LASER INSPECTION FOR CRACK DETECTION AND PROFILOMETRY MEASUREMENT IN NUCLEAR APPLICATIONS

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ABSTRACT
Laser-based profilometry inspection is a versatile emerging technique for measurement and flaw detection of a variety of critical components. Recently, this technology has been adapted to two critical nuclear power inspection needs, detection of cracks in the reactor pressure vessel (RPV) upper head penetration control rod drive mechanism (CRDM) J-groove weld wetted surface and precision mapping of the inside diameter (ID) of bottom mounted nozzle (BMN) tubing with large tube offsets and bends due to field repairs.

For CRDM J-groove welds, surface-breaking cracks associated with primary water stress corrosion cracking (PWSCC) are of primary concern. For traditional nondestructive examination (NDE) methods such as eddy current and liquid penetrant, the topography of J-groove welds has made surface examinations difficult. Laser Video Imaging™ (LVI), a non-contact method that has been used to inspect flaws in a variety of applications such as the ID and OD surfaces of tubing and linear plate welds, generates a high-resolution photograph-like scatter image of the surface. This method uses a scanning laser to detect surface-breaking flaws of at least 0.001 inches. A prototype robotic delivery device and surface-scanning sensor for inspection of the CRDM J-groove welds was developed. This device employs five axis of motion for automatic inspection of the contoured weld region. The scanning laser sensor makes use of a high-speed rotating mirror for weld surface mapping, and two detection axes to uniformly collect scattered light from the weld. High resolution scans of the full weld region were successfully generated and stitched together using the LaserViewer™ software, and known flaws were identified and characterized.

BMN’s in RPV lower heads are also susceptible to PWSCC. Several reactors contain field-repaired BMNs that have an inconsistent weld fit, with tube offset errors of up to 1/8 inch and angular errors of up to 4 degrees, which makes volumetric inspection of the field repair weld zone extremely difficult. Laser Profilometry (LP), a proven technique for high-resolution imaging and measuring of tubing ID with diameters above 0.1 inches, is well-suited for mapping a variety of tube geometries. This technology generates two high-resolution images, a profile map and an LVI. A laboratory study was conducted to develop a LP sensor for this application. This sensor was optimized for under-water measurement with a flexible shaft for traversing the ID weld region transition. It successfully maneuvered through the transition in the mockup and created a high resolution 3D profile map. Internal surface flaws near the transition were also located and mapped.

These results confirm that laser-based inspection technology, with its unique capability for inspecting unusual geometries, has potential as an additional method for reliable and accurate flaw location and indication confirmation.

LASER SCANNING TECHNOLOGY

Laser Profilometry

Laser profilometry is a precision measurement technology that uses point triangulation of a laser spot on a target surface. Figure 1 is an optical sketch of a typical laser triangulation sensor. The diode laser, a very small laser source that enables miniature sensors, is focused onto a target surface with the source lens. A receiving lens images the laser spot on the target surface onto a position-sensitive detector. The position...
of the imaged spot on the detector depends on the location of the target surface. Electronic circuitry and software convert the detector signal to a calibrated position measurement.

Figure 1. Point triangulation.

Figure 2. Helical scanning.

Figure 2 shows a typical profilometry sensor for measurement of tubes or pipes. The sensor rotates while moving axially so that the laser beam traces a helical path on the surface. At each point, the sensor records the distance to the surface and the amount of light scattered from the surface. The distance measurements create a detailed profile map of the surface, while the scattered light creates a high-resolution LaserVideo Image (LVI™) of the surface (Figure 3). The two images are frequently used together in order to measure and evaluate surface features and potential indications.

Figure 3. Profile (left) and LVI (right) for a BMN tube section
PROFILOMETRY IN BOTTOM-MOUNT NOZZLES

Background

Bottom-mounted nozzles (BMN’s) in pressurized water reactor (PWR) vessel lower heads are fabricated from Alloy 600 material, while the weld material attaching the nozzles is Alloy 182/82. These materials are susceptible to active age-related degradations such as primary water stress corrosion cracking (PWSCC). Stress is induced during the process of welding the nozzles to the lower vessel head, a contributing factor for PWSCC.

During initial construction of the B&W nuclear facilities, it was determined that the BMN configuration was not robust enough and that a field repair would be necessary on all nine B&W plants that were being constructed. This repair included attaching a 0.625 inch inside diameter (ID) tube to the original 0.614 inch ID tubing. This mismatch and the inconsistent weld fit up makes it difficult to volumetrically inspect the field repair weld zone with current ultrasonic (UT) forward scatter time of flight diffraction (TOFD) or with eddy current (ET) inspection techniques.

In 2004, the American Society of Mechanical Engineering released Code Case N-722 [2] in order to address the inspection frequency and method of examination for reactor coolant leakage. This Code Case covers both the use of bare metal visual and non-visual nondestructive examination (NDE). If any leaks are discovered during the visual examination, further evaluations must be completed with the use of non-visual NDE. This examination must characterize any flaws discovered. Since the issuance of the Code Case, the Nuclear Regulatory Commission (NRC) has dictated, (citing Title 10 Code of Federal Regulations 50.55 Rule) [1] [2] [3] that in order to implement Code Case N-722 it is required that a qualified NDE method be used to characterize, locate and size the flaws.

A proof-of-concept laser probe for profiling the field repair zone was previously developed [4]. In that study, the sensor was mounted on a rigid shaft, and various tube samples were scanned, with internal flaws clearly detected. A scan of a B&W mockup was attempted with this sensor, but severe tube deformity in the weld region and significant angular mismatch of the welded tubes prevented the rigid sensor from fully traversing the weld region. In order to scan through the weld region, a flexible shaft geometry and shortened sensor head were proposed.

This work extends the prior demonstration to a water-sealed prototype sensor with a flexible shaft [5]. The key requirements for the sensor are:

- The sensor must be able to transition the repair offset.
- The range of the sensor must be adequate to measure the full tube on either side of the actual weld.
- This technology must be able to operate under water, with field conditions including depths up to 60 feet.

Mockup

The B&W mockup design built by EPRI is shown in Figure 4 and was built in accordance with the manufacturer’s following specifications:

- This penetration in the field is a repair with a centering plug holding the upper tube to the lower tube.
- The lower thin-wall tube (1.028” OD, 0.614” ID) coming through the vessel head has been cut off at an angle parallel to the vessel ID and an angled thicker-walled tube (2.00” OD, 0.625” ID) has been attached with weld material onto the cut lower tube and the J-groove weld.
- After the weld is completed, the centering plug is drilled out from above.
- According to the repair design, the penetration weld is accepted only if a 9/16” ball drops freely
through the penetration. This is the only written acceptance of this field repair weld. 

*On the right side of* Figure 4 is a rubber replica of the mockup, showing the mismatch in the weld region.

![Figure 4. BMN Mockup(left) and rubber replica of the nozzle (right)](image)

**Sensor Design**

A three-dimensional image of the Laser Profilometry Sensor is shown in Figure 5. The sensor head is attached to a flexible shaft that can bend around the welded joint and tube deformities. For optimal maneuverability, the sensor head is made as short as possible. To achieve this, the laser is fiber-pigtailed and located to a separate sealed housing, along with the motor. Centering devices are placed on either side of the sensor optics to insure the smoothest possible transition through the weld zone. The centering devices are made from Delrin, with curved surfaces to minimize the chance of getting caught on sharp edges. The flexible shaft that drives the sensor has periodic Nylon beads to minimize irregular shaft motion that could impact the sensor measurement as the shaft and sensor rotate. The shaft is composed of a polyethylene outer cover for waterproofing, with an internal anti-twist stainless steel flexible shaft.
Figure 5. Profilometry sensor with flexible shaft.

**Test Setup**

Figure 6 shows the sensor mounted in the test assembly with the BMN mock-up. The translation stage has 24 inches of travel to allow motion of the sensor through the full tube, past the weld transition in a single scan. A water reservoir at the top of the tube allows the tube to be water-filled throughout a full scan of the test article. Although the sensor is designed to withstand pressure from up to 60 feet of water, there was no provision to test the sensor in deep water during this phase of the project. The calibration ring is mounted on the mock-up for ease of setup; the same water reservoir is used for measuring the calibration rings as well as the mock-up.

Results
A set of three calibration rings was fabricated to precision diameters and measured using National Institute of Standards and Technology (NIST) traceable equipment at a third party quality control (QC) firm. The sensor calibration is verified with a scan of the calibration tooling, and minor adjustments are made to the first and second order calibration constants, if needed. For all rings, the measurement repeatability was better than 0.0005 inches.

<table>
<thead>
<tr>
<th>Ring</th>
<th>Measured Diameter (inches)</th>
<th>Std Dev (in)</th>
<th>Error</th>
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<tr>
<td>1</td>
<td>0.7376</td>
<td>0.0003</td>
<td>0.0000</td>
</tr>
<tr>
<td>2</td>
<td>0.6387</td>
<td>0.0002</td>
<td>0.0000</td>
</tr>
<tr>
<td>3</td>
<td>0.5885</td>
<td>0.0004</td>
<td>0.0000</td>
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The B&W mock-up was scanned multiple times at high resolution under water, with no problems moving through the weld region.

Figure 7 is a series of false-color 3D images of the weld region, at four rotational orientations separated by approximately 90 degrees each. These images illustrate a number of interesting features present in these tubes, including thread-like grooves, pitting, and sections where material has been removed across the weld. Significant deformity is clearly visible on both sides of the weld region. The shape of the weld transition is accurately replicated by the sensor. However, the overall tube bend is affected by both the centering device motion as it travels through the tube and the flexible shaft. Since the flexible shaft is designed to follow the tube axis as it travels through the tube, any tube size or geometry changes are only visible locally. The axes of the two welded tubes are clearly oriented at an angle with respect to each other.

Figure 8 shows an axial cross section through the largest weld offset. The abrupt transition has an amplitude of 0.090 inches, with a gradual taper of another 0.035 inches, for a total axial variation to 0.122 inches. This transition was measured on the polymer replica using an optical comparator at 0.96 inches. The constant re-centering of the sensor as it traverses the severe offset affects the gradual transition, but...
the abrupt change should match the actual value since the centering devices do not immediately re-center the sensor as it crosses the transition.

Figure 8. Axial cross section of weld

CRACK DETECTION IN CRDM WELDS

Background

Regulatory enforcement through federal rulemaking requires surface examinations of the reactor pressure vessel (RPV) upper head penetration J-groove welds if the volumetric examination of the penetration does not provide essentially 100% coverage [2] [3] [6]. The surface examinations of J-groove welds have been difficult at best when examined with the eddy current and liquid penetrant nondestructive examination (NDE) methods.

In previous work, a proof-of-concept sensor was developed to evaluate the possibility of employing laser inspection technology to examine Reactor Pressure Vessel (RPV) upper head J-groove weld surfaces and detecting surface-breaking cracks associated with primary water stress corrosion cracking (PWSCC) [4]. The results of this study demonstrated the ability of laser scanning technology to provide high-resolution surface images of test plates with a variety of indications. This inspection method can also be used to confirm and characterize indications detected by other NDT methods.

This work has recently been expanded with the development of high-speed scanning sensor and robotic delivery device to follow the profile of the CRDM penetration. The goal of this work was to perform a high-resolution scan of a J-groove weld on a CRDM penetration mock-up provided by, and to determine the presence of simulated cracks in the scan data.

Sensor Design

Figure 9 shows the scanning sensor, which measures the surface profile LaserVideo™ imaging (LVI) on each of two detection axis. The detectors are positioned on opposite sides of the laser beam, so that variations in the direction of scattered light can be averaged out. During scanning, an internal mirror rotates at a rate of 500-1000 rpm, creating a line scan with an angular span of approximately 130 degrees. The sensor has a 0.30 inch depth of field, a 0.5 inch radius in the center of range, and a spot size of 0.0015 inches. The primary purpose of this sensor is to produce a high resolution visual image of the weld. The profilometry measurement is, however, useful in positioning the sensor at the optimal distance from the
The sensor has been optimized for detection of the concave weld profile. Thus, the scanning beam has a measurement arc with a radius of 0.5 inches, which is slightly larger than the minimum weld radius. Figure 10 shows an image of the sensor at the top portion of the weld, which has the tightest curvature. The small radius of the upper weld requires the sensor to be close to the weld, with a standoff distance of 0.15 inches.

**Robotic Delivery Device Design**

The stage design is shown in Figure 11. The assembly is attached to the inside of the tube with a lathe scroll chuck, which is fitted with aluminum shoes to insure that the chuck does not mar the internal surface of the tube. A 45° angle bracket is mounted on the scroll chuck. For the laboratory demonstration, this bracket is a rigid mount designed to match the tube exit angle on the mockup supplied by EPRI. For field inspections, this mount will be replaced with an adjustable mount in order to accommodate the range of tube angles present on a typical head. The rotary stage, mounted on the angle bracket, has an internal drive motor, as a more standard external motor would interfere with the motion of the other axes.

The vertical and radial linear stages maintain the sensor at a constant distance from the tube and pressure vessel surface during the scan. The linear stages have long carriages to maximize rigidity and therefore positional accuracy of the sensor. The radial stage also has a wide body to further enhance rigidity.
Figure 11. Stage assembly

Figure 11 has a zoom of the pivoting sensor head assembly mounted on the end of the vertical stage. The scanning sensor is mounted on a hinged joint in order to optimize the angular scanning range. The hinge is intended to give some flexibility in the positioning of the sensor during the development stage, but is not intended for frequent adjustment.

During a scan, the rotary stage moves the scanning sensor 360 degrees, following the weld around the tube. Because the variation in the geometry of the weld cross section around the tube, the sensor does not stay in range for the full weld on the lower weld section. The weld region must therefore be scanned in several passes. In order to get a complete picture of the weld, the scans are stitched together in LaserViewer™ software.

RESULTS
Figure 12 shows LaserVideo Images™ (LVI) of portion of the weld, with images from the two detectors annotated as LVI A and LVI B. The variation in the scatter profile causes some regions to be dark on each of the two scans. These two data sets are averaged together to form a merged LVI. The flaws are barely visible in LVI A, but are clearly visible in LVI B and the merged image. The dark regions in both of the images is essentially eliminated, giving uniform coverage of the scanned region. The variation shown in these images is typical over the full scan area. It may sometimes be useful to look at unmerged LVI images from the individual detectors, but in general the best total view comes from the merged data.
Figure 12. Merging of the LVI images from the two detectors

Figure 13. Stitched 360° scan

Figure 13 shows a stitched sample of multiple scans at different radii. To align the scans, the data is nudged on two axes until features visible on both scans are aligned. The data at 180 degrees does not extend as far up (toward the tube) because the weld region is smaller at the top weld than the bottom. The primary variations in the image are due to differences in surface texture caused by the preparation of the mock-up. In closer detail, a number of small artificial features are also visible.

CONCLUSION
Laser-based scanning has been applied to two different reactor NDE inspection requirements, measurement of the internal tube geometry of BMNs and crack detection in CRDM J-groove weld inspection. A BMN mockup was scanned with a custom laser sensor in an underwater environment to
create high resolution profile and LaserVideo Images™, enabling the measurement of weld offset and distortion, as well as the identification of pitting and other features. High-resolution laser imaging was also demonstrated on a CRDM mockup, using a custom laser-scanning sensor and a 5-axis robotic sensor delivery device. The development of the laser scanner, a fundamentally new design that incorporates a rotating mirror to enable faster two dimensional scanning, was a key outcome of this work.

Laser-based inspection technology is an emerging method for surface flaw detection. Several aspects of this technology, including high spatial resolution capability (0.001 inch), relatively large surface standoff, and the ability to inspect unusual geometries, enable the inspection of surface flaws that are very difficult to detect with other NDE technologies.

REFERENCES