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Automation of Moiré method Using Methods of Image Processing

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One of the experimental strain analysis methods is the moiré method. Its automation using methods of processing of digital image of interference patterns is presented in this paper.

1 Introduction

The phenomenon of moiré fringes forming was first described by Lord Rayleigh in 1874. Then scientists dealt extensively with the distribution of light in figures formed by the superposed bars. Finally, the creation of moiré fringe patterns by parallel line gratings and their application to the measurement of the relative displacement of gratings was treated.

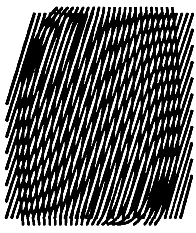

Figure 1: Example of moiré pattern

Moiré fringes can be produced by using two slit-and-bar gratings. If two gratings of approx. equal frequency are superposed, sharp moiré fringes will be observed (see Fig. 1).

The behaviour of two superposed gratings provides *highly sensitive* means of measuring linear and angular displacements or expansion of gratings. Therefore, the phenomenon of formation of moiré fringes from irregularities of specimen grating due to its deformation is extensively used in a variety of ways for the measurement of displacement in plane stress and plane strain problems [Theo69].

2 Principle of Experimental Moiré Method

Moiré fringes are the loci of equal relative displacement in the principal directions of the gratings.

Keeping this fundamental in mind let us consider the plane problem being solved by the use the moiré method in the Cartesian coordinate system. On the basis of the mechanical interference of the non-deformed reference grating (RG) and the deformed specimen grating (SG) we obtain the array of moiré fringes. Recall that the medial axis of fringes[1] are the geometrical points ofthe equal relative displacement component perpendicular to the reference grating. Values of displacement at points of two neighbouring medial axes differ just by the pitch p of the reference grating.

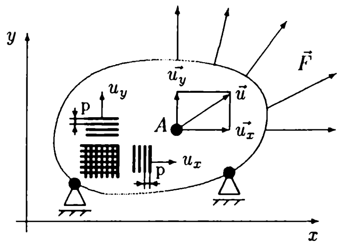

Figure 2: Displacement components

An arbitrary point $A[x_A, y_A]$ on the specimen surface is moved to its new position, because of deformation. This movement is expressed by the displacement $\vec{u} = \vec{u_x} + \vec{u_y}$, where $\vec{u_x}$ and $\vec{u_y}$ are components of the displacement (see Fig. 2). The directions of displacement components are determined by the reference grating orientation and the absolute values of displacement components which are the functions of independent variables x and y, so $u_x = u_x(x, y)$ and $u_y = u_y(x, y)$ can be imagined as three-dimensional surfaces over the observed region. Then the medial axes of moiré fringes $u_x = u_y = kp$ are the contour lines of these surfaces and the moiré patterns are the contour maps of the functions u_x and u_y. The parameter $k = 0, 1, 2, \ldots, n$ is the order of fringe and it characterizes each fringe. The order $k = 0$ can be given to any fringe since we consider only the relative displacement (i.e. for the computation of the strain we use only the partial differentiates of displacement components).

Let us assume the case when the reference grating is perpendicular to the x-axis of the coordinate system. Then from Fig. 3 it is clearly seen how to obtain the displacement curves $u_x(x, y_A)$ and $u_x(x_A, y)$. *Normal strain* and the component of *shear strain* in the considered point $A[x_A, y_A]$ are represented by slopes of appropriate displacement curves. It could be mathematically expressed as:

$$\varepsilon_x = \tan \alpha_x \qquad \text{and} \qquad \gamma_{yy} = \tan \alpha_y \tag{1}$$

[1] the curves that approximate the centres of bright or dark fringes

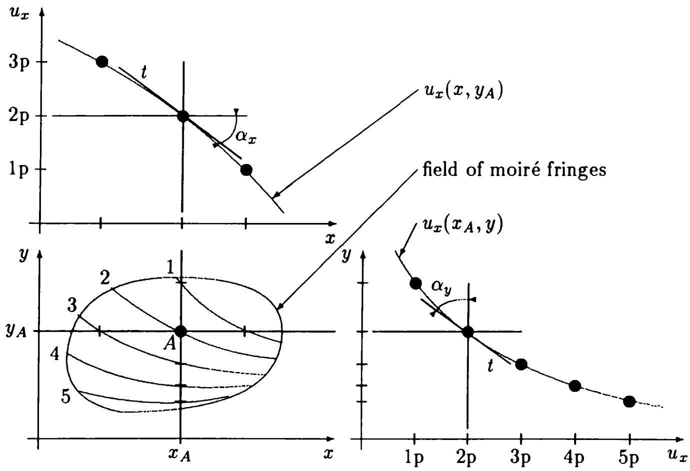

Figure 3: Displacement curves and strain components

In the second case, when the second image of moiré pattern is used and where reference grating is perpendicular to the y–axis of the coordinate system, we analogically obtain $u_y(x, y_A)$ and $u_y(x_A, y)$ displacement curves. From these curves values of ε_y and γ_{xx} are determined. So, a differentiation of four displacement curves yields the four components of strain ε_x, γ_{yy}, ε_y and γ_{xx} from which the normal and shear Cartesian strain components are evaluated. The shear strain component γ_{xy} is found by the algebraic addition of the terms γ_{xx} and γ_{yy}. The discussion above leads to the fact that we are able to get all the required values graphically or analytically by the interpolation of displacement curves and then their deriving.

3 Automation of Moiré Method

The original procedure of the determination of strain and then the computation of stress at desired points of the observed region of the specimen, using the images of moiré fringes, consists of several steps: taking a snap of the moiré pattern produced by superposing of SG with RG, developing the film (including the enlarging the image), and finally the boring and time–consuming manual graphical or numerical determination of all necessary partial differentiates of displacement components at all required points.

Moreover, the strain analysis requires the precise recording of the medial axis of each moiré fringe. This is not an easy task because the edges of moiré fringes are not clearly defined. Therefore this procedure is extremely laborious and reduces the precision of obtained results. In addition we must consider the human factor of making mistakes.

The automation of moiré analysis has been developed to avoid all disadvantages of manual processing. The automation includes the automatic scanning of the moiré pattern image, image data saving and finally the processing of these data. This way leads to more accurate analysis and it speeds of the whole procedure up. This report describes[2] only the final part of the above mentioned chain of the automation – i.e. the **image data processing** (including the image enhancement and thinning of moiré fringes) and then the **strain determination** and the **stress computation.** It means the first part of automatized process that has to be done before images of moiré fringes are stored in the computer external memory is not considered here; the starting point is a number of computer files concerning all the data required for the plane strain problem solving.

3.1 Possibility of Further Automation

My work considers only the case when TV camera directly records the images of moiré patterns. But there is another way based on the recording of deformed specimen grating only; the image of reference grating of appropriate pitch is generated and then the moiré pattern is formed from generated and scanned gratings by the computer.

But when considering the Shannon's theorem, we find that for snapping the specimen grating with a small pitch we should have a TV camera with, in present days, impossible distinguishing capability.

4 Moiré Pattern Processing

In the *preprocessing* of images of moiré patterns, the goal is to accentuate the moiré fringes to be clearly separable from the gray background of the image. Sometimes an additional manual image *editing* has to be done. Then the *binarization* and *segmentation*[3] of moiré fringes is performed. The final and the most expensive procedure is the *thinning*[4] of separated moiré fringes – a modification of the Stover-Iverson algorithm [Stov86] is implemented. A set of eight masks (see Fig. 4) with two appendices is used for thinning. A trimming[5] phase with a set of conventional trimming masks has to follow.

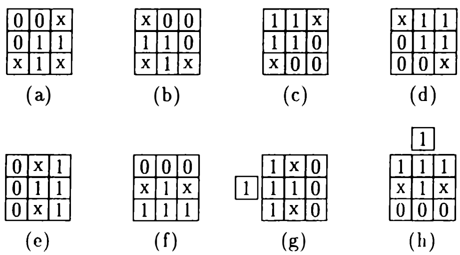

Figure 4: Moiré Fringes Thinning Masks (x's are don't cares)

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[2]and the software package implements

[3]separation

[4]known also as skeletonization

[5]prunning

5 Main Algorithm

1. **Image processing**
   - *for both images, for $x-$ and y-direction, of moiré patterns do*

   (a) image preprocessing
      - *including* filtering, thresholding, equalization, editing, etc.

   (b) determination of medial axis of all moiré fringes
      - fringes finding (binarization and segmentation)
      - fringes thinning (skeletonization)

2. **Strain components determination** *at the point* $A[x_A, y_A]$

   To obtain ε_x strain component use x–direction image of centre lines and make a cut going through point A and parallel with x–axis ($y = y_A$) and then construct the displacement curve $u_x(x, y_A)$:

   (a) determine u_x values at intercepts B_i of the cut $y = y_A$ with center lines

   (b) obtained values interpolate by cubic polynom

   (c) determine normal strain component $\varepsilon_x = \partial u_x/\partial x \doteq \Delta u_x/\Delta x = \tan \alpha_x$

   Repeat this procedure for the cut going through point A parallel with y–axis ($x = x_A$) to obtain the displacement curve $u_x(x_A, y)$. Then determine the γ_{yy} component of shear strain γ_{xy}. $\gamma_{yy} = \partial u_x/\partial y \doteq \Delta u_x/\Delta y = \tan \alpha_y$

   Both preceding steps repeat for y-direction image of centre lines. Obtain $u_y(x, y_A)$ and $u_y(x_A, y)$ displacement curves and determine ε_y and γ_{xx}.

   Generally we can write:

   $$sc = \frac{f(i+\Delta) - f(i)}{\Delta} \tag{2}$$

where	sc	means strain component,
	i	represents point A,
	Δ	is increment and
	$f(x)$	is value displacement curve.

3. **Stress components computation**

   All formulae necessary for the evaluation of stress components from determined strain components and additional general data such as stress–strain diagram can be found in [Plan95].

6 Evaluation of Moiré Method

One of the main advantages of moiré method is that it is able to determine directly strain distributions from purely geometric relationship derived from the interference of the specimen and reference gratings without depending on additional measurements of intermediate physical properties of the material.

Another advantage of the moiré techniques, which must not be underestimated, is the flexibility of the methods to determine changes in strain from small elastic deformations to very large plastic deformations with the same means and with almost the same accuracy.

And all moiré techniques are simple and easy to apply. Except the general data only *two* images of moiré patterns after each loading step are sufficient for a complete and accurate evaluation of strain distribution over the considered field. This sufficiency of two images is independent to the state of stress and strain in which the specimen is subjected.

But sometimes we need to use the sensitivity increasing techniques of the moiré method, such as mishmash methods and fringe shifting methods to obtain a sufficient number of fringes.

7 Conclusion

The image processing technique has opened the new possibility of the automation of the moiré strain analysis and the stress determination both in elastic and elastic–plastic states. The computer eliminates the human inaccuracy and allows the solution of the full field problems. Hence more precise results are obtained and the whole procedure is notably accelerated.

Acknowledgement

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