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Abstract

The objectives of this research project are –

1. To design sensor data fusion algorithms that can synergistically combine defect related information from heterogeneous sensors used in gas pipeline inspection for reliably and accurately predicting the condition of the pipe-wall.
2. To develop efficient data management techniques for signals obtained during multisensor interrogation of a gas pipeline.

During this reporting period, Rowan University fabricated test specimens with simulated defects for nondestructive evaluation (NDE); designed and developed two versions of a test platform for performing multi-sensor interrogation of test specimens under loaded conditions simulating pressurized gas pipelines; and performed magnetic flux leakage (MFL), ultrasonic testing (UT), thermal imaging and acoustic emission (AE) NDE on the test specimens. The data resulting from this work will be employed for designing multi-sensor data fusion algorithms.

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Executive Summary

The objectives of this research project are:

1. To design sensor data fusion algorithms that can synergistically combine defect related information from heterogeneous sensors used in gas pipeline inspection for reliably and accurately predicting the condition of the pipe-wall.
2. To develop efficient data management techniques for signals obtained during multisensor interrogation of a gas pipeline.

The principal progress during this reporting period involved *Task 4.0 – Design and Development of the Validation Test Platform*. This is because; *Task 3.0 – Design and Development of Data Fusion Algorithms* requires nondestructive evaluation (NDE) data for meeting the task objectives.

The important research accomplishments during this research period are:

1. Fabrication of a test specimen suite for performing NDE in the laboratory. The test specimens consist of 0.5” thick SA-516-Gr. 70 steel coupons containing simulated cracks and 4” x 6” ASTM-836 steel specimens with simulated benign and anomalous indications. (*Subtask 4.1 – Specimen Fabrication*)
2. Design and development of two versions of a test platform for performing multi-sensor NDE of test specimens under bi-axial load simulating the conditions inside a pressurized pipe. (*Subtask 4.2 – Test Platform Development*)
3. Obtaining magnetic flux leakage (MFL), ultrasonic testing (UT), thermal imaging and acoustic emission (AE) data from test specimens. (*Subtask 4.3 – Obtain Multisensor NDE Data*).

Experimental

The principal progress during this reporting period involved *Task 4.0 – Design and Development of the Validation Test Platform*. This is because, *Task 3.0 – Design and Development of Data Fusion Algorithms* requires NDE data for meeting the task objectives.

Task 4.0 – Design and Development of the Validation Test Platform

The test platform allows for validation of the data fusion algorithms that will be developed as part of Task 3.0. The platform is intended to support multi-sensor interrogation of pipe-wall test specimens using Magnetic Flux Leakage (MFL), Ultrasonic Testing (UT) Acoustic Emission (AE) and Thermal Imaging as needed. The specimens will consist of steel coupons from actual pipeline segments and will have simulated cracks of varying depth. This report describes research and development activities in *Subtask 4.1 – Specimen Fabrication*, *Subtask 4.2 – Test Platform Development* and *Subtask 4.3 – Obtain Multi-Sensor NDE Data*.

Subtask 4.1 – Specimen Fabrication

While the development of the final version of the test platform was underway, the research team began the fabrication of a new suite of test specimens that will provide a diversity of NDE data when subjected to multi-sensor interrogation. The team focused on developing test specimens that provide two specific types of NDE signatures – benign indications and anomalies. The benign indications that were selected included pipe-welds and straps. Anomalies included pitting corrosion, narrow cracks indicative of SCC and gouges/dents indicative of mechanical damage. ASTM 836 steel stock was purchased for fabricating these specimens in thicknesses of $\frac{5}{16}$, $\frac{3}{8}$ and $\frac{1}{2}$ inch.

All of the specimens have length and width dimensions of 6" x 4" and can be viewed in Figure 1. Three specimens, one of each thickness, have been fabricated with no defect as shown in Figure 1(a). Figure 1(b) displays one of the specimens developed to mimic pitting corrosion defects. A total of nine slotted defect specimens were produced in a milling machine with 0.1", 0.2" and 0.3" defect depths for all three specimen thicknesses discussed earlier. The suite also contains one specimen of each thickness with crack, gouge/dent and weld defects. Figure 1(c) shows the specimen simulating stress corrosion cracking by producing a saw cut in the center of the specimen with a depth of 80% of the overall thickness. The specimens with gouges/dents were produced using a hydraulic press to cause mechanical damage of the specimens. The welds

were produced by machining two pieces of steel that were half the size of the original specimen size and welding the pieces together at the midline. Finally the specimens with straps were produced by welding an external strip of metal over the spliced specimen to join the two pieces. These specimens can be viewed in Figure 1(d), 1(e), and 1(f) respectively. All of the specimens are numerically identified and outlined in Table 1.

(a) No defect

(b) Slotted defect

(c) Saw cut defect

(d) Mechanical damage defect

(e) Weld defect

(f) Strap Defect

Figure 1: Test specimen suite.

Table 1: Details of the test specimens in the suite.

Specimen #	Plate thickness (in)	Indication Type	Depth (in)
00	0.5	None	N/A
01	0.5	Pitting	0.3005
02	0.5	Pitting	0.198
03	0.5	Pitting	0.0945
04	0.5	Crack	80% Sawcut
05	0.5	Mechanical Damage	Varies
06	0.5	Weld	Varies
07	0.5	Strap	Varies
10	0.375	None	N/A
11	0.375	Pitting	0.298
12	0.375	Pitting	0.199
13	0.375	Pitting	0.1105
14	0.375	Crack	80% Sawcut
15	0.375	Mechanical Damage	Varies
16	0.375	Weld	Varies
17	0.375	Strap	Varies
20	0.3125	None	N/A
21	0.3125	Pitting	0.303
22	0.3125	Pitting	0.1955
23	0.3125	Pitting	0.0995
24	0.3125	Crack	80% Sawcut
25	0.3125	Mechanical Damage	Varies
26	0.3125	Weld	Varies
27	0.3125	Strap	Varies
Note: All specimens have a length of 6 inches and a width of 4 inches.			

Subtask 4.2 – Test Platform Development

The Version 3 of the AE test platform uses a set of four (4) A-572 grade 50 steel blocks referred to as specimen-clamping brackets. During this reporting period these clamping brackets were designed and machining was begun. The brackets are used in connecting the specimens to the loading mechanism and load transducers of the test platform that can be viewed in Figure 2. Each specimen-clamping bracket is joined to the specimen with a 1" diameter pin to allow for pivoting of the specimen during testing. The new clamping brackets allow for the load cell to screw directly into the bracket instead of screwing into a nut that was welded onto the face of the bracket from the previous versions. These new additions will keep loading forces linear during testing of the specimens. In addition the specimen clamping brackets have been redesigned to be fabricated as a single unit. Where as the clamping brackets of Version 2 were an adapted version from the first design, they are now newly manufactured components further minimizing sources of loading noise.

Figure 2: Version 3 of the Test Platform.

During this reporting period, hydraulic mounting assembly brackets were machined to support the hydraulic rams during testing and can be viewed in Figure 3. This assembly will utilize the existing test platform frame design. The Grade 8 high tensile bolts that were previously tightened to apply the load, will now be coupled through the frame to a female threaded rod made of C-1018 type steel. The rod will be attached to the back plate where the

hydraulic ram will be seated. As the hydraulic ram is actuated, the shaft will extend and push off of the frame pulling the clamping bracket and stressing the specimen.

Figure 3: Design Version 3, hydraulic assembly.

The Version 3 of the test platform, shown fully assembled in Figure 4 has many advantages over the previous versions. The main addition to the validation test platform is the incorporation of hydraulic cylinders for loading the test specimens. The addition of hydraulic loading cylinders will allow for the maximum desired load of 30 ksi to be placed on the specimens in the biaxial direction. This also provides for uniform testing to be performed in a controlled loading situation. Discarding the previous mechanical loading method and replacing it with the hydraulic loading will also minimize the need for additional signal processing by reducing the amount of spurious loading noise. In addition, the specimen clamping brackets have been redesigned to be fabricated as a single unit. Whereas the clamping brackets of version 2 were an adapted version from the first design, they are now newly manufactured components further minimizing sources of loading noise. The new clamping brackets will allow for the load cell to screw directly into the bracket instead of a nut that was welded onto the face of the bracket from the previous versions. Each clamping bracket is joined to the specimen with a 1" diameter pin to allow for pivoting of the specimen during testing. These new additions will keep loading forces linear during testing of the specimens and prevent deformations of the specimen at the connection point. The hydraulics consist of Enerpac RC-Series single acting cylinders with 15 & 25 ton capacities. A 10,000 psi hand pump will be employed to reach a required full load of 45,000 lbs.

Figure 4: Assembled Version 3 of the Test Platform.

Results and Discussion

Task 4.0 – Design and Development of the Validation Test Platform

Subtask 4.2 – Test Platform Development

The test platform was subjected to a finite-element methods (FEM) analysis using COSMOS Works in order to simulate loading conditions. FEM analysis was performed on the new clamping brackets to ensure they could handle the maximum load of 30 ksi. Figures 5 and 6 contain FEM analysis diagrams of both bracket types. Figure 5 shows that the loading clamping bracket experienced a maximum force of 27,900 psi, which is well under the maximum yield stress of the steel. Figure 6 shows the rear of the load-cell clamping block where the load cell will be threading into the back of the block. This block experienced a maximum force of 33,590 psi, which also is under the yield stress of the steel.

Figure 5: FEM analysis of design Version 3 loading clamping block.

Figure 6: FEM analysis of design Version 3 load cell clamping block.

FEM analysis on the hydraulic assembly was performed using COSMOS Works and can be viewed in Figure 7. The analysis demonstrates that the hydraulic assembly will experience a maximum of 23,850 psi, which is well under the yield stress of the Grade 8 bolts (120,000 psi), C-1018 steel rods (50,000 psi), and the A-572 grade 50 steel (58,000 psi).

Figure 7: FEM analysis of design Version 3 hydraulic assembly.

Subtask 4.3 – Obtain Multi-Sensor NDE Data.

Although the AE test-platform was built during this reporting period, and tested for requisite loading ability, we were unable to complete AE testing of the specimens – these will be available in a future report. This report will present results on magnetic flux leakage, ultrasonic testing and thermal imaging of the test specimen suite.

Magnetic flux leakage (MFL) testing was performed on the specimen suite outlined in the previous section. The specimens tested were those containing simulated pitting defects with a rectangular slotted shape machined from the specimen. Each of the specimens was then energized with 200 amps to induce the needed magnetic field. A Hall probe was then used to record any magnetic leakage around the defect. Figure 8 contains the resulting magnetic images. Rows 1 through 4 show the progression of increasing defect depth starting with no defect followed by 0.1", 0.2", and 0.3" deep. Column A, B, and C display the varying specimen thickness with Column A being 1/2" thick, B 3/8" thick, and C 5/16" thick. Table 2 has been included to further specify the specimens and defects.

Figure 8: MFL scans of slotted shape defects.

Table 2: Slotted shape defects scanned using MFL and UT.

Specimen #	Plate thickness (in)	Defect Type	Defect Depth (in)
A1	0.5	None	N/A
A2	0.5	Pitting	0.3005
A3	0.5	Pitting	0.198
A4	0.5	Pitting	0.0945
B1	0.375	None	N/A
B2	0.375	Pitting	0.298
B3	0.375	Pitting	0.199
B4	0.375	Pitting	0.1105
C1	0.3125	None	N/A
C2	0.3125	Pitting	0.303
C3	0.3125	Pitting	0.1955
C4	0.3125	Pitting	0.0995

Ultrasonic testing (UT) was also performed on the same test specimens. Each specimen was submerged in water and scanned with a 10MHz UT transducer. The threshold and gating of the UT signal was adjusted to display changing depths of the specimen defects. Figure 9 contains the resulting time-of-flight (tof) ultrasound images. Rows 1 through 4 show the progression of increasing defect depth starting with no defect followed by 0.1", 0.2", and 0.3" deep. Column A, B, and C display the varying specimen thickness with Column A being ½" thick, B 3/8" thick, and C 5/16" thick. Table 2 has been included to further specify the specimens and defects.

Figure 9: UT scans of slotted shape defects.

Thermal imaging NDE was performed on the specimen suite. The specimens tested were those containing simulated pitting defects with a rectangular slotted shape machined from the specimen; the specimen suite is described in Table 1. The thermal imaging test set-up consists of a high-power 110 W Halogen lamp that is sinusoidally excited at a rate of 8-10 seconds/cycle. The specimen is placed on an optical table and is thermally insulated with an Aluminum honeycomb panel. The thermal images of the test specimens are captured using a FLIR Systems Microbolometer camera. The images were obtained at 1 second intervals over the excitation cycle. Five images at equally spaced time intervals over each cycle were processed to extract the phase images – these are shown in Figure 10. The images are scaled and registered to reflect a resolution of 100 pixels/inch. It can be noticed that the defect related information in the thermal phase images is less than that contained in the UT and MFL NDE images.

Figure 10: Thermal phase images of slotted defects in the test specimen suite shown in Table 1.

Conclusion

The principal progress during this reporting period involved *Task 4.0 – Design and Development of the Validation Test Platform*. This is because; *Task 3.0 – Design and Development of Data Fusion Algorithms* requires nondestructive evaluation (NDE) data for meeting the task objectives.

The important research accomplishments and the conclusions drawn during this research period are:

1. Fabrication of a test specimen suite for performing NDE in the laboratory. The test specimens consist of 0.5” thick SA-516-Gr. 70 steel coupons containing simulated cracks and 4” x 6” ASTM-836 steel specimens with simulated benign and anomalous indications. (*Subtask 4.1 – Specimen Fabrication*)

As subsequent NDE tests indicate, these specimens provide repeatable NDE signatures of the corresponding benign or anomalous indications. The adequacy of the size and the diversity of the test specimen suite will be determined based on the results obtained by exercising the data fusion algorithms on the NDE signatures. These conclusions will be available in a future report.

2. Design and development of two versions of a test platform for performing multi-sensor NDE of test specimens under bi-axial load simulating the conditions inside a pressurized pipe. (*Subtask 4.2 – Test Platform Development*)

Finite element simulations performed on the various loading components of the test platform indicate that they have been designed to exceed maximum loads along both loading axes. The set up is ready for AE testing.

3. Obtaining magnetic flux leakage (MFL), ultrasonic testing (UT) and thermal imaging data from test specimens. (*Subtask 4.3 – Obtain Multisensor NDE Data*).

In this reporting period, we were unable to obtain consistent acoustic emission inspection data from the test specimens – the reasons for this will be investigated in a future report. As indicated earlier, the loading conditions are accurate – it remains to be seen if the test specimens for AE inspection are the source of the problem.

MFL, UT and thermal images are demonstrated to be consistent NDE signatures – deeper defects yield more pronounced signatures. As expected, defect related information in these signatures is highest in UT, followed by MFL and thermal. The data fusion algorithms will be able to quantify the relative information among these signatures.

During the next reporting period, existing sensor data fusion algorithms will be modified for interpreting multi-sensor NDE signals in order to predict the condition of the test specimens.

References

No references to be listed for this technical report.

List of Acronyms and Abbreviations

AE Acoustic emission

FEM Finite element method

MFL Magnetic flux leakage

NDE Nondestructive evaluation

PSI Pounds per square inch

SCC Stress corrosion cracking

UT Ultrasonic testing