity. The plot contains the results from all nine inspection cycles. The indication level for all unflawed cavities is shown as the cluster of points at 0.145” remaining wall thickness. The single missed inspection at S/N713 acoustic cavity 16 (0.040” remaining wall thickness) is clearly out of family with the remainder of the data and, as discussed above, is the result of a missed inspection of that site. Otherwise the data show a strong correlation between indication strength and remaining wall thickness with a clear distinction between all flawed and unflawed cavities. An indication strength of 0.5 volts was set by procedure to be the threshold for a relevant flaw indication [3].

Figure 1. Hit ratio for flaws at all 1512 cavities inspected during validation testing.
Figure 2. Indication strength for all notches originating across from an acoustic cavity.

Figure 3 displays the results for all flaws originating directly between acoustic cavities. As in figure 2, the plot contains the results from all nine inspection cycles. A drop in the indication level as compared to flaws originating across from the cavities is evident. The indication level for between cavity flaws at 0.060” remaining wall thickness overlaps the distribution for the unflawed cavities. All flaws within 0.040” of the cavity are clearly separated from the unflawed cavities and were detected in the study.

Another factor which was found to influence the measured indication strength is the angle of the flaw with respect to the thruster mounting flange. As reported earlier, flaws
were introduced at angles of 30, 45 and 60 degrees. While the 30 and 45 degree flaws showed a similar response to the inspection system, edge effects associated with the proximity of the 60 degree flaw tip to the thruster face resulted in slightly reduced detection sensitivity. It should be noted that such high angle flaws appear to be rare. Destructive analysis performed by the NASA Engineering and Safety Center on PRCS Thruster S/N 132 found flaw angles to be typically between 40 and 50 degrees with a maximum measured flaw angle of 54 degrees [6].

In figures 4 the 60 degree flaws have been removed to show the strong correlation between remaining wall thickness and indication strength for the 30 and 45 degree flaws originating across from an acoustic cavity. The missed inspection at S/N 713 AC 16 has also been removed for clarity. Figure 5 shows the equivalent data for flaws originating between adjacent acoustic cavities. Here the plotted indication strength is the average of the recorded signal from the acoustic cavities on either side of the flaw. Averaging these values helps to correct for potential misplacement of the flaw between the cavities.

**Relationship Between Validation Artifacts and PRCS Thruster Cracking**

The applicability of electric discharge machine notches to simulate naturally occurring cracking in PRCS thrusters for the development of nondestructive evaluation standards has to be taken into account to predict the detectable size of such damage. To this end a limited number of intergranular cracking sites previously identified in PRCS thruster S/N 132 have been maintained for NDE development and system calibration. As realistic flaws are difficult to fabricate, especially in statistically relevant quantities for NDE system validation, validations are typically performed with fabricated notches. A (knockdown) factor describing the response of the system between the validation artifacts and actual flaws is then sought to bound the flaw detectability on real hardware.

**30 and 45 Degree Notches Across From Cavities**

![30 and 45 Degree Notches Across From Cavities](image)

Figure 4. Indication strength for 30 and 45 degree notches originating across from an acoustic cavity.
In this work the eight remaining inspection sites on PRCS Thruster S/N 132 were examined with the OPEC system. As described in the NESC Report [6], sections of this thruster have been destructively examined and crack depths measured. Figure 6 displays the indication levels from this naturally occurring damage along with measured crack depths. The data acquired from acoustic cavities 37 and 38 each showed saturation in the low frequency (12 kHz) response along with a very strong vertical response in the high frequency (100 kHz) data. As the standard depth of penetration of the electromagnetic field in the thruster is approximately 0.070” at 12 kHz but only approximately 0.025” at 100 kHz, this indicates that the discontinuity in the material extends very close to the acoustic cavity wall and is potentially a through wall flaw in these locations.

By extrapolating the measured crack depths from the destructive analysis of S/N 132 through an area with a preserved acoustic cavity an approximation of the remaining wall thickness at the OPEC inspection site can be determined. Figure 7 plots the extrapolated remaining wall thickness in thruster S/N 132 versus indication strength for the OPEC system inspections. The responses from acoustic cavities 37 and 38 have been removed from the plot due to system saturation at these inspection sites. Figure 7 also contains the data for the 30 and 45 degree notches placed across from an acoustic cavity. The data show that the signal level from naturally occurring damage is comparable to, or even higher, than that for the validation notches. A likely cause for the increased signal levels on naturally occurring damage is the flaw profile. All naturally occurring damage identified to date has 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 likely flaw aspect ratio also minimizes the potential for deep cracking between acoustic cavities without appreciable damage directly in front of a single cavity.

Figure 5. Inspection Results for 30 and 45 degree notches originating between adjacent acoustic cavities. Indication strength calculated from average of cavities on either side of notch.
Figure 6. Inspection results for intergranular cracking in PRCS thruster S/N 132. Plot contains OPEC inspection results along with destructive analysis of thruster.

Figure 7. Plot of indication strength versus interpolated remaining wall thickness for naturally occurring intergranular cracking in comparison to 30 and 45 degree notches placed across from an acoustic cavity.
Summary

An extensive validation of the orthogonal probe eddy current system for the detection of intergranular cracking in the relief radius of primary reaction control system thrusters has been performed. All flaws in the validation study with 0.040” remaining wall thickness or less were detected and no false calls were reported. In addition to remaining wall thickness, two other factors influencing the detectability of damage in PRCS thrusters have been identified as the location of the flaw (either across from or between acoustic cavities) and the angle of the flaw with respect to the acoustic cavity wall. A comparison with naturally occurring damage indicates that the most likely flaw profile produces the strongest OPEC response, comparable to the response from validation notches placed in front of an acoustic cavity at angles between 30 and 45 degrees. At this flaw orientation flaws with as much as 0.060” remaining wall thickness can be clearly separated from unflawed cavities.

The results reported here show the OPEC system to be a robust, operator independent (with sufficient training), and reliable inspection method for intergranular crack detection in the relief radius of PRCS thruster components. Deployment of the system for depot level inspections at NASA WSTF will provide valuable information and can be implemented with minimal impact on thruster processing.

Acknowledgements

This work was conducted as part of an integrated team of participants from NASA-JSC, NASA-WSTF, NASA-LaRC, NASA Engineering and Safety Center, United Space Alliance, and Boeing formed to address NDE requirements for orbiter PRCS thruster inspections.

References

The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

1.  REPORT DATE (DD-MM-YYYY)  01-11 - 2007
2.  REPORT TYPE  Technical Memorandum
3.  DATES COVERED (From - To)
4.  TITLE AND SUBTITLE
   Validation Test Results for Orthogonal Probe Eddy Current Thruster Inspection System
5a.  CONTRACT NUMBER
5b.  GRANT NUMBER
5c.  PROGRAM ELEMENT NUMBER
5d.  PROJECT NUMBER
5e.  TASK NUMBER
5f.  WORK UNIT NUMBER
377816.06.02.03.05
6.  AUTHOR(S)
   Wincheski, Russell (Buzz) A.
7.  PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
   NASA Langley Research Center
   Hampton, VA  23681-2199
8.  PERFORMING ORGANIZATION REPORT NUMBER
   L-19426
9.  SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
   National Aeronautics and Space Administration
   Washington, DC  20546-0001
10. SPONSOR/MONITOR'S ACRONYM(S)
    NASA
11. SPONSOR/MONITOR'S REPORT NUMBER(S)
    NASA/TM-2007-215087
12. DISTRIBUTION/AVAILABILITY STATEMENT
    Unclassified - Unlimited
    Subject Category 26
    Availability: NASA CASI (301) 621-0390
13. SUPPLEMENTARY NOTES
    An electronic version can be found at http://ntrs.nasa.gov
14. ABSTRACT
    Recent nondestructive evaluation efforts within NASA have focused on an inspection system for the detection of intergranular cracking originating in the relief radius of Primary Reaction Control System (PCRS) Thrusters. Of particular concern is deep cracking in this area which could lead to combustion leakage in the event of through wall cracking from the relief radius into an acoustic cavity of the combustion chamber. In order to reliably detect such defects while ensuring minimal false positives during inspection, the Orthogonal Probe Eddy Current (OPEC) system has been developed and an extensive validation study performed. This report describes the validation procedure, sample set, and inspection results as well as comparing validation flaws with the response from naturally occurring damage.
15. SUBJECT TERMS
    Eddy Current; Intergranular Cracking; Thruster; Validation
16. SECURITY CLASSIFICATION OF:
    a. REPORT  U
    b. ABSTRACT  U
    c. THIS PAGE  U
17. LIMITATION OF ABSTRACT
    UU
18. NUMBER OF PAGES  13
19. NAME OF RESPONSIBLE PERSON
    STI Help Desk (email: help@sti.nasa.gov)
    (301) 621-0390
19b. TELEPHONE NUMBER (Include area code)