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Sensitivity analysis of full field methods for residual stress measurement

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Abstract

The hole drilling technique is a well known experimental method for residual stress investigation. This technique is usually used in combination with electrical strain gauges but there is no reason to enforce this choice and other approaches, in particular some full-field optical techniques, can be advantageously used. Since all these techniques give full field data, it becomes important to properly use this redundant information content to increase the robustness and reliability of the analysis.

In this work, various well known approaches to the hole drilling/full-field data analysis will be investigated using a two-step approach. In the first one, a sensitivity analysis will be performed on the simpler algorithms and then the reliability of the methods will be estimated by Montecarlo analysis using a known displacement field as a reference.

Keywords: Residual stress; Hole drilling; Noise sensitivity

1. Introduction

The hole drilling method is a well-known technique for residual stress analysis [1–7]. The "standard" version consists in measuring the strain components produced by drilling a flat-bottomed hole in the centre of a specifically designed strain gauge rosette. Strain gauges are extremely practical measuring devices, but the finite dimensions of the sensitive elements impose several limitations on their use. In fact, the acquired signal is obtained by integrating the strains over the strain gauge surface, whereas it is practically impossible to perform measurements in the vicinity of the hole edge (which is actually the region where deformation gradients are higher). Moreover, strain gauges are particularly sensitive to off-centre drilling errors [8].

Full-field optical measurement techniques (moiré interferometry, speckle interferometry, holographic interferometry and shearography) can overcome these limits as they are able to acquire the whole displacement (or strain) field along the sensitivity direction. The quantity of available data, which largely exceeds the required minimum number of three values, therefore poses the problem of their effective utilization to exploit the intrinsic redundancy of the data so as to reduce measurement errors.

Numerous approaches to solving this problem have been proposed in the literature, the most well-known being the measurement of three displacement components at a single point [9] (repeated, if necessary, in different points), measurement of a single component [10], Fourier analysis of the displacement field around a circumference [11] and the least squares fit of the displacement field [12].

In this work, we analyse the performance of the above techniques in terms of accuracy and robustness to noise, using known stress fields for the classical case of a thin plate with through-hole and constant stress [13–16]. For this purpose, we generated synthetic data fields which were then perturbed by adding various levels of noise. The resulting "experimental" data were then analysed using the different algorithms and their results compared with the expected values.

The final aim of the work is to determine the optimum combination of experimental technology and analytical methodology for measuring residual stress using optical methods.

2. Analysis of some full field algorithms

The number of unknowns to be determined in the residual stress problem is three (either σ_x, σ_y and τ_{xy} or σ_1,

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σ_2 and ϑ), so its solution simply requires knowing three experimental values. The algorithms described in the following differ in the quantities being measured and their numerical treatment; however all of them can be described using the same cylindrical reference system of Fig. 1. In this system, the displacement field can be written, in a somewhat simplified form, as [10]

$$u_r = A(\sigma_x + \sigma_y) + B[(\sigma_x - \sigma_y)\cos(2\vartheta) + 2\tau_{xy}\sin(2\vartheta)],$$

$$u_\vartheta = C[(\sigma_x - \sigma_y)\sin(2\vartheta) - 2\tau_{xy}\cos(2\vartheta)],$$

$$u_z = F(\sigma_x + \sigma_x) + G[(\sigma_x - \sigma_y)\cos(2\vartheta) + 2\tau_{xy}\sin(2\vartheta)], \quad (1)$$

where A…G are calibration coefficients depending on material properties, geometric configuration and point location only (note that the F parameter is zero in this case)

$$A = r_0/(2E)(1+\nu)\rho, \quad B = r_0/(2E)[4\rho - (1+\nu)\rho^3],$$

$$C = r_0/(2E)[2(1+\nu)\rho + (1+\nu)\rho^2]\, G = (\nu t/E)\rho^2,$$

where E is the Young module and $\rho = r/r_0$ is the normalized distance, ratio of the distance r from the centre of the hole and the hole radius r_0.

The following points should be noted:

- Whatever solution algorithm is adopted, it should (directly or indirectly) use the radial component. In fact, by simple algebra, or considering the Mohr circle, it is easy to show that if there is no radial component in the experimental field (e.g. it uses a pure out-of-plane-sensitivity data acquisition system), it is impossible to determine the stress components, as the displacements depend on the size of the Mohr circle but not on its position.
- Apart from the specialized optical configuration described in [17], it is not possible to directly measure the radial strains/displacements. Thus these quantities have to be estimated by combining two (or three) acquisitions using different sensitivity vectors.

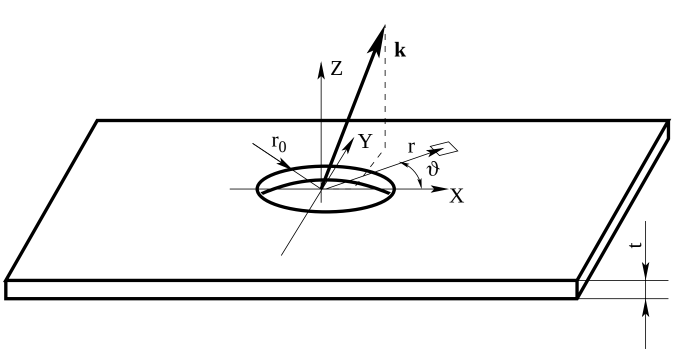

Fig. 1. Reference configuration for hole drilling system. A cylindrical reference system is used, with the Z axis coincident with the hole axis.

2.1. Nelson and McCrickerd algorithm (1986)

In 1986 Nelson and McCrickerd proposed using holographic interferometry to overcome certain limitations inherent in strain gauges and grating interferometry [18].

Eq. (1) shows that radial deformation is the same for points symmetrically located with respect to (WRT) the hole centre. This makes it possible to determine radial displacement in a simple way. In fact, the relation between phase and displacement can be written, in the case of holographic interferometry, as [10]

$$\phi = \mathbf{k} \cdot \mathbf{u} = k_x u_x + k_y u_y + k_z u_z, \quad (2)$$

where $\mathbf{k}$, the sensitivity vector, depends on the illumination vector $\mathbf{k_1}$ and the observation vector $\mathbf{k_2}$: $\mathbf{k} = \mathbf{k_2} - \mathbf{k_1}$, where $|\mathbf{k_1}| = |\mathbf{k_2}| = 2\pi/\lambda$, λ being the wavelength of the laser source.

Denoting with γ and ζ the angles between the illumination vector and the X–Y plane and X axis, respectively (Fig. 2), and with α and η the corresponding quantities for the observation vector, it is easy to show that $\mathbf{k_1}$ and $\mathbf{k_2}$ can be written as (note that $\mathbf{k_2}$ depends on the point considered, while $\mathbf{k_1}$ remains constant, provided the illumination beam is collimated)

$$\mathbf{k_1} = -\frac{2\pi}{\lambda}\begin{Bmatrix}\cos\gamma\cos\zeta\\ \cos\gamma\sin\zeta\\ \sin\gamma\end{Bmatrix}, \quad \mathbf{k_2} = -\frac{2\pi}{\lambda}\begin{Bmatrix}-\sin\alpha\cos\eta\\ -\sin\alpha\sin\eta\\ \cos\alpha\end{Bmatrix}, \quad (3)$$

where $\alpha = \arctan(r/z_0)$, z_0 being the z component of the distance between the hole centre and the observation point.

Using (3) the sensitivity vector can be written as

$$\mathbf{k} = \mathbf{k_2} - \mathbf{k_1} = -\frac{2\pi}{\lambda}\begin{Bmatrix}\cos\gamma\cos\zeta - \sin\alpha\cos\eta\\ \cos\gamma\sin\zeta - \sin\alpha\sin\eta\\ \sin\gamma - \cos\alpha\end{Bmatrix}, \quad (4)$$

which can be considered almost constant if the observation point lies at some distance from the X–Y plane.

As is well known the interference fringe field is sensitive to displacements in the sensitivity vector direction, so, in this case, both the in-plane and out-of-plane displacements contribute to its creation. To solve this problem the authors suggest subtracting the phase data for two symmetrical points WRT the hole centre. In fact, the out-of-plane component is the same in these two points (so their contribution is nullified when the phase values are subtracted), whereas the radial components are opposed (so they sum together).

Once the procedure for determining the radial displacement u_r is known, this quantity can be evaluated in three different directions ϑ, $\vartheta + \pi/4$ and $\vartheta + \pi/2$, where ϑ, the angle between the principal directions and the first acquisition direction, is not yet known. In this way the radial strain for each direction can also be calculated by forward differences using the displacement in two neighbouring points A and B located along a radius: