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Abstract

The Corrosion Monitoring System (CMS) program developed and demonstrated a continuously on-line system that provides real-time corrosion information. The program focused on detecting pitting corrosion in its early stages. A new invention called the Intelligent Ultrasonic Probe (IUP) was patented on the program. The IUP uses ultrasonic guided waves to detect small defects and a Synthetic Aperture Focusing Technique (SAFT) algorithm to provide an image of the pits. Testing of the CMS demonstrated the capability to detect pits with dimensionality in the sub-millimeter range. The CMS was tested in both the laboratory and in a pulp and paper industrial plant. The system is capable of monitoring the plant from a remote location using the internet.

Executive Summary

A Project Goals document was written in collaboration with the Materials Technology Institute of the Chemical Process Industry. An Intelligent Ultrasonic Probe (IUP) was invented on the CMS program (patent issued) to detect pitting corrosion in its early stage. The IUP uses ultrasonic guided waves to detect pits. Baseline corrosion algorithms (SAFT Vs.1) for pit detection were defined. A prototype version (first generation) of the IUP, including its custom ultrasonic transducer array, was designed and fabricated. Laboratory corrosion data was collected using the first generation Intelligent Ultrasonic Probe. Version 2 of our Synthetic Aperture Focusing Technique (SAFT) algorithm, with an improved detection capability, was developed and tested. A second-generation prototype IUP was fabricated and successfully tested against both real and simulated corrosion pits. Testing showed detection down to .25mm dimensionality for corrosion pits. The second generation IUP was installed in the MeadWestvaco pulp and paper plant in Evadale, Texas. Data was collected at Evadale for three months with no pits formed on the IUP. No detections occurred on the ultrasonic image from the IUP, which was the correct result for this situation. The CMS was moved to Oak Ridge National Laboratories (ORNL) to speed up the pitting corrosion process. Data was collected at ORNL for three months. At the end of this period we noticed that microscopic pits were beginning to form on the probe. The CMS detected this early pitting. The test result was compared to the measurements taken with a Scanning Electron Microscope (SEM) and excellent correlation was obtained. We continued the test until the IUP was completely corroded with pits. Again excellent correlation occurred between the pit images and the corrosion pits. These tests confirmed that the CMS met its technical goals of developing a real time system capable of sub-millimeter pit detection.

Section 1. Program Description

1.1. Problem Statement

Virtually every manufacturing operation in the chemical processing industry is adversely affected by corrosion. The current practice in the chemical industry is to detect and monitor corrosion by:

- Internal inspections that require process shutdowns,
- Corrosion probes that provide on-line data about corrosion rate but provide no information on diagnostics or prognostics, and
- Ultrasonic thickness measurements and corrosion coupons, which also provide no information on diagnostics or prognostics.

When process upsets or intentional process changes lead to unexpected increases in corrosion, it is often the responsibility of process operators, untrained in corrosion, to diagnose the cause of the problem and predict the eventual consequences. Experts are available in some cases to assist in this analysis, but often no help is available, which can result in an unplanned process outage and restart that wastes energy and reduces productivity. Clearly, the chemical processing industry would greatly benefit from a Corrosion Monitoring System (CMS) that provides detection and diagnostic information that can be used to help prevent process outages and reduce waste in our energy resources.

1.2. Proposed Program

The CMS program team worked with the Materials Technology Institute to determine corrosion monitoring needs and define CMS requirements. An analysis was performed on existing technologies to determine the best sensor candidate for the CMS. After initial tradeoffs, ultrasonic guided waves, electrochemical noise, and acoustic emissions were selected as the final candidates. Experts from these three technologies were brought in by the CMS team to evaluate the capability of each technology. Ultrasonic guided wave technology was selected for the CMS. The concept of an Intelligent Ultrasonic Probe (IUP) was invented and developed on the program to provide the required pitting information. The ultrasonic guided wave system was built and tested in the laboratory. A Synthetic Aperture Focusing Technique (SAFT) was optimized for the detection of corrosion pits in SS304 assets. Several iterations of the probe design and SAFT detection algorithm were performed. Testing was done at both a MeadWestvaco pulp and paper plant as well as at a testing site in Oak Ridge National Laboratory. Results from these tests showed that the program requirements for early pit detection were obtained by the CMS.

1.3. Technical Goals and Objectives

The performance requirements and performance goals of the CMS are listed below.

Performance requirements:

- Continuous on-line operation
- Remote monitoring capability
- System parameter setting (sample rate, acoustic parameters)

- Capability to monitor multiple types of plant equipment
- Testing in an industrial plant

All performance requirements were met.

Performance goals:

- Early pit detection with pit dimensionality is $<1\text{mm}$ ($<.25\text{mm}$ achieved)
- Ability to image multiple pits
- Visual pit size and growth rate information from pit image

All performance goals were met

1.4. Approach

The corrosion monitoring market suffers from fragmentation, with dozens of small companies selling various corrosion products/services. However, none of these companies have the necessary expertise and experience to develop and commercialize a solution to the corrosion problem. This project directly addressed these issues by 1) assembling a team with the required technical, commercialization, and user knowledge to provide a system level solution, and 2) proposing a solid technical approach to solve the problem. Some of the key ingredients in our technical approach were:

- Apply diagnostic technology to the corrosion problem—The chemical industry relies on experts (man-in-the-loop) to interpret corrosion data. This project will replace the current approach with an autonomous system using state-of-the-art diagnostic technology.
- Trade available technology to select the best CMS sensor—The CMS project used a two-step approach to optimize its choice for the corrosion sensor. First, a set of three corrosion sensors (chosen for manageability) that best meet the requirements of the CMS were selected. Then, we compared the diagnostic performance of each of these sensors to determine the best sensor to meet CMS goals.
- Use accelerated testing for diagnostic algorithm development—Corrosion can occur at various rates in industrial plants, sometimes taking months or even years. A way to address this problem is accelerated testing. The chemical industry has procedures using chemical additives that speed up the pitting corrosion process. These procedures were used to obtain data for initial algorithm development and testing. To balance the risks associated with using accelerated data, the second half of this project focused on plant data collected at MeadWestvaco and Oak Ridge National Laboratory.

Section 2 Key Tasks

2. Key Tasks

For this section of the project, efforts were concentrated on solving the dispersion curves for 316 stainless plates, selecting optimized modes for pit corrosion detection, developing image reconstruction and synthetic averaging for defects interpretation and visualization, designing arrays and probe enclosure and putting together a processing RMC hardware including control software. All these tasks were investigated and developed successfully. The CMS prototype system was completed and fully integrated.

2.1. Calculation of Dispersion Curves

For mode selection and optimization of Lamb waves for 304 stainless plates, theoretical dispersion curves were computed. These curves also help to verify the velocity of the pre-selected modes to excite, to choose at which point(s) on the dispersion curves these modes are to be excited and to design the piezo-electric array probes.

The dispersion curves are plots of phase/group velocities versus the frequency thickness product of the structure. They are obtained by solving for the real roots of the Rayleigh-Lamb equation.

The following figure shows the calculated dispersion curves for 304 stainless plates which corresponds to the tested specimen sent by Honeywell with longitudinal and shear wave velocities of 5.630 and 3.120 mm/ μ s respectively. .

Figure 1. Lamb waves phase velocity dispersion curves for a stainless steel plate

The above phase velocity dispersion diagrams are used for proper mode selection. However, for mode identification and interpretation group velocity dispersion curves are used. Group velocity graphs (Figure 2) are also used for defect location by the measured arrival time (time-of-flight) of the selected mode.

Figure 2. Lamb waves group velocity dispersion curves for a stainless steel plate

Algorithms for calculating dispersion curves were developed and integrated in the following task to calculate the phase variation and group velocity values of the selected modes.

2.2. Algorithm Development and Testing (FD Lamb-SAFT)

Conventional ultrasonic testing uses C-Scans for data representation and defect visualization. Under this task, we developed algorithms for proper display of guided waves for defect detection and localization. Modified FD Lamb-SAFT C-Scans representation for the combination of signals collected from several sensors was developed (Figure 3). The developed software application produces raw Lamb C-Scans and Lamb-SAFT C-Scans. Color scale and threshold can be used to evaluate the existence of pitting corrosion defects.

The developed software analyzes the data collected with the CMS workstation (files with extension .aet). The collected data with the CMS system/probe represents the non-processed raw Lamb wave scans as shown in Figure 3a. Once the data is processed using the FD Lamb-SAFT algorithm, the results are presented as shown in the Figure 3b. Scanning direction is along the X-axes and scanning depth or distance is along the Y-axes.

Figure 3. C-Scan results a) without SAFT b) with SAFT

The principle of conventional SAFT is to extrapolate for each transducer position and provide the sum of energy reflected and transmitted at all transducer positions (Figure 4). More details on the theoretical formulation of the FD-Lamb SAFT algorithm is presented in task 5.

Figure 4. Illustration of SAFT extrapolation principle

The SAFT algorithm was developed on the Matlab platform and have the following main menu (Figure 5). This main menu allows starting a new SAFT calculation based on the collected data from the CMS system. It also allows loading saved SAFT results or simulated B-scans.

Figure 5. SAFT main menu

The developed software loads the data files as *.aet and calculates the FD-SAFT by first calculating the phase velocity and then constructing the SAFT image. The effective frequency bandwidth of the system are the only parameters required to compute the selected mode phase velocity curve (Figure 8).

Figure 6. SAFT load data file

Once the data is loaded, the main SAFT analysis window opens (Figure 7). The frequency bandwidth is selected manually on a representative A-scan taken from the inspection data.

Figure 7. SAFT analysis window

More details on how to operate the software are provided in the User Manual of the FD Lamb-SAFT software developed under this task.

Figure 8. SAFT analysis window

The developed FD Lamb SAFT algorithm was tested on several simulated samples with pitting corrosion. The results showed that by combining Lamb waves with SAFT post-processing, one could exploit the full detection potential of those wave modes. Lamb-SAFT processing also proved to be efficient for pitting detection and localization even for small depth-to-wavelength ratio. Single mode detection was used during testing and proved sufficient and easy to implement.

2.3. Ultrasonic Parameter Selection (mode, frequency, bandwidth)

The multi-mode characteristic of guided waves permits selection and optimization of wave modes suitable for specific inspection requirements. The performance of different guided wave modes can be analyzed by studying their wave structure to determine the most appropriate mode(s) for pitting corrosion detection. For our task, two modes were selected for pitting corrosion detection in stainless steel plates with thickness $\sim 1.82\text{mm}$. Table I shows the characteristics of the selected modes.

Table I. Selected mode parameters

	Wave mode	Frequency MHz	Wavelength mm	Frequency Bandwidth MHz	Phase Velocity mm/ μs	Group velocity mm/ μs
Tested	A_1	2.00	2.60	1.75 – 2.25	5.22	3.09
Selected	S_1	2.40	2.28	2.00 – 3.00	5.49	4.75

These modes have an acoustic wavelength of 2.6mm and 2.28mm and are selected based on the analysis of their mode structures. To optimize the generated wave modes for pitting corrosion detection in thick structures, to maximize detectability and sensitivity of modes, out-of-plane particle displacements are minimized, while in-plane displacements are maximized, and the ultrasonic power was concentrated in the upper and lower part of the inspected specimen.

Figure 9. Calculated mode shapes for S_1 mode @ 2.40 MHz

Mode selection and optimization was done by selecting modes with maximum group velocities (minimum dispersion) and analysis of their wave mode structures (particle displacements, stresses and power distributions). These modes were then used for pit corrosion detection and the evaluation of structures. Using a tone-burst system, the wave modes are selected, excited and tested in pulse-echo and pitch-catch setups. Launch angles were obtained from the calculated dispersion curves. Theoretical group velocities were compared to tested group velocities to confirm the excited modes at frequency-thickness product and launch angle.

Testing was performed with all the above selected modes. Scans with these modes were performed on the same specimen. This helps us to experimentally determine the modes with the most suitable energy transfer and highest detectability. Following the tests, a theoretical calculation of the cross-sectional stresses, displacements, and power density was performed (Figure 9).

2.4. Ultrasonic Transducer Array Design and Fabrication

Piezo-electric transducers are generally used in conventional ultrasonic, nondestructive inspection techniques. The most common way of exciting Lamb waves uses a broadband piezo-ceramic transducer with an incident angle wedge. The wedge is necessary because Lamb waves of a particular mode will only be excited at a specific angle. The launch angle is calculated from the computed dispersion curves. Theoretical group velocities were compared to tested group velocities to confirm the modes at frequency and launch angle. An array ultrasonic probe was

designed for exciting Lamb modes to cover the entire area of the monitored plate on the probe. Figure 10 illustrates the concept of the designed setup for the array.

Figure 10. Array concept installed on the plate

However, before the fabrication of the arrays, single element probes were designed and fabricated to demonstrate the feasibility of the array concept. The following figure shows the fabricated single element probes.

Transducer K

Transducer S

Figure 11. Single element transducers

	Frequency MHz	Width Mm	Length mm	Height mm	Material
Transducer K	2.0	3.2	5	4	Piezo-composite
Transducer S		2.8	5	4	Piezo-composite

A schematic representation of the array angle wedges is shown below (Figure 12). The fixed angle wedge was made of a one piece 28° Loten wedge with a constant emission point on which the array of piezo-ceramic transducer is installed.

A viscous coupling (ultrasonic gel) is used to mount the transducer element on top of the holder element (the upper part of the wedge). The array probe was fabricated with the following characteristics:

Figure 12. Array probes mounted on Loten wedge

The arrays are hosted in the monitoring probe. The monitoring probe was designed to fit in standard flanges used in the chemical processing industries. The material for the sensor casing was selected in accordance with the industry standards. The UT arrays are located in a liquid tight chamber inside the monitoring probe.

Figure 13. The designed monitoring probe

2.5. Processing Hardware Design and Fabrication

The overall CMS prototype consisted the following components:

- Remote computer
- Host computer
- Monitoring probe
- Analysis algorithms

Figure 14. CMS Overall system components

The remote computer connects to the host computer by internet or modem connection. It uploads the different control setups to allow different sessions to be monitored automatically. The remote computer also downloads the acquired data automatically and analyzes the downloaded data using the SAFT algorithms.

The host consists of a “lunch box” with a STEALTH SBC computer PIV 2.0MHZ with 1.0 GHz RAM. The system is optimized to facilitate maintenance, modifications, and upgrades. The processing cards in the computer are COTS (components-off-the-shelf). The COTS electronic boards and components from well-known manufacturers and are:

- 1- Digitizer (1 item): NI-5102 from National instrument. It is a high speed PCI digitizer.
- 2- MUX (2 items): PCI-702/703 from PC INSTRUMENTS. They are 8-to-1 multiplexers capable of routing high frequency analog or digital signals. The two MUX were modified based on our request to support high voltage excitation.
- 3- Pulser receiver card: TB1000 from Matec Instrument. It represents a tone burst card for narrow band excitation. The card was modified to support additional cycles which is equivalent to more pulse power.

Figure 15. Developed CMS Workstation

The main component in an instrumentation set up to excite guided waves is the tone-burst pulser/receiver system. It is used to excite the arrays with a narrow-bandwidth ultrasonic signals. The schematic diagram of the system setup is given below.

Figure 16. Schematic diagram of the host system

We also developed a control software to communicate between the above mentioned components of the system. The control software also allows us to set up the system to automatically acquire signals at a scheduled rate.

Section 3 Laboratory and Field Test Results

3. Laboratory and Field Test Results

For this section of the project, efforts were concentrated on performing laboratory and field tests. Three samples were evaluated in laboratory conditions and two probes were evaluated during scheduled field tests. The laboratory test results were successful, and indications from the simulated pits were clearly visible. The field tests were done using the designed probes in which array elements were inserted to monitor the testing plate. The setups were similar in most of the cases. A1 and S1 were used for frequencies varied between 2.4-2.5MHz. Details on the setups are defined in Section 2.

3.1. Laboratory

Specimen 1: SS-304 stainless steel plates with simulated pits. 5 drilled holes machined up to 50% of the wall thickness ~1mm. The physical properties of this particular plate were previously measured as:

-Thickness = 1.895 mm

-Shear Velocity = 3120 m/s

-Longitudinal Velocity = 5630 m/s

Figure 1. SAFT images resulting from GW inspection using array transducers

Specimen 2: SS-304 stainless with real pit and was prepared by Dr. Dan Wilson

The physical properties of this particular plate were previously measured as

-Thickness = 1.87 mm

-Shear Velocity = 3140 m/s

-Longitudinal Velocity = 5680 m/s

Figure 2. SAFT images resulting from GW inspection using (a) Transducer S (b) Array Transducers

Specimen 3: SS-304 stainless with real pits

The physical properties of this particular plate were previously measured as

-Thickness = 1.895 mm

-Shear Velocity = 3120 m/s

-Longitudinal Velocity = 5630 m/s

Figure 3 shows the detected pits with correlated locations. Most of the pits were very small and it was difficult to evaluate their diameter. However, two relatively big pits were also detected and estimated at <0.5 mm in diameter. Results were repeatable and probability of detection was high.

Figure 3. SAFT images resulting from GW inspection

3.2. MeadWestvaco Pulp and Paper Plant

Field tests were carried out during from April 16, 2003 until July 30, 2003 at MeadWestvaco mill. The probe was designed to fit in standard chemical flanges and was installed in the ClO₂ vent line. During this field test, no pitting corrosion was detected by the CMS system. The results were consistent with the status of the probe when it was pulled out of the vent for visual evaluation. The following figures show selected results taken seven days apart. The initial results were used as calibration results and any changes in the produced SAFT images would indicate pit activities.

Data_Prob1_2.5MHz_2003-06-18-11_53_30.aet

Year-month-day- hour minute second.aet
Data_Prob1_2.5MHz_2003-07-23-00_01_25.aet

Reference edge reflection

Data_Prob1_2.5MHz_2003-06-25-08_05_51.aet

Data_Probe1__2003-06-12-16_20_47.aet

Data_Prob1_2.5MHz _2003-07-02-00_25_33.aet

Data_Prob1_2.5MHz 2003-07-09-04_21_33.aet

Data_Prob1_2.5MHz 2003-07-16-15_18_27.aet

Data_Prob1_2003-07-23-23_47_28.aet

Data_Prob1_2.5MHz_2003-07-28-14_24_35.aet

Data_Prob1_2.5MHz 2003-07-23-00_01_25.aet

3.3. Oak Ridge National Laboratory

Tests were also performed at Oak Ridge National Laboratory in simulated field conditions. Two series of tests were performed. First, the probe was inserted in a test vessel from October 7, 2003 until December 30, 2003. The second series of tests were made from April 28, 2004 until May 5, 2005. We had to interrupt the tests because of a couplant problem on the installed array transducers. The following figures show selected results.

Year-month-day- hour minute second

Data_Probe_Oak__2003-10-20-22_14_20.aet

Probe edge
reflection

Data_Probe_Oak__2003-10-25-04_07_29.aet

Data_Probe_Oak__2003-10-30-16_34_59.aet

Data_Probe_Oak_2003-11-23-06_41_34.aet

Data_Probe_Oak_2003-11-02-02_13_37.aet

3.4. Evaluation of Test Results

For the laboratory tests, the results were successful and small size pits were detected. The detection capabilities of the developed system/procedure proved to be very high—especially in controlled environments and specimens.

The field tests were also successful; however, more difficulties were encountered in the last case where pits were produced at very high accelerated rate. Results reported by the CMS system from the Evadale Mill were negative. Visual inspection of the probe confirmed the state of the probe and it supported the concluded results. The following figure shows the state of the probe after sitting ~120 days in the pipe vent. Hardly visible pits were initiated on the probe, but no actual corrosion pit was formed on the surface plate nor detected by the CMS system.

Surface appear of probe after retrieval from Westvaco plant, Texas.
Probe exposed for 110 days. Very minor non-visible pitting.

During this test, the system had some difficulties sustaining the extreme environmental conditions of the location and we occasionally lost communication with the system. The workstation suffered two major damages during this test. Two cards were damaged, the VGA card and the Multiplexer card. The system was repaired and calibrated before continuing the Oak Ridge tests.

The second series of tests at Oak Ridge were performed at three levels. The first level of results gave minor pit detection, the second level produced high detection of sudden colonies of pits, and the third level was produced in the air with the probe outside the vessel.

2004-10-05-22_54_38.aet

Section 4. Industrial Use

In order to properly describe the existing corrosion monitoring techniques used by the process industries, it is first necessary to briefly describe the major types of corrosion that must be detected and the most common types of equipment to be monitored. The broad categories are general corrosion, localized corrosion, environmentally induced cracking (often called stress corrosion cracking), and elevated temperature corrosion. General corrosion is an electrochemical process whereby the entire surface of the corroding metal is oxidized. When general corrosion takes place, the corroding metal is uniformly reduced in thickness across the entire exposed surface. Localized corrosion is an electrochemical process that results in metal loss in highly specific areas, while the surrounding metal is much less corroded. The most commonly used terms for localized corrosion are pitting and crevice corrosion. Pits are small areas where the rate of metal loss has been much higher than the surrounding metal and they frequently result in process leaks. Crevice corrosion is also an electrochemical process that takes place in occluded areas and results in greater metal loss in the crevice than from the surrounding metal. Creviced areas can be quite large if deposits are present in the equipment. Stress corrosion cracking (SCC) occurs when a specific susceptible material is combined with tensile stress and a specific cracking agent. There is a cracking agent for virtually all metals. Chloride ion and austenitic stainless steel is the most important process industry example of SCC. Stress corrosion takes the form of highly-branched cracks that propagate in areas of high tensile stress. In many cases, the residual stress left in the metal from welding or general forming operations carried out during equipment fabrication is sufficient to cause SCC if the cracking agent is also present. Finally, elevated temperature corrosion is usually a gas or solid phase reaction that is not electrochemical in nature. The three major elevated temperature mechanisms are oxidation, sulfidation and carburization and in some cases they may exist together. Most frequently they occur as metal reacting with a gas phase or a solid that is deposited on the surface of the metal.

Common to all process plants is the use of piping to transport process chemicals from one piece of process equipment to the next. Sizes range from fractions of an inch to many feet in diameter. Studies have shown that a majority of process leaks are associated with piping or piping related equipment such as pumps and valves. Storage tanks and reaction vessels are also basic to all processes. These generally take the form of cylindrical vessels that are either horizontal or vertical. Storage tanks are typically vertical with flat bottoms and cone or dished top heads. Reaction vessels are often pressure vessels with both heads curved rather than flat as with storage tanks. Heat exchangers generally employ cylindrical bodies that contain a tube bundle for heat transfer. Distillation columns are cylindrical vertical vessels that contain internals designed to encourage the separation of chemicals. The internals are either horizontally arranged trays or packing that occupies a volume within the column.

Uses of Corrosion Monitoring in the Process Industries

The reasons for corrosion monitoring fall within two broad categories, condition assessment and process control. Condition assessment ranges from large-scale programs designed to ensure broad system integrity to the monitoring of a single critical asset. Increasingly the data from corrosion monitoring programs is used as input to risk based inspection programs whose purpose is to establish inspection intervals based on condition data rather than arbitrary time limits.

Corrosion data is used to establish equipment expected life at the design stage as well as scheduled retirement. In short, billions of dollars are spent annually by the process industries to ensure that corrosion-related equipment failure does not occur.

Corrosion monitoring is also used for process control although much less frequently due to the limitations of existing techniques. Corrosion monitoring for process control is most frequently used in systems that employ corrosion inhibitors. For example, corrosion inhibitors, chemicals that are added to a process stream to reduce corrosion, are used in cooling water systems and crude oil pipelines. The companies who provide inhibitors often use online corrosion monitoring to ensure that proper inhibitor levels are maintained. Processes that are subject to frequent upset, feedstock variation or contamination use online monitors to detect when increases in corrosion occur.

4.1. Existing Corrosion Monitoring Methods

Corrosion monitoring ranges from very simple methods to fairly sophisticated equipment whose effectiveness is not fully accepted within the industry. At the simple end of the scale is the simple weight loss coupon. A metal sample or coupon is placed in the asset to be monitored and exposed for some period of time. Most often the time is fixed by operating schedules and may be years in the case of processes that operate continuously. After exposure the sample is removed and weighed and an average corrosion rate is calculated. The coupon is also examined visually to determine if localized corrosion is present. If stress corrosion cracking is a concern, specially designed stressed coupons are used and visually evaluated to determine if cracks are present. For elevated temperature corrosion, coupons are the most frequently used method for evaluating corrosion since the other commonly used methods are inadequate. The advantages of coupons are low cost, flexibility, and an ability to detect localized corrosion. Coupon disadvantages include rate information that is an average for the entire exposure period and no data is available while the process is operating. Further, as with any single location monitoring method the result only represents that location. It is common practice to extrapolate the results of single point monitoring to the entire asset; however, there is clearly a risk associated with this practice since corrosivity can vary with location in a single piece of equipment. When it is likely that variations will exist, it is common practice to use more than one monitoring location within that piece of equipment. For example, single point corrosion monitors are often installed in multiple locations along the length of distillation towers since the environment within the tower varies across its entire length. At this time, no practical method exists for universal corrosion monitoring that would be capable of detecting corrosion rate over the entire surface of the asset.

Ultrasonic thickness measurement is probably the most widely used method for corrosion monitoring and condition assessment. Usually a simple ultrasonic thickness gauge is used to periodically measure the thickness of the equipment at a few locations. The thickness is recorded over time and a corrosion rate determined. This data is frequently used to support risk-based inspection programs and to justify longer internal inspection intervals. The advantages of this method are low cost and simplicity. The equipment is inexpensive and relatively unskilled people can be used for the inspection. Unfortunately the information provided by this approach is crude and very limited. Localized corrosion and stress corrosion cracking cannot be detected by this method. Even simple corrosion rate calculations can be unreliable since it may be

difficult to return the transducer to the exact location of the previous measurement. Variations in corrosion rate with time are not detectable. Finally it is a single point monitoring method whose results must be extrapolated to the rest of the asset for it to be of any benefit and the risks of this extrapolation are the same as with any single point monitoring technique. Multiple points are usually recorded for each asset to improve the statistical probability of accurate measurements.

One of the most commonly used online, continuous corrosion monitoring methods is the electrical resistance (ER) probe. When the thickness of a conductor is changed, its electrical resistance changes. When the ER probe element corrodes and gets thinner, its electrical resistance changes, and through the use of a suitable algorithm, the corrosion rate is calculated. The sensitivity of an ER probe depends on the thickness of the measuring element and the sensitivity of the resistance measurement. The principle advantage of this technique is that it provides online data that is much more representative of actual corrosion rate than the averaged data provided by coupons or UT measurements. The ER probe can be designed to operate under a wide variety of conditions. The primary disadvantage of this method is its inability to detect both localized corrosion and stress corrosion cracking. Also, as with coupons and ultrasonic measurements, it is a single point method and has the limitations described above.

Another widely used method is the linear polarization resistance (LPR) technique. LPR probes are based on a widely used laboratory method for studying corrosion that depends on the electrochemical nature of liquid phase corrosion. The corrosion rate reported by an ER probe is still a historical number in the sense that rate is calculated based on changes in probe thickness that have already taken place. In contrast, the LPR technique provides a nearly instantaneous measure of corrosion rate since it manipulates electrodes based on the principles of electrochemistry to determine the corrosivity of the environment at the instant the measurement is taken. In addition, most LPR devices conduct a second manipulation to provide a pitting factor that is an indication of an environments likely ability to cause pitting corrosion. The two main advantages of this method are its essentially instantaneous corrosion rate measurement and its ability to provide some indication that pitting corrosion is possible. There are many disadvantages to this process. The technique used to determine the corrosion rate is a statistical process based on a curve fit and it has an associated level of error. This error is increased in most commercially available devices because average values are used for certain environment and material specific constants that reduce the accuracy of the calculation. The commercial devices do not provide an indication of the accuracy of the built in statistical processes. Flow past the measuring electrodes can disrupt the measurement to the point that it is useless. Process related fouling can also render the measurement inaccurate. Not all process environments are suitable for the LPR method. LPR does not produce accurate results in low conductivity liquids. Finally, like all the other methods it is a single point measurement.

Another technique that relies on electrochemistry is electrochemical noise (EN). EN detects small fluctuations in potential and current that theoretically represent individual pit growth events. EN analysis utilizes proprietary data processing algorithms to rate the probability of pitting corrosion. Commercial systems provide a warning when the system calculates that pitting corrosion is likely. Since EN does not provide any general corrosion rate information, the commercially available equipment is combined with conventional LPR. The advantage of the EN system is a more positive indication of pitting corrosion than is supplied by the other monitoring techniques. Only LPR provides a similar indication of the potential for pitting

corrosion, however, it is suggested by the proponents of EN that EN pitting data is more reliable than LPR. There are a number of disadvantages associated with the EN method. The theory upon which the method is based is not universally accepted within the corrosion engineering community. There is not a clear and unequivocal method of data interpretation that is commonly used in all EN work. As a result, two EN systems may produce different results and a high level of operator expertise is required to get the most from an EN system. Since it is an electrochemical method it is subject to many of the problems faced by the LPR method. Electrode fouling and two-phase flow at the electrodes can produce spurious data. Because the system is measuring extremely small currents and potentials an EN system is subject to electrical interference that can produce bad data. EN provides only a qualitative evaluation of pitting. It does not provide any indication of pit size or pit growth rate. As a result, EN can at best provide an indication that pitting is possible, but no hard data on whether damage has occurred or estimation of the time required for damage to occur. Like all the other techniques described it is a single point monitoring method and is subject to the same problems this causes in all the other techniques.

Intelligent Ultrasonic Probe

In many respects the Intelligent Ultrasonic Probe (IUP) would be used in process equipment in much the same way as the ER, LPR and EN probes. Like the other probes, the IUP would be installed at single or multiple locations depending on the complexity of the process and equipment to be monitored. The IUP's primary function would be to provide data on the initiation and growth of localized corrosion. The IUP capability developed to date is specific to pitting corrosion, the most common form of localized corrosion. This data would be used for a variety of common corrosion monitoring purposes. For example, when used as an online monitor the IUP could detect the initiation and growth of pits which could be used by the process operator as an alert that some aspect of the process had changed and was causing pitting corrosion. The benefit of this approach over both LPR and EN is that it provides a positive indication that pitting is really occurring. Both LPR and EN can provide pitting alarms that require the operator to conduct an additional inspection to verify that pitting actually occurred and in some cases these alarms will be false. In contrast, the IUP provides a positive measure of the existence of actual pits on the surface of the probe. In this way short-term fluctuations in the ability of an environment to cause pitting, such as might be caused by intermittent insignificant contamination of the process, do not disrupt operations.

The IUP provides an indication of the severity of the pitting and the extent of accumulated damage that no other technique provides. This advantage can be used in condition assessment to establish the remaining life of the asset as well as condition based inspection intervals. The latter is perhaps the most significant benefit provided by the IUP. By combining general corrosion rate data provided by ER probes with pitting data provided by the IUP an owner can make a data based decision on inspection intervals that cannot be made using any other method. In many jurisdictions owners are required to conduct internal inspections of pressure equipment every two years. This requires a shutdown that usually is very costly to conduct. Using ER and IUP data as part of a risk based inspection program it will be possible to extend the time between these inspections resulting in both cost and energy savings.

In practice the reasons for IUP usage will be as variable as the process industry itself. Large-scale plants operating processes having a history of pitting corrosion problems or a process that is likely to cause pitting could install probes in a large network in both piping and equipment. Such an installation would best be tied into the plants process control system. The data would be used for condition monitoring and establishing inspection intervals and equipment life. Smaller plants might only need one or two probes to monitor critical equipment or equipment with a known history of corrosion problems. In this case a small handheld device for data collection would be appropriate.

The primary disadvantage of the IUP concept is the fact that it is a probe rather than a sensor attached directly to the asset. As with all the other techniques this approach requires the data provided by the probe to be extrapolated to the rest of the asset. Even if the transducers were mounted directly to the asset, unless they provide coverage of the entire surface it would still be necessary to extrapolate the results to the rest of the item. This is true of all corrosion monitoring methods currently in use and is accepted practice within the industry. Experienced corrosion engineers are relied upon to assess a process and determine the best location to mount probes or measure the thickness of the item. Use of the IUP does not require any changes in the current industry approach to corrosion monitoring.

4.2. Future Enhancements

In its current state of development the IUP is capable of detecting pits. This capability should be expanded to include detailed quantification of pit depth and diameter in order to provide an accurate measure of pit growth rate. Pit growth rate data could be used to estimate time to failure that would allow better inspection and maintenance planning.

The probe's capabilities should be expanded to include detection of crevice corrosion. Most process equipment includes many internal crevices. Often these crevices are locations for accelerated corrosion that does not occur in any other part of the equipment. A simple modification of the probe to include an artificial crevice would permit detection of this type of corrosion.

No method is currently available to detect stress corrosion cracking in on line equipment. Shear wave ultrasonic inspection is one of the accepted methods for detecting SCC; however, this inspection is labor intensive and very difficult to carry out on line. SCC usually occurs as a result of a process upset, and manual inspections are used after a leak has occurred in order to determine the extent of the damage. For example, a chemical company had an upset that allowed sodium hydroxide to enter their high-pressure steam system. This caused a catastrophic SCC event in a matter of days that destroyed many pieces of stainless steel equipment. The plant was out of service for months and the cost in lost production and repairs ran into the millions. Early detection of the SCC—before it progressed to the point of equipment failure—would have greatly reduced the impact of this event. The IUP probe could be configured to detect SCC.

Finally, the capabilities built into the probe could be transferred directly to the asset surface. A series of wedges and transducers could be developed that would permit monitoring of the asset itself instead of the probe. In most cases it is likely that this method would only be used to monitor a small portion of the asset surface, however, in some cases it is impossible to detect

corrosive conditions using a probe and a direct mounting system is needed. For example, velocity effects can greatly accelerate corrosion in piping elbows. A probe mounted only a few inches away would not be able to detect this corrosion. Mounting the transducers directly to the pipe would solve this problem.

Section 5 FD Lamb-SAFT ver. 4 Algorithm

5. FD Lamb-SAFT ver. 4 Algorithm

In this section, we describe in detail the theoretical formulation of the FD Lamb-SAFT algorithm. Schematic illustration of the developed algorithm is also presented. The manual of developed software is also described.

5.1. FD Lamb-SAFT Background

SAFT is a backpropagation technique based on the angular spectrum method of the scalar diffraction theory. Diffraction theory basically states that if a wave passes through an aperture, its behavior on the other side of the aperture, caused by constructive and destructive interferences of the outgoing waves, can be described from the knowledge on the incoming wave, the physical properties of the medium and the aperture dimensions.

In the case of the SAFT processing, the aperture is the line of inspection (more generally the surface covered by the scanning positions). Let's consider that each A-scan acquired along the inspection area contains information about the inspected material (echoes from defects or from the material boundaries). If the acquired A-scans are used as the input of a synthetic aperture corresponding to the inspection area, the application of the diffraction theory using inverse propagation properties (backpropagation) allows it to create interferences between the recorded echoes. The process therefore allows one to identify the position of the defects in front of the aperture, as long as the A-scan are properly sampled along the inspected area. The proper spatial sampling must be no more than half the minimum wavelength value of the generated signals.

Figure 1. Illustration of SAFT extrapolation principle

The 2-D mathematical form of the SAFT principle can be expressed as

$$B(x, y) = \frac{1}{4\pi^2} \int_{-\infty}^{\infty} \left[\sum_{\omega \in \Omega} \bar{S}(k_x, 0, \omega) \exp \left(iy \sqrt{\frac{4\omega^2}{V_P^2} - k_x^2} \right) \right] \exp(ik_x x) dk_x \quad (1)$$

where $\bar{S}(k_x, 0, \omega)$ is the 2-D Fourier transform of the set of acquired signals $S(x, t)$ at depth $y=0$, k_x is the x -component of the angular wavenumber, x is the lateral position along the scanning line, Ω is the effective frequency bandwidth and $B(x, y)$ is the defect function. The square root term of equation (1) is the y -component of the wavenumber, more explicitly

$$k_y = \sqrt{\frac{4\omega^2}{V_P^2} - k_x^2} \quad (2)$$

Thus, we can interpret the inner sum of equation (1) as an inverse Fourier transform of the frequency Fourier transform (discrete form) of $\bar{S}(k_x, 0, \omega)$ from angular frequency ω to depth y (normal distance from the aperture) using the expression relying the phase velocity to ω and k :

$$V_P = \frac{\omega}{k} \quad (3)$$

The constant sampling step along y is chosen in order to meet the sampling criteria. Therefore, the sampling step of y must be at most half the minimum wavelength of the mode included within its generated frequency bandwidth.

$$\Delta y \leq \frac{\lambda_{\min}}{2} \quad (4)$$

In order to use this procedure with Lamb waves, the correct application of the process requires the knowledge of the phase velocity curve $V_p(\omega 2h)$ of the effective frequency bandwidth Ω . Since Lamb waves are often generated using an angle-wedge probe, the backpropagation process needs to take the propagation in the wedge into account. Thus, equation (1) becomes

$$B(x, y) = \frac{1}{4\pi^2} \int_{-\infty}^{\infty} \left[\sum_{\omega \in \Omega} P_w(k_x, y, \omega, \beta) \bar{S}(k_x, 0, \omega) \exp \left(i\beta(y - D_{\perp}) \sqrt{\frac{4\omega^2}{V_p(\omega 2h)^2} - k_x^2} \right) \right] \exp(ik_x x) dk_x \quad (5)$$

The expression corresponding to the wedge backpropagator is given by

$$P_w(k_x, y, \omega, \beta) = \exp \left(i \left\{ (1 - \beta)y + \beta D_{\perp} \right\} \sqrt{\frac{4\omega^2}{V_{Wedge}^2} - k_x^2} \right) \quad (6)$$

where β is a parameter depending on whether the reconstructed depth y is within the wedge ($y \leq D_{\perp}$, $\beta = 0$) or within the plate ($y > D_{\perp}$, $\beta = 1$, i.e. a constant wedge backpropagator for distances corresponding to propagation within the plate). The required parameters are the wedge velocity V_{Wedge} and the normal distance of propagation within the wedge from the transducer to the plate $D_{\perp}$.

The SAFT process produces images with limited resolution. While the resolution of the L-SAFT is still under investigation, the SAFT process produces images with lateral (Δx , parallel to the scanning line) and axial (Δy , perpendicular to the scanning line) resolution provided by

$$\Delta x = \frac{0.6\lambda}{2\sin(\varphi)} \quad (7)$$

$$\Delta y = 2 \left[\sqrt{\left(\frac{4\pi}{\lambda_{\min}} \right)^2 - \left(\frac{\sin(\varphi)}{0.6\lambda} \right)^2} - \frac{4\pi}{\lambda_{\max}} \right]^{-1} \quad (8)$$

where λ is the mean wavelength of the generated waves, $\lambda_{\min}$ and $\lambda_{\max}$ are respectively the minimum and maximum wavelength values corresponding to the effective frequency bandwidth of the waves and φ corresponds to the angle of the refracted waves within the inspected material. This angle is provided by

$$\varphi = \tan^{-1} \left(\frac{\tan(\alpha)}{\sin(\theta)} \right) \quad (9)$$

where θ is the incidence angle of the wedge and α is half the divergence angle of the transducer. It should be noted that those expressions apply to point sources of limited divergence angle 2α and that the resolution is different when real transducers are considered. The resolution of the process for real transducer geometries commonly used for the generation of Lamb waves (flat circular or rectangular) is still under investigation.

5.2. Algorithm Description

The L-SAFT computation algorithm is not simple and is separated in two main parts: the Lamb wave phase velocity computation and the image construction. The plate elastic properties (shear velocity V_s and longitudinal velocity V_L) and thickness ($2h$) as well as the effective frequency bandwidth of the system are the only parameters required to compute the selected mode phase velocity curve. The frequency bandwidth is selected manually on a representative A-scan taken from the inspection data. The output of this first part is the phase velocity curve $V_p(\omega 2h)$. The only manual input required for the image construction is the wedge properties (wedge velocity V_{Wedge} , wedge height H and incidence angle θ from which $D_{\perp}$ is computed). Figure 2 presents the algorithm flowchart, from the B-scan acquisition to the image presentation.

Figure 2. FD Lamb-SAFT algorithm flowchart

5.3. Software Documentation

The operation of the developed software for the FD Lamb-SAFT is described in the following sections from the user guide.

Getting Started

The new Matlab version of SAFT is called from the command prompt:

```
>> saft_main
```

Open B-Scan Data

To begin a new SAFT analysis, press the “Start New SAFT” button.

This action will automatically open an “Open file” window (“Open B-Scan Data”). Two data format are currently supported:

- Previously used “*.dat” format
- New format (no extension for now)

Select a data format (*. * for new data format) followed by the data file to open:

Once the data is loaded, the main SAFT analysis window opens. If the “Cancel” button is pressed, i.e. no data is loaded; the main SAFT analysis window will open anyway.

A “Load B-Scan” option can be found in the “File” menu in order to come back to the “Open B-scan window:

Data Analysis Setup

This SAFT Analysis window allows the user to set the parameters for the SAFT analysis about to be performed.

To resample the data the + and – buttons beside the “Sampling Frequency” box can be used (in the “Data Properties” section). In the same section the offset that was used in the acquisition can be entered (this will be automated in the future).

In the temporal windowing section a Hanning window can be applied to the B-Scan.

The plate properties are entered in the Plate Properties section.

In the SAFT Properties section, the properties of the SAFT image that will be produced (image length and resolutions) can be adjusted.

When pressed, the “Set Properties” button in the “Wedge and Array Properties” section allows the user to specify the physical properties of the transducer array and wedge that were used for the inspection.

This window allows the user to select:

- One or two transducer arrays (select “Number of arrays=1” for a standard, mono-element scan and “Number of arrays=2” for the current scans)
- Which transducer array has the first firing element (first A-scan recorded), as shown on the corresponding graph on the right
- The distance between the array on the wedge (plane of the wedge)
- The distance between the transducer elements within an array
- The wedge velocity
- The wedge incidence angle
- The vertical height of the arrays

The graph on the right will show the selected geometry automatically. The “Scanning increment” box is disabled (its value is given by $\frac{\text{Distance between array elements}}{\text{Number of arrays}}$).

Once the wedge properties are set, simply press the “Accept” button. This will bring you back to the previous window.

Data Analysis

After all the parameters have been adjusted, the analysis can begin. To start the analysis, press “Do SAFT” in the bottom-left.

It is important to note that each time the program is used, a default parameters file is created so that the user does not have to enter the same values at each use. However, the current version of the program does not save those parameters until the whole program is closed, i.e. as long as the program is not completely closed, the default parameters are reset for each new analysis.

Once the “Do SAFT” button is pressed, the user has to select the Lamb mode he wants to see treated. In order to perform the Lamb mode selection the following window appears:

All the Lamb modes that can be found in the frequency range for the selected plate/wedge properties are shown on this graph at their central frequency. The following procedure is to select the mode that is to be considered (in this case, the A1 mode)

First press the “Continue” button. Once this button is pressed, there is no way to go back (an external interruption of the program will cause an interface problem and the user will need to press the “Continue” button anyway). If the user wants to go back to the previous window, he must press the “Cancel” button BEFORE “Continue”.

Once “Continue” is pressed, the frequency bandwidth needs to be selected:

As for the previous version of the program, the user must select the lower frequency component (left-click followed by Enter) and then the higher component:

The SAFT procedure then starts. Two windows appear while SAFT is being performed; a Phase velocity and Wavelength dispersion curve as a function of frequency for the selected bandwidth.

When the process is completed, the following result window appears:

To save the result, the user can either use the standard save button in the top-left corner or use the “Save as...” option in the “File” menu. It is important to note that loading previous SAFT data erases the current data.

The user can see the image profiles (B-Scan of SAFT) by clicking on the image:

- The first click activates the function
- Second click displays the vertical and horizontal profiles at the selected position. The coordinated of the profiles are given in the lower-right boxes from the image.

The lateral resolution (interpolation) of the SAFT image can be increased by pressing the + button and decreased by pressing the – button on the top-right of the SAFT image. (+ increases resolution i.e. decreases resolution value in mm, while – decreases the resolution until the original resolution is reached).

If the user wishes to work on the SAFT data from the command prompt, the original SAFT result is named “SAF” while the increased resolution SAFT data is named “SAFT_Mod”. The horizontal and vertical axes are respectively “Xaxe” and “Zaxe”.

Different color palettes can be used (“Color Maps” menu).

Note: The “Lateral Sizing” at the right button is not implemented yet.

The “Properties” button on the right will display the following window, which displays the important properties selected before running SAFT (Data Analysis Setup). Pressing the wedge set-up button will display the wedge and transducer property window.

The image shows a software window titled "SAFT Properties". At the top, there are two text fields: "B-Scan File" with the path "D:\Documents and Settings\René\Bureau\SAFT_AET10\Samples_Last\Samples_Last__2003-01-21-17_50_40" and "SAFT File" with the text "SAFT Data not Saved". Below these are three main sections: "Data", "Plate", and "Image". The "Data" section contains "Lamb Mode" (Antisymmetric) and "Order" (1), "Sampling Frequency" (10 MHz), and "Offset" (0 points). The "Plate" section contains "Thickness" (1.85 mm), "VT" (3140 m/s), and "VL" (5630 m/s). The "Image" section contains "Temporal Windowing" (None), "Depth Resolution" (0.0488 mm), and "Lateral Resolution" (1.5 mm). To the right of these sections are two buttons: "Wedge Setup" and "Close".

Data		Plate		Image	
Lamb Mode	Order	Thickness		Temporal Windowing	
Antisymmetric	1	1.85 mm		None	
Sampling Frequency	Offset	VT	VL	Depth Resolution	Lateral Resolution
10 MHz	0 points	3140 m/s	5630 m/s	0.0488 mm	1.5 mm

Closing SAFT

To leave the analysis, press the “Close button” on the main analysis window:

Pressing this button sends the user back to the first window:

Note that once the SAFT procedure is performed, the “Display Results” button is activated on the main window. This button allows the user to go back to the analysis window (current SAFT image).

At this point, the user can start a new analysis (“Start New SAFT”), load a previously saved SAFT data (“Load SAFT Result”), display the current SAFT data (“Display Results”), or quit the program (“Quit”). If the “Quit” button is pressed and a SAFT result is in the workspace, the user is asked if he wants to save the current SAFT data before closing the program:

- “Yes” opens a “Save as...” window
- No Closes the program and clears all variables in the workspace
- “Cancel” shows the previous window.

File Formats

File Data Format: Data are stored in separate files with simple format. All required header information is saved in separate file name extension.

Data files (.dat): One 8-bit signed byte (-128 to +127) per digitizer point, N points per record, where N lies in the range [1..4096]. Record length = N bytes.

Control files (.cnt): The control file is a text file containing 1 numeric datum per line. The rest of each line following the number is comments.

0	Header size
128	Number of points per record
0	Start record (usually 0)
10200	End record (usually `Total number of records-1')
101	Number of records per line
1	Starting direction (1 forward or 0 reverse)
1	Bi-directional or uni-directional (1 or 0)
0	Pixel display offset (usually 0)
1	Content: 1)FULL waveform -1)Amp. -2)AMP & TOF

Defined file (.def): Saved or default file for parameters from a previous setup

Label files (.lbl): Saved

128	Record size (number of points)
10000000	Output pulser frequency (Hz)
100000000	Sampling rate (Hz)
2.0	Peak-to-peak voltage gain (volts)
333.0	Speed of sound
m/s	Unit of speed of sound
XY	Plane (Scanning, Indexing)
0.040	Scanning axis increment
0.040	Indexing axis increment
inch	Unit of scanning axis
inch	Unit of indexing axis

Section 6 Financial Summary

Budget Data: Data is through June 30, 2004 and uses the new program plan to complete. We expect to complete the program within the original budget that was \$1,785,015.

Project Spending and Estimate of Future Spending							
Quarter	From	To	Estimated Federal Share of Outlays*	Actual Federal Share of Outlays	Estimated Recipient Share of Outlays*	Actual Recipient Share of Outlays	Cumulative
	Start	6/30/04		718K		914K	1632K
3Q04	7/1/04	9/30/04	53K		67K		1752K
4Q04	10/1/04	12/31/04	15K		18K		1785
1Q05	1/1/05	3/31/05					
2Q05	4/1/05	6/30/05					
3Q05	7/31/05	9/30/05					
4Q05	10/1/05	12/31/05					
1Q06	1/1/06	3/31/06					
Etc.							
Totals			68K	718K	85K	914K	1785K