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A MODERN APPROACH TO CONDITION-BASED MAINTENANCE OF REINFORCED RUBBER COOLING SYSTEM EXPANSION JOINTS UTILIZING A MICROWAVE NON-DESTRUCTIVE INSPECTION METHOD

Jack Little
ILD, Inc./Evisive,Inc.
Baton Rouge, Louisiana, USA

Robert Stakenborghs
ILD, Inc./Evisive,Inc.
Baton Rouge, Louisiana, USA

ABSTRACT

Reinforced rubber has found broad application as a construction material for expansion joints in heat exchanger inlet and outlet piping. Traditionally, the products have been replaced based on age, regardless of the service time or conditions. The fundamental reason for this has been the absence of a suitable nondestructive examination (NDE) method which characterizes the true health of the component. Until recently, the primary tools for condition assessment of such rubber products have been:

- Visual examination of surface condition
- Durometer inspection in accordance with ASTM D-2240 (also a determination of surface condition).

Microwave Interferometric inspection represents a method for characterizing the condition of such an industrial rubber product volumetrically. This paper will provide technical information on this new NDE technology as well as present inspection results of cooling water system expansion joints installed in US commercial nuclear power plants.

INTRODUCTION

Reinforced rubber has found broad application as a construction material for expansion joints in heat exchanger inlet and outlet piping. These joints are used to permit movement of the heat exchanger relative to the piping, to permit small amounts of misalignment between the piping and exchanger nozzles, and to isolate the exchanger and piping from vibration originating in the other. Traditionally, these products have been replaced based on age, regardless of the service time or conditions because of the absence of a suitable NDE method which characterizes the true health of the component. Until recently, the primary tools for condition assessment of such rubber products have been visual examination of surface condition and durometer inspection in accordance with ASTM D-2240 (also a determination of surface condition). Microwave Interferometric inspection represents a method for characterizing the condition of such an industrial rubber product volumetrically.

RUBBER EXPANSION JOINT PRODUCT DESCRIPTION

The rubber expansion joints are available in a variety of elastomers to give the best possible performance for any set of operation conditions. Many of the most popular combinations of lining and cover materials are shown below in Table 1. The available rubber types also provide good temperature tolerance ranging from 80° C to 105° C, as can be seen in Table 2. All of these cover options offer outstanding to very good resistance to sunlight and oxidation. For most applications, the linings will stand up to most chemicals or hydrocarbons or to abrasion, as described below the tables.

TABLE 1-POPULAR COMBINATIONS OF EXPANSION JOINT MATERIALS

Lining	Cover
EPDM	EPDM
Neoprene	Neoprene
Natural	EPDM
Nitrile	Neoprene
Hypalon	Hypalon

TABLE 2-TEMPERATURE DURABILITY OF RUBBER TYPES

Rubber Type	Natural	EPDM	Neoprene
Max Temp	80°C	110°C	100°C
Rubber Type	Nitrile	Hypalon	Butyl
Max Temp	105°C	105°C	100°C

- Natural Rubber: Suitable for water, air, most moderate chemicals, dilute acids and alkalis. Good for abrasion. Not suitable for exposure to strong sunlight, ozone, oil or petroleum.
- EPDM: First choice for hot water, steam, oxidizing chemicals, animal and vegetable oils. Excellent for sunlight and ozone. Good for high and low temperature applications.
- Neoprene: Suitable for water, sewage, oxidizing chemicals and non-aromatic hydrocarbons. Good for oil resistance and weathering.
- Nitrile: Suitable for most hydrocarbons, oils and petroleum fuels and hydraulic fluids. NOT good for sunlight aging, ozone or flame.
- Hypalon: Suitable for many acids, alkalis, industrial chemicals and aliphatic hydrocarbons. Very good resistance to ozone, sunlight, weathering and abrasion.
- Butyl: Suitable for animal and vegetable oils, water and many oxidizing chemicals. Particularly good for low gas permeability. NOT for petroleum fuels or oils.

RUBBER EXPANSION JOINT FAILURE MECHANISMS

Provided the appropriate material has been chosen for the fluid being transported and provided the design temperature and pressure have been correctly specified, a reinforced rubber expansion joint can last for many years. As will be discussed later, rubber hardness changes throughout its life. Increasing hardness will, eventually, lead to surface cracking, analogous to the cracking that occurs on the sidewalls of tires near the end of their useful life. Once some maximum hardness is reached, anticipated design-basis relative piping movements and piping vibrations, which are all-together acceptable for a soft, flexible joint, may lead to crack propagation from the inner surface to the fabric's structural "carcass". This cracking permits process fluid to come in contact with the structural fabric beneath the inner cover. Once the fluid wets the fabric, fluid "wicks" down the fabric weave by capillary action, eventually saturating a large area of the joint. In this area, the saturated fabric weakens the adhesive forces holding the rubber cover to the reinforcing fabric and the two layers delaminate. Typically, process fluid collects between the now separate cover and fabric, resulting in a fluid blister. The outer cover, also made of rubber, soon delaminates from the saturated fabric, leading to blisters on the outside surface of the component, a breach of the pressure boundary, and ultimately, failure.

TRADITIONAL RUBBER NDE METHODS

Traditional NDE methods, such as ultra-sonic inspection (UT) and eddy current inspection (ECT) are ineffective. UT cannot penetrate the rubber, as the material absorbs and dissipates the sound waves. Additionally the reinforcing fabric used in the rubber joint scatters the ultra-sound waves, further reducing sensitivity and spatial resolution. ECT is only effective on materials which conduct electricity (conductors). While potentially effective, conventional radiography (RT) requires access to both the inner and outer diameter of the joint. This is typically impractical or extremely inconvenient and clearly not possible while the equipment is in service (full of fluid). As discussed briefly earlier, durometer inspection in accordance with ASTM D-2240 has been used extensively as a quantifiable indication of surface condition. In durometry, a needle-like mechanism is pressed onto the surface of the rubber and the amount of force required to obtain a particular surface deflection is measured. This value is proportional to surface hardness. Since most compounded rubbers continue to become harder throughout their useful lives, surface hardness is one possible indicator of remaining life. Surface hardness does not, however, give any information regarding sub-surface or volumetric condition, therefore another NDE method was sought.

MICROWAVE INTERFEROMETRIC NDE BASICS

In interference, or virtual standing microwave NDE, a specimen to be inspected is bathed in microwave energy of a constant frequency. A portion of the out-going beam is impinged upon a detector, with the balance being projected onto the specimen. As the microwaves propagate through the dielectric specimen, some portion of the energy is reflected and the rest transmitted at each interface of differing dielectric constant (or index of refraction). This is similar to the reflection and transmission of ultra-sonic waves in metals when encountering interfaces of differing speed of sound. The reflected microwaves impinge on the detectors, mixing with the out-going microwaves, creating an interference voltage which is mapped at many different places across the specimen surface. From these data sets (X, Y, and Detector Voltage), an image of the specimen is created and subsequently displayed on a computer screen. Since the voltage at the detector is the result of the interaction between a beam and many reflections, which differ in both phase and amplitude, information about the entire volume of the specimen is superimposed to create a single, 3-dimensional image through the thickness of the part.

Figure 1 below represents the virtual standing waves in the inspected part created by a single microwave emitter and two detectors which are separated in the axial, or "Z" dimension by ¼ wavelength (¼ λ). The two results of this hardware configuration are two virtual standing waves, offset by ¼ λ through the thickness of the part. The amplitude of the virtual standing waves in Figure 1 are proportional to the expected detector voltage (with the constant of proportionality being the gain setting) which would result from moving the specimen back wall (dashed line) to that position.

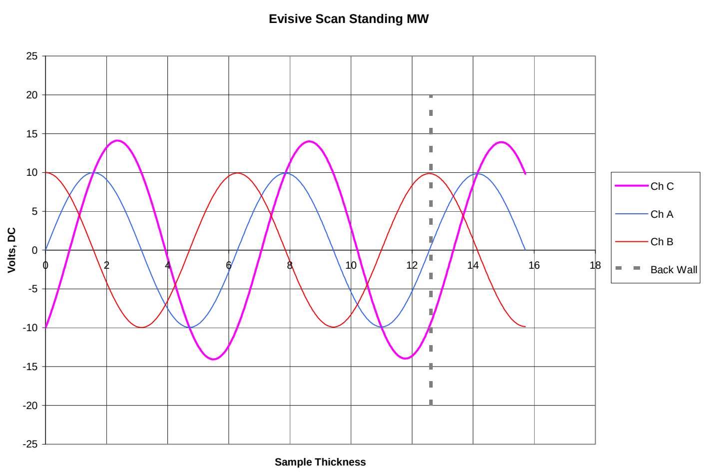

FIGURE 1: STANDING MICROWAVE

It is clear from the figure that, if using a single detector, there are regions where a substantial change in back wall position will result in very little change in detector voltage. These are referred to as regions of low intrinsic sensitivity. They occur where the first derivative of the virtual standing wave approaches zero, when either transitioning from positive to negative or negative to positive. In a dual-detector arrangement, with the detectors staggered in "Z" by ¼ λ, the region of low intrinsic sensitivity for one detector corresponds to a region where the first derivative of the virtual standing wave for the other detector is at its maximum. Arranging the detectors in this way ensures that a defect of interest will always be detected by at least one of the hardware channels, because a defect which escapes detection by one channel must, by definition, occur at the position of maximum sensitivity for the other. A "C" channel, or mathematical construct channel is also plotted in Figure 1. It represents the arithmetic difference between the two available hardware channels. It can be used to highlight defects and inhomogenieties associated with a particular, relatively limited thickness range in the inspected part. Such defects, including delaminations and disbonds will appear more strongly in one channel than another and typically be accentuated in the "C" channel image. Features which result from bulk properties such as porosity or density will typically be suppressed in the "C" channel.

LABORATORY MICROWAVE INSPECTION OF RUBBER EXPANSION JOINTS

In order to ascertain whether the proposed microwave method could be used effectively for in-field inspection of rubber expansion joints, first a laboratory mock-up must be developed. The laboratory environment permits a modicum of control over parameters which are typically far more difficult to control in a commercial power plant. These parameters include temperature, humidity, cleanliness and the quality of available AC power. This mock-up was developed utilizing a rubber joint which had been removed from a commercial nuclear power plant after several years of service. The joint was twelve inches nominal pipe size and approximately eight inches long. This joint is manufactured from multiple layers of synthetic fabric (the pressure-retaining or structural sub-component) surrounded on both the inner and outer diameter by a rubber "jacket" or "tube" which protects the inner "carcass" from the outside environment and the process fluid within. A fixture was developed to move the microwave transducer the full 360° around the circumference of the joint, and then permit a small axial motion before reversing the circumferential motion and repeating. This scan-and-raster arrangement is typical of the devices used commercially to scan a right circular cylindrical shape while performing NDE (for example, a pipe weld). The device records its position in orthogonal coordinates, such as (X,Y) or (R,θ) using optical encoder devices. These locations are associated with the appropriate detector voltages and the data is then used to create an image. A photograph of the expansion joint used in the lab mock-up is shown in Figure 2.

FIGURE 2: EXPANSION JOINT MOCK-UP

Once an image of the joint has been created, it is necessary to ensure that the NDE method under development has sufficient sensitivity to detect defects which are smaller than what is referred to as a “critical defect”. A critical defect is one which will result in unacceptable field service of the component. Any smaller defect will, theoretically, not result in component failure, so the ability to detect, locate ands size a sub-critical defect yield margin in the inspection. For the lab development being described here, several small, superficial defects were introduced on the specimen inner diameter, one at a time. These introduced defects appear in Figure 3.

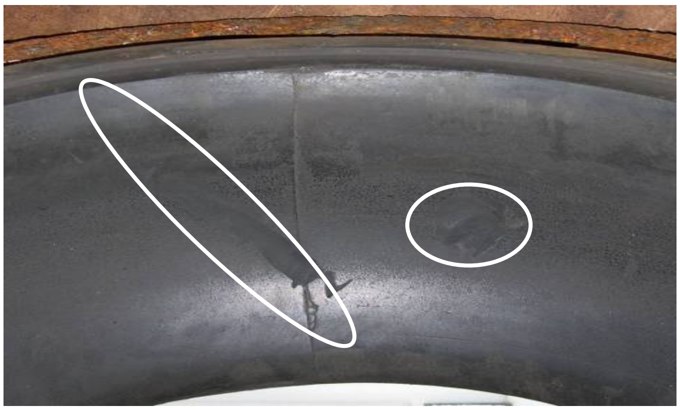

FIGURE 3: SPECIMEN WITH DEFECTS

The first defect to be introduced was the rounded defect. It was approximately 1inch in diameter and approximately 0.030 inches deep. It was created using a small high-speed rotary grinding tool. The defect did not penetrate the rubber inner layer and did not expose the inner structural fabric “core” or “carcass” of the expansion joint. The joint was scanned after the introduction of the round defect. The scan image can be seen as the top image in Figure 4.

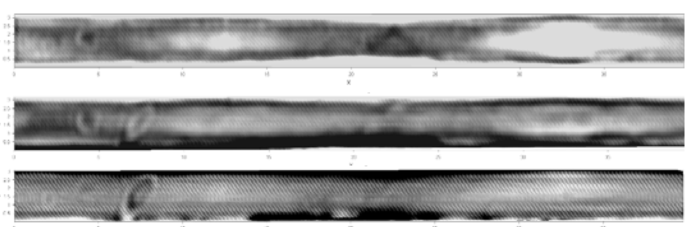

FIGURE 4: SCAN RESULTS OF EXPANSION JOINT MOCK-UP

Next, a second defect, this time a linear defect, oriented at an oblique angle across the inner surface of the part, was introduced. This defect was created in precisely the same way as the earlier, rounded defect. The linear defect was approximately 3 inches long and, again, about 0.030 inches deep. The joint was then re-scanned, resulting in the image corresponds to the middle image in Figure 4. It is often desirable to monitor the health of a component over a substantial period of time. To accomplish this, it is attractive to be able to image only what has changed since the last inspection. To prove the feasibility of this approach to rubber expansion joint inspection, the top image in Figure 4 was subtracted from the middle image, resulting in the bottom image. Note that the rounded indication, present in both images, virtually disappears, resulting in a much clearer image of the most recently introduced linear indication.

FIELD MICROWAVE INSPECTION OF COOLING WATER EXPANSION JOINTS IN A COMMERCIAL PRESSURIZED WATER REACTOR (PWR)

Having been proven feasible in a laboratory environment, the microwave NDE method was applied to cooling water expansion joints in a commercial PWR nuclear unit in the United States. The PWR environment was selected because of its lack of ionizing radiation and radioactive contamination challenges. This approach permits the further development from a laboratory method to a true field method in a setting where the task is less time-critical than would be the case in a Boiling Water Reactor (BWR) type plant. For the pilot PWR project, twelve cooling water expansion joints were chosen for inspection. These were located on the inlet and outlet cooling water lines for each half-section of a 3-section main steam surface condenser. These joints were each 138 inches in diameter and approximately 8 inches long. These joints were scanned with the system in service and full of water using a modified commercially available industrial robot. Both a representative joint and the scanning robot can be seen in Figure 5.

FIGURE 5: EXPANSION JOINT WITH SCANNING EQUIPMENT

This scanner steps (rasters) incrementally around the circumference of the joint while scanning axially between steps. The image is created in the same way as before. Images of an unconditionally acceptable joint and a conditionally acceptable joint appear in Figure 6. This particular manufacturer of expansion joint utilizes a different approach to fabrication than did the manufacturer of the previous, smaller joint scanned in the lab mock-up and described in that section. In the joints currently under discussion, strips of fabric, saturated in liquid latex rubber are inter-woven at approximately 30° angles relative to the axial direction. These strips provide the structural reinforcement needed to permit such a large component to carry design pressure ratings of over 100 psig.

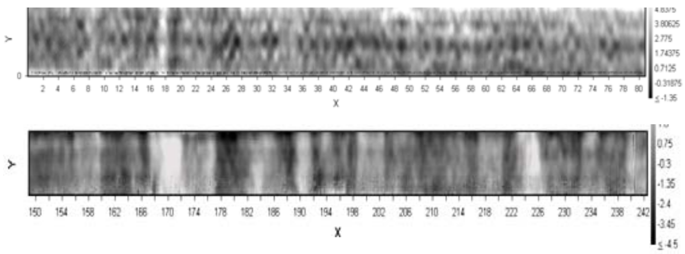

FIGURE 6: SCAN RESULTS OF ACTUAL EXPANSION JOINT IN PWR

The upper image in Figure 6 represents a typical joint of this style. The 30° angles created by the inter-woven fabric strips are clearly visible, leading to a pattern which resembles that of a rattlesnake. Approximately ¼ of the way around the joint is a short, axially linear indication which is due to overlap in the rubber jacket prior to curing (autoclaving). This indication is a result of the method of manufacture and does not represent a defect or flaw. In the lower image in Figure 6, the crisscross pattern of the inter-woven fabric strips has been almost completely obliterated by a series of axially oriented linear indications of varying width, scattered around the entire circumference. These indications are the result of mechanically induced delaminations of the outer jacket caused by rough treatment during maintenance of the adjacent 138 inch butterfly valve. This disbonding was not the result of moisture wicking in the fabric core and did not render this joint unacceptable for continued service. No moisture was detected in the fabric and the joint will be re-inspected during preventative maintenance to ensure continued reliability.

FIELD MICROWAVE INSPECTION OF COOLING WATER EXPANSION JOINTS IN A COMMERCIAL BWR

One goal when developing a field NDE method is to maximize productivity without decreasing the probability of detection (POD) for a critical defect. This added productivity leads to either fewer personnel or less time to perform a given number of inspections. When performing inspections in BWR type nuclear plants, this added productivity is especially important, as it results in less total radiation exposure and is consistent with the US nuclear industry policy to maintain ionizing radiation dose as low as is reasonably achievable (ALARA). In developing the subject microwave inspection technique for BWR plant applications, it became clear that it was not necessary to image the entire joint. If the beam emitted from the transducer is sufficiently wide enough to detect irregularities anywhere in the axial extent of the joint, and there are no indications which exceed a pre-determined voltage, then a simple one dimensional "line scan" may be performed. In order to establish the voltage variation which corresponds to a sub-critical defect it is necessary to construct a "standard defect". As was done in the laboratory, sub-critical defects are introduced into a section of joint identical to the installed joints to be inspected. This standard defect is then scanned to determine the magnitude of the detector voltage changes associated with the introduced defects. A threshold is established, below which a detected defect will be substantially sub-critical and require no further investigation. This threshold is incorporated into the field inspection procedure [1, 2]. When an indication leading to a change in detector voltage beyond the proceduralized limit is encountered, that section of the joint must then be imaged in two dimensions to determine the morphology of the indication. In this way, the vast majority of the work can be performed utilizing time domain line scanning, a very efficient inspection methodology. In places where the piping configuration does not lend itself to automated or robotic inspection, but imaging is required, a way must be found to determine the X and Y position information for each voltage measurement, in real time. For this task, an infra-red (IR) position indication scheme works well. In this scheme, a camera, capable of imaging in both visible light and IR is positioned on a camera tripod adjacent to the area to be inspected. The region of interest (ROI) is centered in the frame and a black and white photograph of the ROI is taken. Installed within the transducer is a small IR light emitting diode (LED) which can be tracked within the frame using sophisticated software. The camera requires 10 milli-seconds to capture a frame, and the resulting frame rate is, therefore, 100 frames per second or 100 Hz. The position within the frame, in both X and Y, is determined 100 times per second and the detector voltages associated with the location is then stored as a series of (X,Y, and Detector Voltage) data sets at 100 Hz. As the data is saved on the inspection computer, the individual locations where detector voltage data was collected is superimposed upon the black and white photograph collected initially as shown in Figure 7.

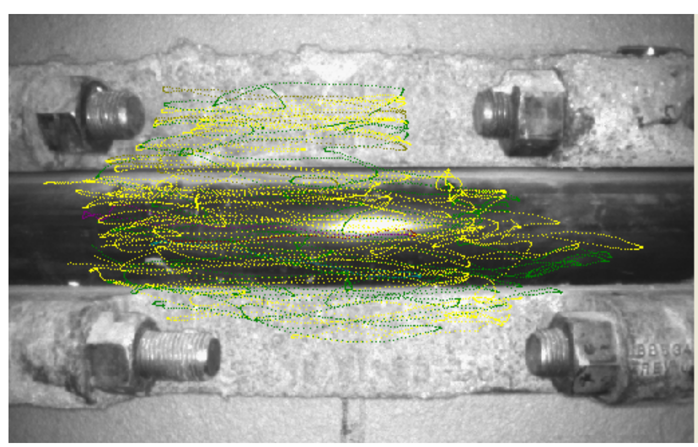

FIGURE 7: ROI WITH PROBE LOCATIONS SUPERIMPOSED

In this way, a permanent record of the actual sample locations on the part is saved for later investigation. The advantages of this method over optical encoder-based position determination, as is used on scan robots, are numerous. Principal among these is that when a robot wheel slips on the surface of the component during inspection and encoder state changes are not registered for this motion, then the location in this dimension is forever incorrect. The image made during such a scan will be "shifted" due to the motion without accumulated encoder pulses. As a wheel slips over and over during the scan of a challenging surface, this position error is accumulated. The resulting error is impossible to correct, as its occurrence is random. In contrast, the IR camera scheme of position determination is not susceptible to accumulated error. This is because, when using the IR camera method, the camera/computer "looks" 100 times per second, and the position of the transducer in X and Y is determined. If the incorrect position was recorded earlier, this does not bias each successive determination as with the encoder position determination scheme. Additionally, there is no wired connection between the transducer and the IR camera set-up, so the two components can be manipulated more freely in the congested in-plant environment. Both the IR camera and the transducer are separately connected to the inspection computer and the detector voltages and position information are associated into (X,Y Detector Voltage) data sets in the computer. A photograph showing field scanning in a BWR nuclear plant utilizing the IR camera position determination method can be seen in Figure 8.

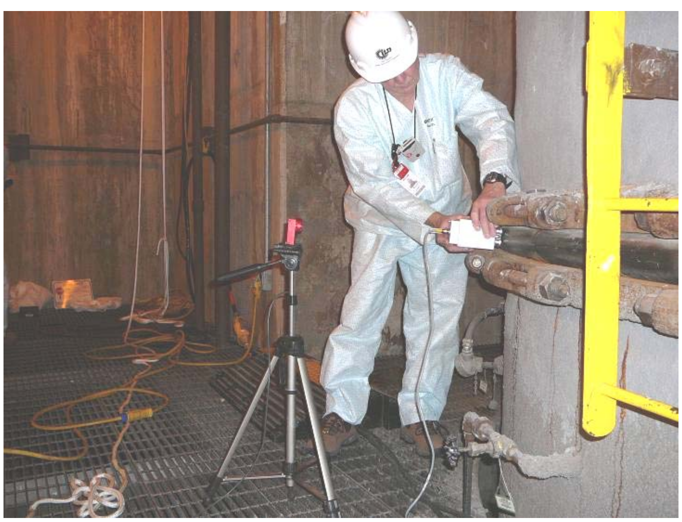

FIGURE 8: IN FIELD INSPECTION

During the BWR expansion joint inspections, several indications were encountered during time domain line scanning which required IR camera imaging to determine the morphology of the detected irregularity. The resulting image is shown in Figure 9.

The image in Figure 9 has been displayed in "false color", where a color gradient from magenta to red has been associated with a voltage gradient from minimum to maximum voltage, respectively. The irregularity or feature imaged in Figure 9 is, again, the overlapping of the cover rubber, characteristic of the manufacture of these components and does not represent a defect or flaw.

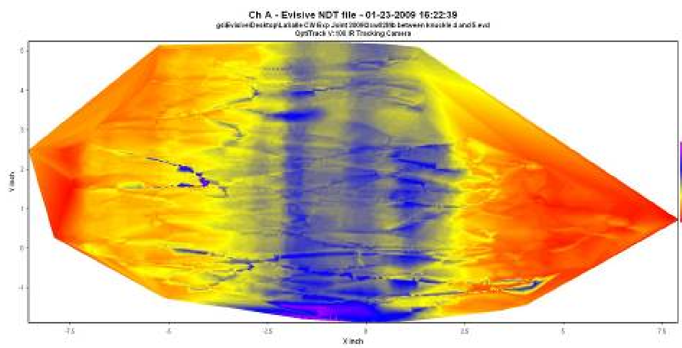

FIGURE 9: RESULTING IMAGE USING IR CAMERA

SUMMARY AND CONCLUSIONS

Reinforced rubber products are quite prevalent in the industrial sector. The actual condition of such components has traditionally been very difficult to determine, and replacement has been performed based on in-service time, not actual component condition. Given the high cost of these components, and particularly the high cost associated with their replacement (in both labor and lost production capacity), a non-destructive examination method which would permit a high probability of detection of a marginally sub-critical defect is attractive. Additionally, a method which would permit such inspection with the equipment in service would represent the optimal solution. As has been shown in this paper, virtual standing microwave NDE is capable of providing this inspection capability. This method can penetrate the full thickness of such components and provide a full volumetric inspection technique. Additionally, virtual standing microwave NDE can detect defects which are substantially sub-critical and the probability of detection of a critical defect can be quite high. The method can be configured as a manual, semi-automated or fully automated system. While the ability to perform two dimensional imaging has appeal, it is not always the best solution where challenging conditions prevail. Production can be improved by one dimensional scanning in the time domain and the system can be adapted for two dimensional field scanning on components with very challenging geometries without being susceptible to accumulation of position error during protracted scans. This technology offers owners of reinforced rubber products a condition-based maintenance alternative to the traditional time-based replacement frequency.

ACKNOWLEDGEMENTS

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