AN AUTOMATED SYSTEM FOR ANALYSIS OF THE SURFACE TOPOGRAPHY OF FRETTED U-BEND STEAM GENERATOR TUBES

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ABSTRACT

Physical measurement and analysis of the fretting scar geometry on tubes removed from operating steam generators provide valuable information regarding the tube orbital motion, and other in-service conditions, namely, misalignment, and eccentricity. This type of information is required to justify the assumptions made in the finite element impact simulation analysis and to qualify NDT techniques.

An automated surface scanning and analysis system has been developed at the Fretting Laboratory, Ontario Hydro Technologies, to determine the maximum depth and volume of the fretting scars on steam generator tubes. To define the true shape and topography of the fret mark, the analysis accounts for the unknown curvature of the U-bend section, and the ovality of the tube cross section. A description of the measurement system and the formulation of the analysis are presented in this paper. An error analysis for the effect of the measurement uncertainties is also given. Examples of the three-dimensional maps of the topography of fretted samples are presented to demonstrate the accuracy of de-trending the curvilinear surface of the U-bend tube.

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1. INTRODUCTION

Steam generator tubes are occasionally removed from operating boilers in order to examine the topography of the fretting wear scars, in terms of the maximum wear depth and the total wear volume. Maximum reduction in the tube wall thickness at various scar location provides also the data required to verify the accuracy of in-situ eddy current measurements, and to assess the growth rate of fretting. Physical measurement and analysis of the fretting scar geometry provide the following additional information for:

1. Inference of the tube orbital motion, and other in-service conditions, namely, misalignment, and eccentricity. This information is required to justify the assumptions made in the finite element impact simulation analysis [1,2].
2. Estimating the ratio between the average and maximum wear depth. This information is again required in the analytical predictions of long-term fretting wear of SG tubes [2].
3. Characterization of the fretting scar texture and geometry. This data is needed for machining artificial fretting scars for fatigue and leakage testing [3].

An automated surface scanning and analysis system has been developed at the Fretting Laboratory, Ontario Hydro Technologies, to determine the maximum depth and volume of the wear scar. In order to handle U-bend sections, the analysis accounts for the unknown curvature of the U-bend tube sample and the ovality of the tube cross section. A description of the measurement system and the formulation of the analysis are presented in the paper. An error analysis for the effect of the measurement uncertainties is also given. Three-dimensional maps of the topography of fretted samples are presented and discussed.

2. DESCRIPTION OF THE SURFACE MEASUREMENT AND ANALYSIS SYSTEM

A general purpose stylus-type surface roughness profilometer has been modified to scan and measure the depth and volume of the fretting wear scar on straight tube sections. The modifications included the following two items:

1- Automation of the surface scanning process, using programmable linear and rotary tables.
2- Incorporation of a data acquisition and analysis system, which provides three-dimensional maps of the surface topography, and numerical assessment of its parameters, e.g., maximum depth, wear volume, and other statistical values; the probability density function, cumulative probability function, autocorrelation function, power spectrum and structure function [4].

To obtain the true shape of the fret marks on U-bend tube sections, the analysis module of this system has been modified to account for:

i- the curvature of the U-bend tube, which causes the center of rotation of the drive of the rotary table not to coincide with the center line of the tube specimen.

ii- the fact that the cross section of the tube is elliptical and not perfectly circular.
iii- the radius of curvature of the U-bend is unknown.

A schematic diagram and a close-up view of the Surface Topography Scanning and Analysis System ST-SAS are shown in Figs. 1 and 2, respectively. The basic unit of the surface roughness profilometer consists of a stand (1), a linear drive unit (2), and a pick-up (3). The conventional roughness measurement stylus is replaced by a linear variable differential transformer (LVDT) probe (4), which has an extended measurement range of ± 1 mm. The maximum linearity deviation is ± 0.8 %, and the measuring force is < 0.1 N. Horizontal and vertical magnification can be as high as 500 and 10^5, respectively.

To map the worn surface of the tube, discrete data points $z\{x,\theta\}$ of asperity heights of the fretting wear scar are obtained at sampling positions arranged in a uniform grid. In the present set up, the LVDT probe is held motionless while the x-table, on which the tube sample (5) is attached, moves in the axial direction by a stepping motor (Δx =100-200 μm) to obtain a linear trace. For detailed analysis of some areas of the fretting scars, an increment as small as Δx = 3 μm can be obtained. The tube specimen is then rotated around the x-axis with an incremental angle as small as $\Delta\theta$= 0.25°. A PC (6) is used to synchronize the movement of the stepping motor-driven tables and to perform the data analysis. The controller (9) of the stepping motors is shown in Fig. 1.

The amplified signal from the pick-up is fed to a signal-conditioning unit for filtration, and demodulation. Following the A/D conversion, the digitized raw data are stored as an array. The data reduction and analysis module of the ST-SAS performs the following functions: *de-trending* the surface profile data to remove the effect of tube curvature, *calculating* the maximum wear depth and wear volume using the unworn surface as a datum, and providing three-dimensional *graphical presentation* of the scar surface. Other parameters that can be estimated from the analysis include the probability density function, cumulative probability function, autocorrelation function, power spectrum and structure function.

To minimize the measurement errors and to reduce the set up time and cost, a special fixture was designed to provide the analysis program with accurate and repeatable input data and to allow a direct drive of the U-bend specimen (Fig. 2). The figure also shows the x-table, the rotary θ-table, the special fixture designed to for clamping and indexing the tube sample.

3. MATHEMATICAL APPROACH FOR DE-TRENDING CURVILINEAR TUBE SURFACES

3.1 Formulation

The mathematical basis for de-trending a curvilinear surface is based on the theory of analytical geometry, provided that the geometry of the object in question is well defined. Therefore, the following assumptions are made:

1. The section of the boiler tube to be measured is part of, or can be closely approximated by, an arc of a circular tube.
2. The cross section of the tube is an ellipse and the radii are constant through the section to be measured.

The cross-section of a boiler tube is nominally circular. However, when the tube is bent at the U-bend, its cross-section is deformed into an elliptical shape. Since each sample is just a small section of the U-bend, which has a rather large curvature, the first two assumptions are justifiable.

Radius of the U-bend Circular Arc From the first assumption, one can determine the inside radius of the circular U-bend by knowing the co-ordinates of three points on the inner surface of the U-bend. Let A, B, and C be the three points with co-ordinates (a_1, a_2, a_3), (b_1, b_2, b_3), and (c_1, c_2, c_3), respectively. Without lost of generality, we assume that the z co-ordinate is constant, i.e., $a_2 = b_2 = c_2 = 0$. Let L_1 and L_2 represent lines perpendicular to and passing through the mid-points of the lines $\overline{AB}$ and $\overline{BC}$, respectively. The lines L_1 and L_2 are defined by the equations

$$\mathrm{L}_1\text{: } z = m_2 + \frac{x - m_1}{s_1} \quad \text{and} \quad \mathrm{L}_2\text{: } z = p_3 + \frac{x - p_1}{s_3} \tag{1}$$

where $m_1 = \dfrac{a_1 + b_1}{2}$, $m_3 = \dfrac{a_3 + b_3}{2}$, $p_1 = \dfrac{b_1 + c_1}{2}$, $p_3 = \dfrac{\beta_3 + \gamma_3}{2}$, $s_1 = \dfrac{b_3 - a_3}{b_1 - a_1}$ and $s_3 = \dfrac{c_3 - b_3}{c_1 - b_1}$

As long as A, B, and C are not collinear, L_1 and L_2 will intersect at point K whose co-ordinates are:

$$k_1 = \frac{-p_2 + m_3 + \dfrac{m_1}{s_1} - \dfrac{p_1}{s_3}}{\dfrac{1}{s_1} - \dfrac{1}{s_3}} \quad \text{and} \quad k_3 = m_3 - \frac{k_1 - m_1}{s_3} \tag{2}$$

The distance $|AK|$ between A and K is the sought-for radius R:

$$R = \sqrt{(a_1 - k_1)^2 + (a_3 - k_3)^2} \tag{3}$$

To improve the estimate of R, the problem can be made over-determined by choosing a larger number of points, $n > 3$, to statistically determine the most likely value of R.

Equation of the curvilinear U-bend tube surface

With the centre at the origin, the equation for the cross section of the tube is:

$$\frac{z^2}{r_1^2} + \frac{y^2}{r_2^2} = 1 \tag{4}$$

where r_1 and r_2 are the radii of the ellipse. The equation of the ellipse with its center at (y_a, z_a) is given by:

$$\frac{(z-z_a)^2}{r_1^2}+\frac{(y-y_a)^2}{r_2^2}=1 \tag{5}$$

In the set up of the apparatus, the specimen travels along the x-axis with respect to the probe. At the initial position, the width and the height of the tube are defined as the y-axis and the z-axis, respectively. This means that y co-ordinate of probe is always equal to 0. Let us define that the centre of the U-bend section, (x_0, y_0, z_0), initially lies on the plane that is parallel to the xz-plane and passing through y_0. At a given value of y, the plane that is parallel to the xz-plane and passing through the y-axis at y, will intersect the surface of the tube in two circular arcs with radii (see Figure 3):

$$\left(R+r_2+r_2\sqrt{1-\frac{(y-y_0)^2}{r_1^2}}\right),\ \text{and}\ \left(R+r_2-r_2\sqrt{1-\frac{(y-y_0)^2}{r_1^2}}\right) \tag{6}$$

Clearly, if $|\,y-y_o\,|>r_2$, then the plane and the tube do not intersect. Now, one can derive an equation for the curvilinear surface of the tube, at the initial position:

$$(z-z_0)^2+(x-x_0)^2=\left(R+r_2\pm r_2\sqrt{1-\frac{(y-y_0)^2}{r_1^2}}\right)^2 \tag{7}$$

Since the U-bend tube rotates around the x-axis with a clockwise rotational angle θ, the transformation of the co-ordinates of a point (x_1, y_1, z_1) to the new co-ordinates (x_2, y_2, z_2) is given by the following matrix notation (Fig.4):

$$\begin{bmatrix}x_2\\y_2\\z_2\end{bmatrix}=\begin{bmatrix}1&0&0\\0&\cos\theta&\sin\theta\\0&-\sin\theta&\cos\theta\end{bmatrix}\begin{bmatrix}x_1\\y_1\\z_1\end{bmatrix} \tag{8}$$

Note that the co-ordinate of x does not change, i.e., $x_1=x_2$. Conversely, if (x, y, z) is the co-ordinates of a point after the rotation, the co-ordinates of this point before rotation are given by

$$\begin{bmatrix}x_1\\y_1\\z_1\end{bmatrix}=\begin{bmatrix}1&0&0\\0&\cos(-\theta)&\sin(-\theta)\\0&-\sin(-\theta)&\cos(-\theta)\end{bmatrix}\begin{bmatrix}x\\y\\z\end{bmatrix} \tag{9}$$

Now, if the point (x_1, y_1, z_1) is on the surface of the tube, it must satisfy the equation:

$$(z_1-z_0)^2+(x_1-x_0)^2=\left(R+r_2\pm r_2\sqrt{1-\frac{(y_1-y_0)^2}{r_1^2}}\right)^2 \tag{10}$$

The equation of the surface of the tube after rotation is therefore:

$$(y\cdot\sin(-\theta)+z\cdot\cos(-\theta)-z_0)^2+(x-x_0)^2=\left(R+r_2\pm r_2\sqrt{1-\frac{(y\cdot\cos(-\theta)-z\sin(-\theta)-y_0)^2}{r_1^2}}\right)^2 \quad (11)$$

Using the fact that sine function is an odd function and cosine function is an even function, one can simplify Eq. 11 into the following form:

$$(y\cdot\sin\theta+z\cdot\cos\theta-z_0)^2+(x-x_0)^2=\left(R+r_2\pm r_2\sqrt{1-\frac{(y\cdot\cos\theta-z\sin\theta-y_0)^2}{r_1^2}}\right)^2 \quad (12)$$

Measurement of the true shape of the fret mark

Since the y co-ordinate of the stylus is always zero, its position at each x location is the z co-ordinate of the surface. Therefore, for a given value of x, the functional relationship of x and z is given by:

$$(z\cdot\cos\theta-z_0)^2+(x-x_0)^2=\left(R+r_2\pm r_2\sqrt{1-\frac{(z\cdot\sin\theta+y_0)^2}{r_1^2}}\right)^2 \quad (13)$$

The above equation implies that we can express the position of the stylus as a function of x. Although this would be an implicit function, we can determine the position of the stylus by finding the roots of the following function:

$$f(z)=(z\cdot\cos\theta-z_0)^2+(x-x_0)^2-\left(R+r_2\pm r_2\sqrt{1-\frac{(z\cdot\sin\theta+y_0)^2}{r_1^2}}\right)^2 \quad (14)$$

In other words, for a given value of x, one can determine the value z_x when there is no fret mark in the tube. The position of the stylus is measured from a fixed z position, say Z_s, to the surface of the sample. If $Z_r(y)$ is the reading of the stylus at x position, then this reading becomes $Z_r(y) = Z_s - z_y$ when there is no fret mark on the sample. If the calculated value of z_x is added to $Z_r(y)$, then the value Z_s remains constant. With proper position of the rotation axis, the constant value Z_s can be set to zero. Therefore, any deviation from the constant (zero) will be the depth of the fret mark.

3.2 Error Analysis

Sources of Errors

There are three possible sources of errors in this approach:

1. The U-bend tube sample may deviate from an arc of a circle.
2. The cross-section of the tube deviates from an ellipse or a circle.

3. Measurement errors introduced by the surface roughness apparatus due to the radius of the tip of the stylus, and A/D signal processing [4].

The latter two sources of errors are relatively small. Examination of a large number of SG U-bend tubes indicated that their cross section could accurately be described by Eqs. 4 and 5. Also, by calibrating the profilometer, the measurement errors can be compensated for. This leaves the error introduced by the deviation of the U-bend section from a circular arc. Let us consider the most probable case when this error results in an error in R which occurs on the z-axis. The total differential of the function f when z is positive is:

$$df = \frac{\partial f}{\partial z}dz + \frac{\partial f}{\partial x_0}dx_0 + \frac{\partial f}{\partial y_0}dy_0 + \frac{\partial f}{\partial z_0}dz_0$$

Since $df = 0$, one can write,

$$dz = -\frac{(x - x_0)dx_0 + R_y dy_0 + (z \cdot \cos\theta - z_0)dz_0}{(z \cdot \cos\theta - z_0)\cos\theta - R_y \sin\theta} \tag{15}$$

where $R_y = \left(R + r_2 + \frac{r_2}{r_1}\sqrt{r_1^2 - (z \cdot \sin\theta + y_0)^2} \right) \frac{r_2(z \cdot \sin\theta + y_0)}{r_1\sqrt{r_1^2 - (z \cdot \sin\theta + y_0)^2}}$

The the error dz is bounded by:

$$|dz| \le \left| \frac{(x - x_0)dx_0 + R_y dy_0 + (z \cdot \cos\theta - z_0)dz_0}{(z \cdot \cos\theta - z_0)\cos\theta + R_y \sin\theta} \right| \tag{16}$$

<u>Minimization of the Errors Using a Lease-squared Method</u>

The error introduced by the uncertainty in profile of the U-bend section will produce a non-constant $Z_r(x)$. Hence, $Z_r(x) = \hat{z}_i + z_i$ becomes a function of y, where z_i is the measured value and $\hat{z}_i$ is the predicted value. Since this function is parabolic, it can be expressed as a second order polynomial:

$$Z_r(x) = \alpha x^2 + \beta x + \gamma \tag{17}$$

To estimate the parameters α, β, and γ, one needs at least 30 measurement points from the undamaged areas on either side of the fret mark. At each rotation of θ, let z_i, i = 1, 2,..., n, be the measurement of $Z_r(y)$. For n samples from the unmarked area, we can use least square fit method to estimate the parameters α, β, and γ.

$$\hat{\alpha} = \frac{c_{22}c_{1z} - c_{12}c_{2z}}{\Phi}, \quad \hat{\beta} = \frac{-c_{12}c_{1z} + c_{11}c_z}{\Phi}, \quad \hat{\gamma} = \bar{z} - \hat{\alpha}\bar{x} - \hat{\beta}\bar{x}_2 \tag{18}$$

where

$$\bar{x}_2 = \sum x_i^2 / n, \quad \bar{z} = \sum z_i / n, \quad \bar{x} = \sum x_i / n$$

$$c_{11} = \sum (x_i - \bar{x})^2, \; c_{22} = \sum (x_i^2 - \bar{x}_2)^2, c_{12} = \sum (x_i - \bar{x})(x_i^2 - \bar{x}_2)$$

$$c_{1z} = \sum (z_i - \bar{z})(x_i - \bar{x}), \; c_{2z} = \sum (z_i - \bar{z})(x_i^2 - \bar{x}_2), \; \Phi = c_{11}c_{22} - c_{12}^2$$

Let $\hat{\alpha}, \hat{\beta}$, and γ be the estimated parameters. Then, we defined

$$Z_s(x_i) = \hat{z}_i + z_i - \hat{\alpha} - \hat{\beta}x - \hat{\gamma}x^2 \tag{19}$$

The value of $Z_s(x)$ will be a constant and equal to zero, where $\hat{z}_i$ is the root of the function f, and z_i is the measured value, both at x_i. Figures 5.a and b show the fret scar measurement on a U-bend tube sample before and after de-trending, respectively. The sinusoidal variation in the raw data collected from the undamaged areas of the specimen is removed by the above described de-trending algorithm, resulting in a plane datum with $Z_s(x) \approx 0$.

4. RESULTS

Figures 5 and 6 show examples for three-dimensional maps of the fretting scars on U-bend specimens, in which the deviations of the U-bend profile from a true circle were pronounced. The figures show clearly the capability of the system to de-trend the multi-directional curvatures on the SG tube surface. For the scar shown in Fig. 5, the wear volume and the maximum wear depth are estimated to be 52.48 mm^3 and 321 μm, respectively. For the fret mark shown in Fig. 6, these values are estimated to be 19.70 mm^3 and 112 μm, respectively. It is also important to notice the high resolution of the mapping technique to identify the micro-irregularities and features of the topography of the fretted surface. This detailed information on surface of the scar reflects the nature of the wear mechanism, e.g., adhesion versus delamination.

5. CONCLUSIONS

An automated surface scanning and analysis system has been developed to determine the topography, the wear volume, and the maximum depth of the fretting scar on U-bend steam generator tubes. To define the true shape of the fret mark, an algorithm has been developed to account for the unknown curvature of the U-bend section and the ovality of the tube cross section. A description of the measurement system, the formulation of the analysis, and examples of the three-dimensional maps analysis of the topography of fretted samples were presented. An error analysis of the measurement uncertainties is also discussed, along with the procedure to be followed to minimize this source of error.

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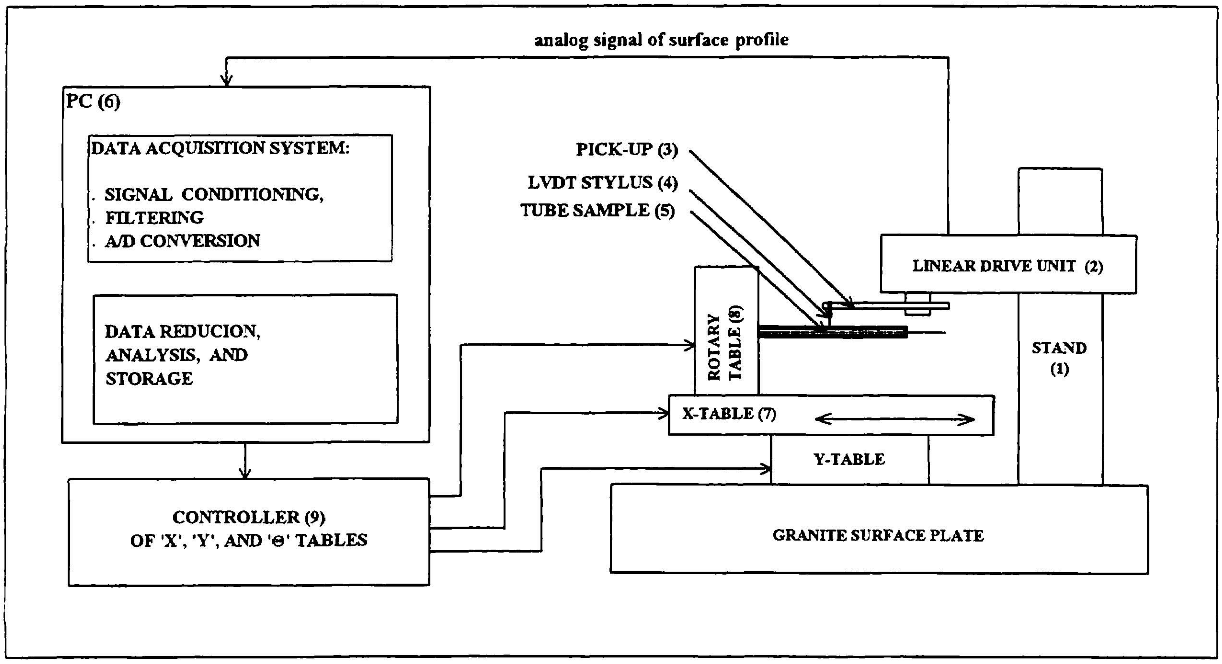

Fig. 1 A Schamatic diagram of the surface topography scanning and analysis system

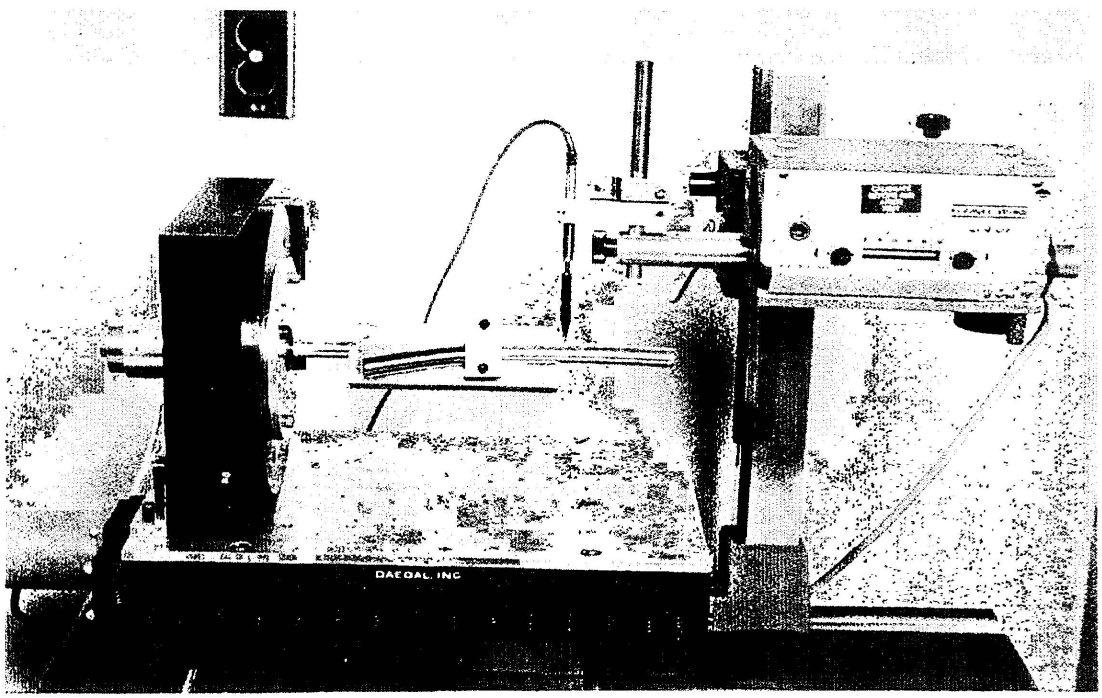

Fig. 2 A Close-up of the U-bend tube sample indexing and scanning mechanism

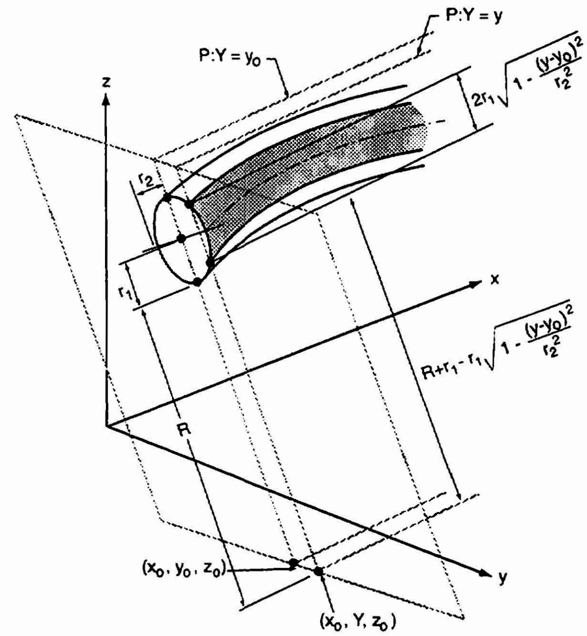

Fig. 3 The coordinate system used to define the curvilinear surface of a U-bend tube section

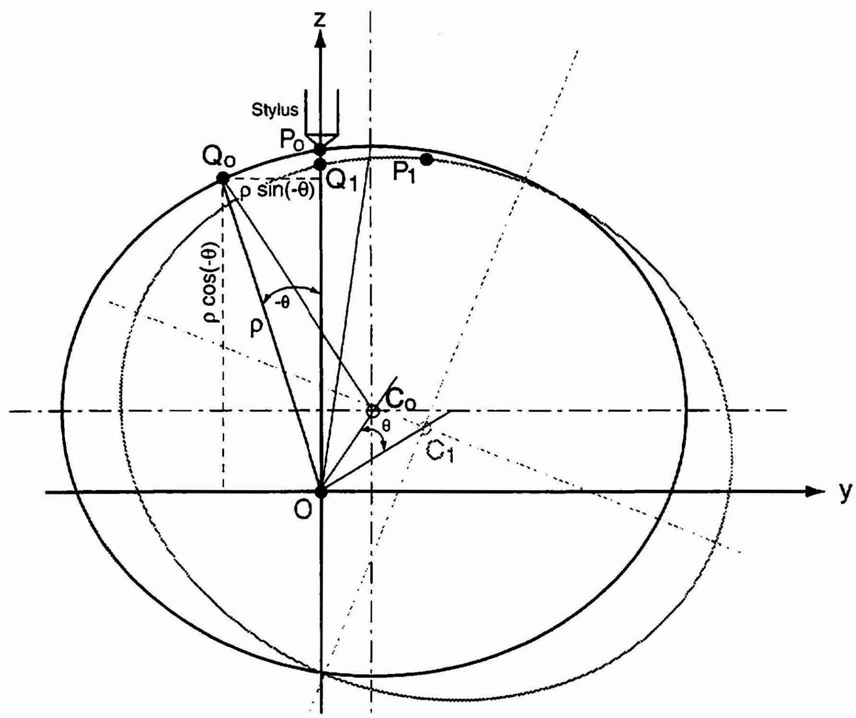

Fig. 4 Transformation of the coordinates of the measurement points with the rotation of the U-bend tube sample around the x-axis

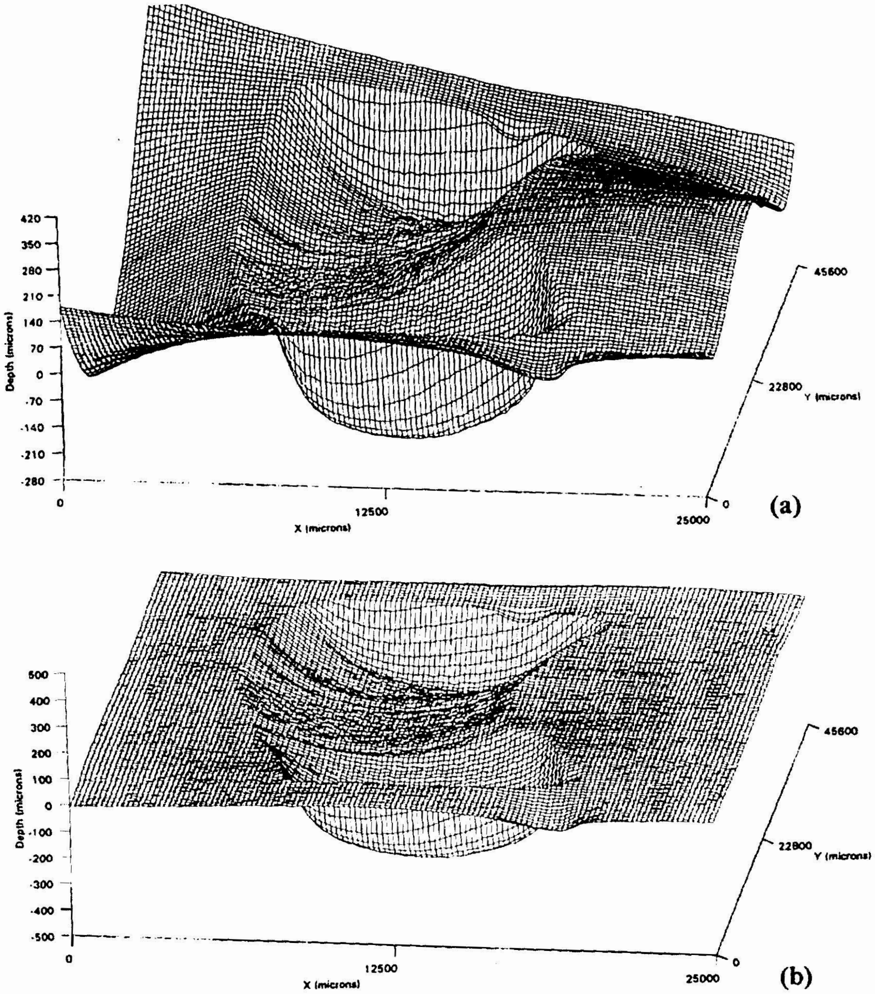

Fig. 5 A three-dimensional map of a fret scar on a U-bend tube:
(a) before, and
(b) after de-trending the curvilinear surface of the tube.

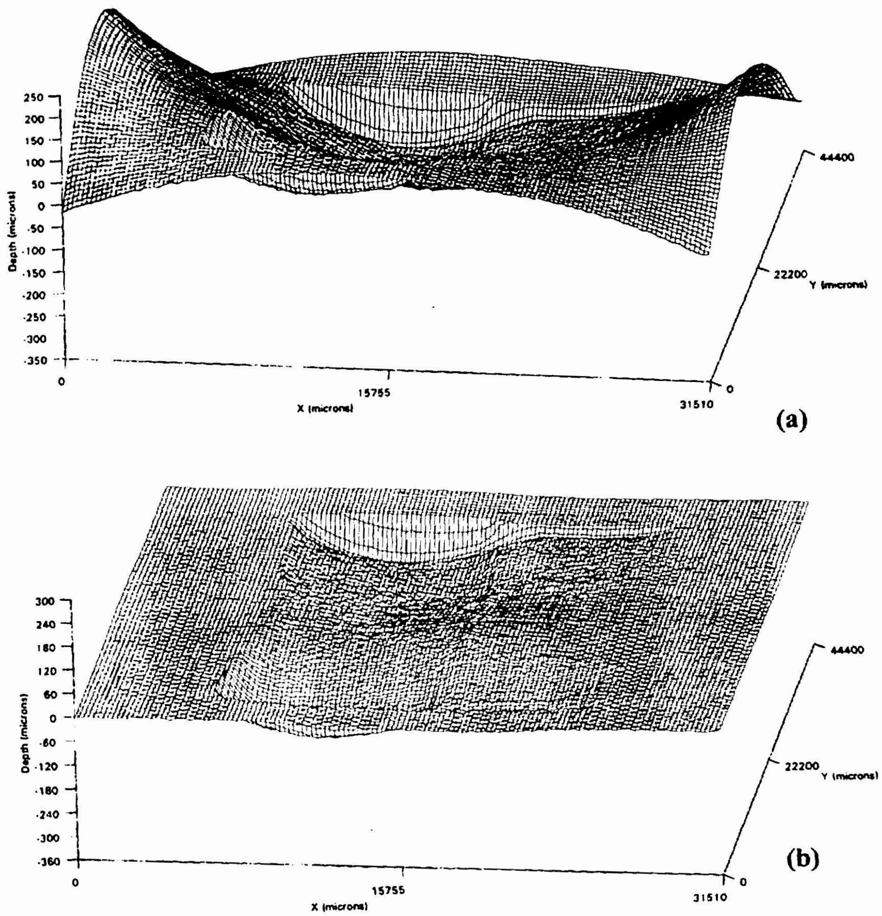

Fig. 6 A three-dimensional map of a fret scar on a U-bend tube:
(a) before, and
(b) after de-trending the curvilinear surface of the tube.