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FIBREOPTIC PROBE FOR IN-SITU INSPECTION OF SURFACE CRACKS IN STEAM GENERATOR TUBES


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ABSTRACT

The automatic inspection of cracks in the inner side of steam generator tubes is routinely carried out using eddy currents techniques. These methods are mature and have quite high performance but the achievable resolution is relatively low (~1 mm) and present drawbacks related to the reliability of the inspection of the areas of tubes at the neighbourhood of the supporting plates. Several years ago we have proposed a solution to these limitations based on a new fibreoptic reflectometric technique that has already been theoretically and experimentally analysed using a first laboratory prototype. In these work we describe a second generation prototype that is integrated in a whole inspection system that could perform an inspection in the field. The results obtained over cylindrical tubes with inner diameter 16.8 mm (corresponding to real steam generator tubes) with cracks created by electrical disintegration and by stress-corrosion and employing conditions close to real operation confirm our previous conclusions: both circumferential and axial cracks of widths as small as 30 μm can be detected and measured and typical resolution capability of 10 line pairs/mm can be obtained.

Keywords: Optical Inspection, Crack detection, Reflectometry.

1. Introduction

Since a few years, the authors are studying the possibility of using optical techniques for the automatic detection and measurement of cracks (with typical width within the interval 10-200 μm) in the inner side of steam generator tubes of nuclear power plants. These tubes are routinely inspected using eddy currents techniques but, though these methods have reached maturity and present quite high performance (specially in terms of sensitivity and speed of inspection), the nature of the measurement principle imposes some limitations to the achievable resolution (~1 mm) even employing probes with optimised configurations and coil orientations. Moreover, in the usual case of steam generators with supporting plates, eddy currents techniques present additional limitations for inspecting the areas of the tubes at the neighbourhood of the plates.

A possible solution to overcome these limitations could be based on optical techniques, that have a great potential to reach a more precise dimensional characterisation of defects than eddy currents and are not affected by the presence of supporting plates. In fact, optical imaging techniques -mainly by means of endoscopes, borescopes and miniature video cameras- are employed by industry since many years ago to get information about the inner surface of tubes, being possible to obtain images with quite good resolution. However, these methods are seldom used as a routine mass-production tool because a human operator is needed to perform a visual inspection as the probe scans the tube, which makes the task tedious, time-consuming and not reliable in long term.
In our knowledge, the first trial to develop an automatic optical inspection system for this task has been done in 1980 by the EPRI institution. In the last years, other optical systems, based on triangulation principle, have been developed and commercialized for the inspection of heat exchanger and steam generator tubes with diameters around 50 mm but, until now, the claimed resolution and sensitivity (around 150-250 \(\mu m\)) are insufficient to detect small cracks within the range of interest in our case. Other optical techniques have been reported for inspecting steam generator and heat exchanger tubes but they were conceived with other objectives than crack detection (inclusions, strange objects and measurement of the tube inner diameter).

Our proposal, that was devised in the frame of a research and development project related to steam generator tubes, is a new technique to obtain an image of the tube inner surface. In the following, we present a brief summary of the theoretical and experimental analysis of the new technique that has been presented elsewhere. Then we describe the specially developed second generation prototype and the results obtained with it using condition very close to real inspection.

2. Summary of previous results

2.1. The reflectometric technique

The new technique is based on a fibreoptic probe that establishes a one-to-one correspondence between the pixels of the image and a 2D grid of points extended along the surface of the tube using a reflectometric principle. The probe is composed of small fibre reflectometers disposed with rotational symmetry around the axis of the tube with a constant circumferential pitch. In this way the ring section of the tube is covered at the same time by the detection fibres. Each point \(Q\) of the grid is defined as the intersection of each detection fibre \(DF\) axis with the surface mean level and so, these points \(Q\) are equally spaced along the circumferential direction with pitch \(pc\) equal to the circumference length divided by the number of detection fibres. The brightness that is assigned in the image to each point \(Q\) is proportional to the output optical power of the corresponding fibre \(DF\), that we will suppose proportional to its input optical power and so, to the integrated irradiance \(E_p\) (the average value of the irradiance along the fibre input face). This 1D circumferential scanning is combined with a 1D scanning of the fibreoptic probe along the axial direction of the tubes with steps of constant width \(pa\) to complete the 2D grid, rendering a global image of the surface without distortion. As the effect of the macroscopic cracks in which we are interested is, in general, to spread or diffuse the incident energy away from the direction of specular reflection or even to block completely the exitance from reflection and, as the detection fibre works in the bright detection field, \(E_p\) will be a maximum if cracks are not present in the area of the surface that contributes to \(E_p\), and will decrease as the area of contribution and the cracked area overlap. This decay characterizes the cracked areas in the output 2D image.

2.2. Theory for the image formation process and measurement principle

We have developed a theoretical model that describes the imaging process as a linear system \(S\) (fig. 2). The theory assumes not relevant and well justified simplifying assumptions related to the illumination detection geometry and the surface geometry. Nevertheless, the main hypothesis of the model is that the intensity reflected by the surface in normal areas follows a lambertian cosinusoidal law inside a cone of semiangle \(\theta_0\) around the direction of specular reflection and that it is zero outside this cone. The linear system \(S\) can be decomposed in three linear systems in cascade (fig. 2a):

(a) \(S_1\) related to the effect of the diffusive behaviour of the surface with an impulse response \(h_D\) characterised by the parameter

\[ M = 2 \cdot QB \cdot \tan \theta_0 \]

that represents the spread of the reflected radiation at a distance \(QB\) from the surface.

(b) \(S_2\) related to the integration by the detection fibres surface with an impulse response \(h_F\) and characterised by the size of the detection fibre input face \(D\).

(c) \(S_3\) related to the sampling process with a not shift-invariant impulse response \(h_S\) characterised by the sampling pitches \(pc\) and \(pa\).

In the simplest case of a uniform reflectance \(R_0\) in normal areas, a uniform incident irradiance \(E_i\) and if the sampling pitches \(pc\) and \(pa\) are lower enough to consider the output as a continuous function, for an infinite straight crack of width \(\delta\) oriented along the circumferential or axial direction (represented by the \(y\) direction in fig. 2c) the imaging process can be describe as the one-dimensional linear system

\[ e_y(x_y) = 1_{DF} (x_y - x) \star r(x) \]

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being \( l_{DF}(x_0 - x) \) and \( l_{IF} \) in cascade) the line-spread function corresponding to the global point-spread function of the subsystem \( S \). \( c_{IF}(x) \) is the normalised values of the integrated irradiance and

\[
r(x) = \begin{cases} 
1 & \text{in normal areas} \\
r_{IF}(x) \leq 1 & \text{in cracked areas}
\end{cases}
\]

is the normalised reflectance of the surface (fig. 2c). Expression (2) can be used to predict the output profile of a crack for a given value of the input \( r(x) \) and to establish the measurement principle of the technique.

In this context, after the image of the surface has been acquired the measurement process is developed in two consecutive stages. First, the detection of cracks is done by, for instance, classifying the points of the image with coordinates \((x_n, y_n)\) according to a threshold filtering criterion

\[
e_{IF}(x_n, y_n) \leq e_d
\]

where an adequate discrimination level \( e_d \) must be selected. After that, the measurement of the width \( \delta \) of the detected crack relays on the assumption that it is equal to the width of the area where the normalised reflectance \( r(x) \) is less than unity (fig. 2c):

\[
\delta = \max \left\{ x_2 - x_1 \mid r(x_1) < 1 \land r(x_2) < 1 \right\}
\]

Hence, defining in the same way the width of the area of influence of the crack over the output image as (fig. 2c)

\[
\delta_F = \max \left\{ x_2 - x_1 \mid c_{IF}(x_1) < 1 \land c_{IF}(x_2) < 1 \right\}
\]

and using in (2) the properties of the convolution operation with (1) results

\[
\delta_F = \delta + 2QB\tan \theta_D + D
\]

Expression (7) relates the quantity \( \delta_F \) that can be directly measured over the image, to the real width \( \delta \) of the crack. Under the assumed hypothesis of a constant value for the semiangle \( \theta_D \) that characterises the diffusive behaviour of the surface, if an image is obtained maintaining QB constant, \( \delta \) can be measured provided that \( M \) (given by (1)) and D are known.

2.3. Previous experimental results

The proposed technique has been previously experimentally analysed using a first laboratory prototype that allows to select independently the parameters of the reflectometric configuration \( QB \) and \( D \) and the sampling pitches. The experiments were performed over calibration tubes of diameter 16.8 mm diametrically sectioned (corresponding to real steam generator tubes). In the inner surface of the tubes cracks of different widths \( \delta \) were created by electrical disintegration and by stress-corrosion. For calibration, the width of each tested crack was independently measured using a toolmaker microscope with translation stage (1 \( \mu \)m resolution). The width measurements were taken at different points along the crack direction and the resulting sample mean is used as the nominal width \( \delta \) of the crack. Typical crack width variations were of the order of 5\textpm10\% of \( \delta \). Average roughness values of \( \sim 5 \mu m \) were obtained for the calibration tubes inner surface.

The results of the experimental analysis have shown that

a) The value of the measured \( \delta_F \) is independent of the reflectance value of the crack.
b) The linear model (7) is valid to describe the evolution of \( \delta_F \) as a function of \( QB \), \( D \) and \( \delta \) (fig. 3a)
c) The diffusive behaviour of the surface of the tubes is characterised by an angle \( \theta_D \approx 5^\circ \).
d) For a fixed reflectometric configuration (\( QB \) and \( D \) constant) and a given type of surface (\( \theta_D \) constant), \( \delta_F \) is proportional to the real crack width plus a constant offset value, i.e

\[
\delta_F(n) = \alpha_0 + \alpha_1 \delta(n)
\]

The values of \((\alpha_0, \alpha_1)\) can be estimated as the best-fit parameters \((a_{x_0}, a_{\delta})\) obtained from a linear regression analysis of \( \delta_F \) with respect to \( \delta \). The data for the regression can be obtained using the images of several cracks of known width \( \delta(n) \) in a reference surface similar to the surface to be inspected (fig 3b).

3. Second generation prototype

The satisfactory agreement between experimental data and theory, combined with the great design flexibility of this reflectometric technique, suggest that a new generation of inspecting devices could be developed on this basis, especially for
remote and difficult access parts. For these reasons, a second generation prototype has been designed and constructed with capability of inspecting the inner side of steam generator tubes in plant.

3.1. System architecture
The new prototype (fig. 4) has an optical probe linked to the remote control unit by a 15 m long umbilical chord. The fibreoptic probe comprises four optical heads (fig. 5) that implement the reflectometric configuration using a nominal detection distance QB of 0.20 mm and detection fibres with 30 µm diameter. Each optical head (fig. 6) can be displaced in the radial direction during the inspection to follow the variations of diameter of the tubes. A small air circuit of vacuum/pressure controls this radial movement. In the optical probe is also implemented a CCD matrix sensor (fig. 4) that detects the output of the detection fibres of the four optical heads. The frame rate (25 Hz) limits the axial speed of inspection of the prototype (~1 mm/s) however, speed values ~300 mm/s can be reached employing high bandwidth CCD linear arrays.

The remote unit controls the probe operation and the image acquisition process and contains the laser source, a pneumatic system for the vacuum/pressure circuit, the driver of the positioning unit of the fibreoptic probe and an A/D converter. The operation and control unit of the whole system is a PC computer that transmits and receives all the commands and stores and analyses the obtained images.

3.2. Results over calibration tubes
With this second generation prototype we have tested, in a first step, the same calibration tubes diametrically sectioned used for the experimental analysis performed with the first laboratory prototype. The images of the inner surface of the tubes obtained with the prototype and the calibration tube closed (fig. 7a-8a) has been compared with images obtained using a conventional CCD camera and the calibration tube opened (fig. 7b-8b).

The results has shown that the prototype obtains images of the inner surface, without employing any optical elements in the reflectometric configuration, that has no distortion and the distances between points can be directly measured without employing corrections algorithms (fig. 7a). The typical spatial resolution is of the order of 50 µm (fig. 7a). Automatic crack detection can be performed using very simple processing algorithms over the row image (fig. 8a-8c). The measured width of the cracks, obtained form the images of the calibration tubes using expression (7) and the experimental value for de diffusive angle θD obtained in the previous experiments (≈5°), has shown very good agreement with the measurement performed with the toolmaker microscope over the real surface of the sectioned tubes.

3.3. Results over real tubes
In a second step, we have also tested real tubes not diametrically sectioned that had been previously inspected using eddy currents and ultrasonic techniques. The obtained images have shown that both axial (fig. 9) and circumferential (fig. 10) cracks can be detected with limit sensitivity of the order of 30 µm.

4. Conclusions
A new technique for the automatic detection and measurement of cracks in surfaces of remote or difficult-access parts has been presented. It combines a reflectometric principle implemented with optical fibres and a scanning process to build up an image of the surface to be inspected. The results obtained with a second generation prototype show that the technique presents significant potential to be usable in practical inspection problems as, for example, the inspection of the inner side of steam generator tubes.

5. Acknowledgements
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6. References
5. Electric Power Research Institute, projects S103-1 & S103-2, "Optical scanner system for the internal inspection of steam generator tubes", sponsored by the "Steam Generator Owners Group", USA, (1980-81).

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**Fig. 1:** Scheme of the reflectometric configuration: IF: illumination fibre, DF: detection fibre, Σ: surface, θ: mean angle of illumination, θd: mean angle of detection, k: normal to the surface mean level, QB: detection distance, D: size of the input face of the detection fibre.
Fig. 2: a) Scheme of the image formation process as a linear system: $R(x,y)$ surface reflectance, $E_0(x,y)$ incident irradiance, $E_D(x,y)$ irradiance at the detection plane, $E_F(x,y)$ integrated irradiance by the fibre, $E_{F'}(x,y')$ sampled values of $E_F(x,y)$, $h_D$, $h_F$ and $h_S$ impulse responses. b) Scheme of the image formation process for a straight crack of width $\delta$, $\gamma(x)$, $e_D(x)$ and $e_F(x)$ normalised values of $R$, $E_D$ and $E_F$. c) Relationship between the normalised reflectance distribution $r(x)$ of the surface and the output integrated irradiance $e_F(x)$ in the image. The rest of the notation is explained along the text.

Fig. 3: a) Comparison between the evolution of $\delta_\gamma$ (theoretical value) and $[\delta_\gamma]$ (experimental value) as a function of QB for different values of $\delta$ with $D = 24$ $\mu$m. b) Calibration curve obtained with four tested cracks for a reflectometric configuration with QB=240 $\mu$m and D=24 $\mu$m.
Architecture of the second generation prototype

Detail of the fibreoptic probe of the second generation prototype located inside a diametrically sectioned steam generator tube of 16.8 mm internal diameter. Three of the four optical heads can be seen. The final version of the fibreoptic probe would have twelve heads in order to perform the inspection of the whole surface of the tube with only one axial travel.
Fig. 6  Detail of one optical head of the second generation prototype showing the relative position between the surface of the tube and the illumination and detection fibres.

Fig. 7  Image of the inner side of a calibration tube with an inner diameter of 16.8 mm. It can be observed on the left several arrays of circumferential and axial cracks of width δ and pith Λ performed by electrical disintegration (from top to bottom δ/Λ in microns are 40/250, 120/250, 195/250, 60/250, 125/250, 195/250, 20/100, 50/100, 20/100, 50/100) and on the right a calibration paper with regular bar patterns: a) Output raw image obtained in the laboratory with the second generation prototype employing QB=0.20 mm and D= 30 μm with sampling pitches pc=pa= 30 μm and the tube closed b) Raw image obtained by pasting several images digitized with a conventional CCD camera and the tube opened.
Fig. 8  Image of a calibration tube with an inner diameter of 16.8 mm and a real crack of mean width 130 μm. a) Output raw image obtained in the laboratory with the second generation prototype employing QB=0.20 mm and D=30 μm with sampling pitches pc=pa=30 μm and the tube closed. b) Raw image obtained with a conventional CCD camera and the tube opened. c) Image a) with a threshold filter.
Fig. 9  Typical output raw image obtained in the laboratory with the second generation prototype of several axial cracks. The parameters of the reflectometric configuration employed were \( Q_B = 0.20 \) mm and \( D = 30 \) \( \mu \)m with sampling pitches \( p_C = p_A = 30 \) \( \mu \)m.

Fig. 10  Typical output raw image obtained in the laboratory with the second generation prototype of a circumferential crack with a variable width \( \delta \). The parameters of the reflectometric configuration employed were \( Q_B = 0.20 \) mm and \( D = 30 \) \( \mu \)m, with sampling pitches \( p_C = p_A = 30 \) \( \mu \)m.