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Numerical Analysis of Fringe Patterns for Structural Engineering Problems

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ABSTRACT

Different software codes useful in fringe pattern analysis are described. The problems of achieving, digitizing and analysing are briefly discussed with reference to a new software code, completely written in our laboratories. Some applications of numerical processing to holographic interferometric fringe patterns are described.

2. INTRODUCTION

Many computer image processing techniques have been developed, exploited or applied only in the last twenty years [1,2]. The modern advancement in this area is mainly due to the recent availability of computer image scanning and display hardware at reasonable cost. However, certain economical computer processing techniques have also contributed to this development. For example, the application of the Fast Fourier Transform algorithm to numerical analysis has made an inmportant contribution to the enhancement and restoration of different images. In this paper only two of the classical topics of Computer Image Analysis are taken into account: enhancement and three-dimensional reconstruction. The technique used here for the three-dimensional reconstruction of objects from two dimensional pictures exploits fringe pattern systems which represent displacements of the objects examined. In particular, both holographic interferometric or moire' fringe patterns are considered.

In the past, holographic interferometry has been widely used for the analysis and validation of many structural components. Recently, digital image processing systems have been used to analyse experimental fringe patterns, and the broad possibilities of numerical calculus in this field have been discussed. The usefulness of exploiting the high precision and sensitivity of optical interferometric methods in conjunction with the high speed of computer analysis has been highlighted.

In previous papers [3,4] one of the authors described the use of a computer system to achieve and enhance fringe patterns. Generally, fringe patterns represent holographic interferometric displacements on mechanical models, such as reinforced circular discs [4]. In this case two different software codes were used, the first allowing the image analysis of fringe patterns picture and the second giving, by means of a semi-automatic procedure, the values of engineering parameters, such as stresses and strains, along different sections of the object.

This paper concerns the description of two different procedures adopted by our research team in the analysis of fringe patterns. The first is based on direct grabbing performed by an A/D conversion set-up running on a personal computer. The second is based on a new software code implemented on a Apollo or Silicon Graphics work-station. This new code, written completely in Fortran standard language, allows both the analysis and enhancement of fringe patterns.

3. DIRECT GRABBING SET-UP

The computer system used for analysing the fringe patterns consisted of a solid-state TV camera (Javelin Model JE-7242X) with 625 lines 50 field for viewing the reconstructed interferograms. Preliminary image processing and analysis was performed in the past, with an IBM/AT personal computer with 640 Kb memory and floating point processor. A real time video digitizer board (Oculus 200, manufactured by Coreco Inc.) was incorporated into the computer. This board can convert a standard (RS-170) television image into an array of 480x512 points (pixels) at a rate of 30 images per second and display it with the same resolution on an auxiliary monitor. The digitized image is written in 256 kbytes of on-board RAM memory (128 gray levels each pixel). The monitor is a TVM-125 with 1200 lines of resolution. The digital image system is shown in Fig. 1.

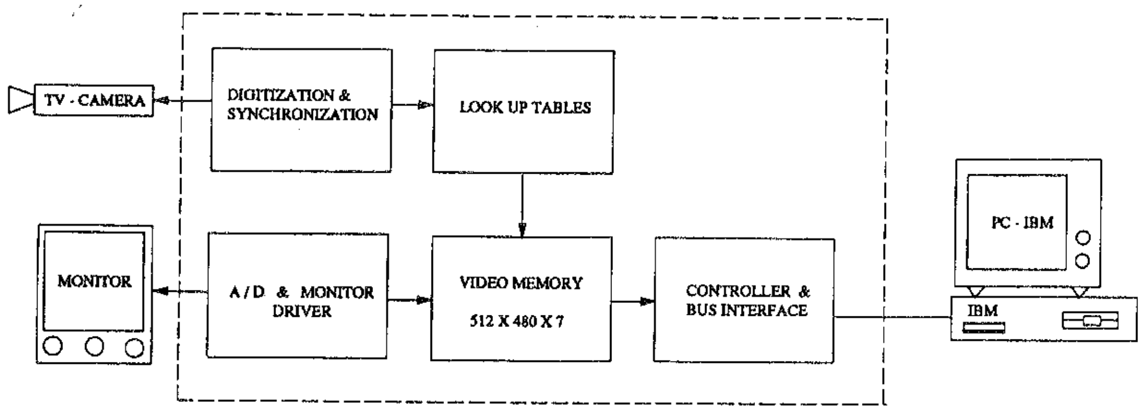


Fig. 1 Digital image apparatus

A commercial software code was then used to enhance and analyse the fringe patterns. This program allows digitization, enhancement, analysis, editing and several special processes on images. It has been used to grab interferograms, enhance fringes and obtain, by means of arithmetic functions, the moire' of fringe patterns.

A second code was set to calculate displacements and strains from interferograms and their moire'. These two codes were used in sequential fashion [3] along the lines suggested by

Templeton [6]. Figure 2 shows a flowchart of the different functions performed by the second program.

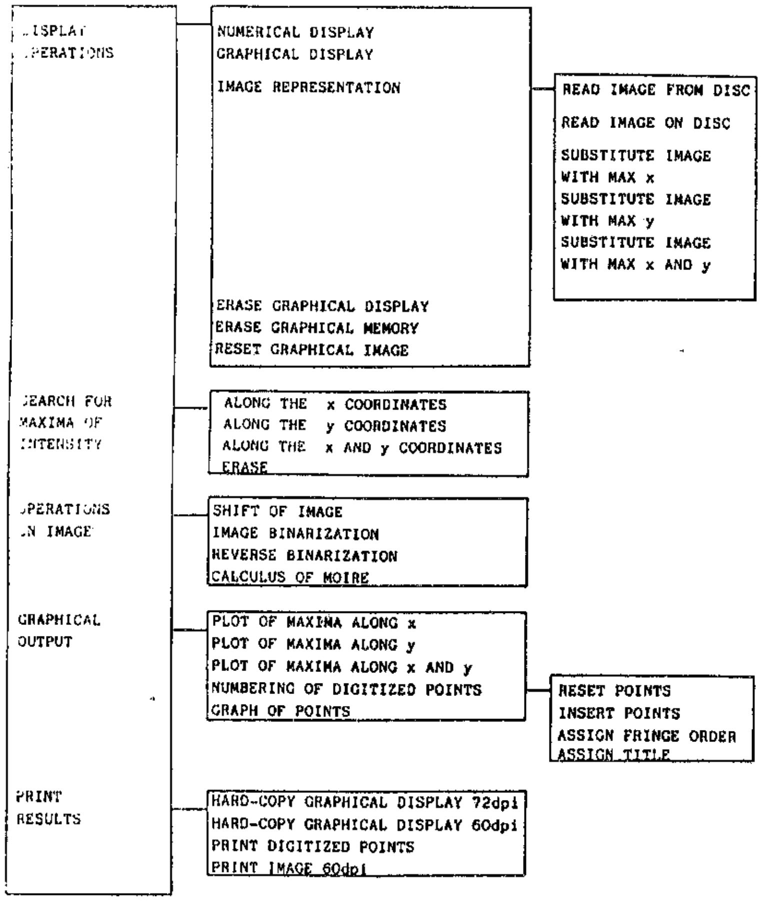


Fig. 2 Functions flowchart - 2nd software code

4. DIGITAL CONVERSION PROBLEMS

The fringe patterns were converted, by TV camera or by digitization of a picture, into numerical arrays. At this point the following problems arose:

a) recognition of the single fringe;
b) determination of the centre of single fringes;
c) determination of the fringe of zero order;
d) calculation of displacements from fringe values;
e) the obtaining of stresses and strains;
f) the obtaining of a three dimensional representation of both the object and the different parameters.

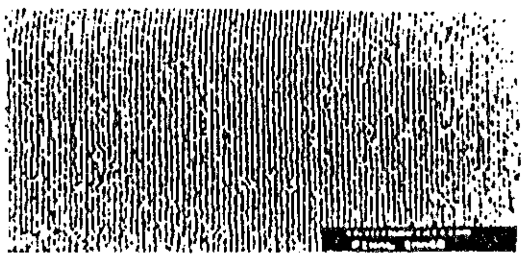
First of all it is necessary to analyse the whole image and note the variation of the average gray level in the different picture areas.
The first step then consists of sharpening fringe patterns using different algorithms, in particular the variation of the look-up table, using either a linear or non-linear variation.
By means of the second program the centre of the fringes was found using different approaches. For example, it was set up taking into account, for each fringe, maximum values of gray levels along both the x and y coordinates. Trivial points between and inside fringes were eliminated.
The carrier fringe technique was used to remove the sign ambiguity which is always present in interferometric fringe patterns. This method imposes monotonicity of phase change across the measurement field. Optically, the carrier fringe can be obtained by rotating either the object or the reference beam [7]. The same result can be achieved numerically: an array, having equal numerical values along columns and varying from a maximum to a minimum along rows, must be added to the array representing the image.

4.1 Moire' grating enhancement

Among the numerous applications of the first and second program codes, special mention must be made of the enhancement procedure used for phase gratings [8]. Gratings were achieved by means of a camera, and the pictures were not always clear and readable. To overcome these drawbacks a digital enhancement technique was used. The original images were read by means of the digital equipment previously described. The software codes were then used to enhance and analyse grating patterns.
A digital filtering technique was used here both to enhance and to analyse the grating pictures, taken by camera and microscope. A list of the processing steps and some representative pictures are reported below.

1 Grab the original image;
2 Histogram stretching;
3 High pass;
4 Convolution I: left-hand edge detection;
5 Convolution II: right-hand edge detection;
6 Binarization.

Original Image



Final Image

Figure 3. Example of image enhancement filtering

The first step allows the achievement of the grating. The second enables the program to define a look-up table that expands the narrow range of gray values of the image to the entire brightness range. In this case the range between 30 and 100 was expanded.
In some cases, the high pass filter (point 3) is very useful in obtaining a good quality grating and affects the binarization in this procedure. Since edges in gray-level are associated with high frequency components, image sharpening can be achieved by high pass filtering, which attenuates the low frequency components without disturbing high-frequency information in the Fourier Transform [1]. Steps 4 and 5 are the most important in the enhancement process. They consist of edge detection by means of a gradient operator [2]. Now the threshold for binarization can easily be obtained from the histogram of the new image. Finally, an image having only two gray-level values, in this case 0 and 127, is obtained.

5. NEW SOFTWARE CODE DIP

DIP is a software code completely written in Fortran standard language and working either on a 3550 Apollo or an IRIS (Silicon Graphics 4D35) work-station.
One of its main features is the automatic treatment of fringes, which is performed by reading fringe by fringe in sequential fashion and stoking the information about the pixels' position. The high power of the work-station allows the creation of data matrices where complementary information about single pixels is stored and this avoids nesting of a single byte for each pixel, which was necessary in previous programs [5].
A new feature is the spatial representation of displacement functions and their derivatives which gives either graphical or numerical values of engineering parameters over the whole model. To study deformations on structural models the procedure outlined below can now be followed:

1) Fringe patterns are grabbed by means of a digital board mounted on a PC computer.
2) The image file is sent, via Ethernet cable, to an work-station.
3) Enhancement and analysis of fringe pattern is performed.
4) Automatic calculus of engineering parameters is obtained.

Fig. 4 shows the main independent program blocks.
The peculiarity of this code is the implementation of some algorithms, specialized in the analysis of fringe patterns and their reconstruction of 3D images. Some applications on holographic-interferometric fringe patterns are shown below. Using these fringes, some difficulties typical of automatic analysis arise. The main difficulties come from light intensity, distance between fringes and noise.

In fig. 5 four particular areas of an holo-interferometric pattern are evidenced:

a) the first is an area without fringes where noise is dominant;
b) the second is an area where a very large fringe-line, whose centre is difficult to detect, is present;
c) the third is a very dark area full of noise where a very narrow fringe-line is present;
d) here a very sharp fringe-line is evidenced.

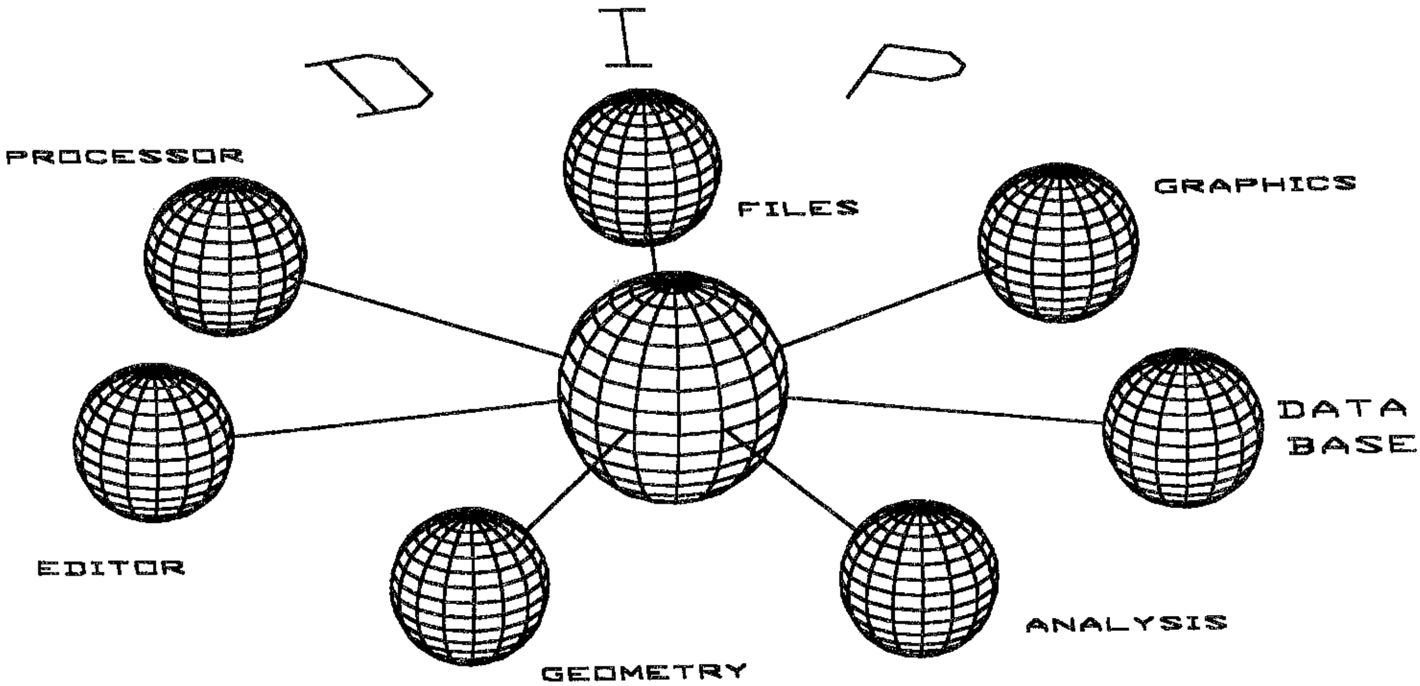


Fig. 4 Main blocks of DIP code

Light intensity on the surface can change radically because of local orientation with respect to the optical axis. Surfaces parallel to the optical axis are dark, while those perpendicular are very bright. It is thus necessary to use a suitable algorithm to read local light intensities. The distance between fringes and the precision of the reconstructed surface are limited by resolution of digitization. To achieve the maximum value from a sinusoidal curve, there must be a range of at least two pixels between fringes. This minimum information does not always exist and essential difficulties arise for a complete process automation. For this reason semiautomatic methods are used.

5.2 The semiautomatic approach

First of all the mathematical operators, typical of image processing, such as smoothing, convolution and filtering, were used, but the results were poor for a complete analysis of fringe patterns. An interactive algorithm, supervised by the man-operator, was set. With reference to areas no. 1 and 2 of fig. 5, the superviser can manually introduce some points by means of a specialized editor. For areas 4 and 5 he can indicate using the mouse-pointer the centre of fringes (i,j), one direction ALFA and a research span DEPTH. The program opens two separate windows to facilitate the operator's work: the first shows the whole image, while the second a zoom of the area near the mouse-pointer. The program works according to the points given below:

a.

Area without fringes

where noise is dominant.

b.

Area with large fringe-line

its centre is difficult to detect

c.

Very dark area with narrow

fringe and full of noise

d.

Area where a sharp fringe-

line is present

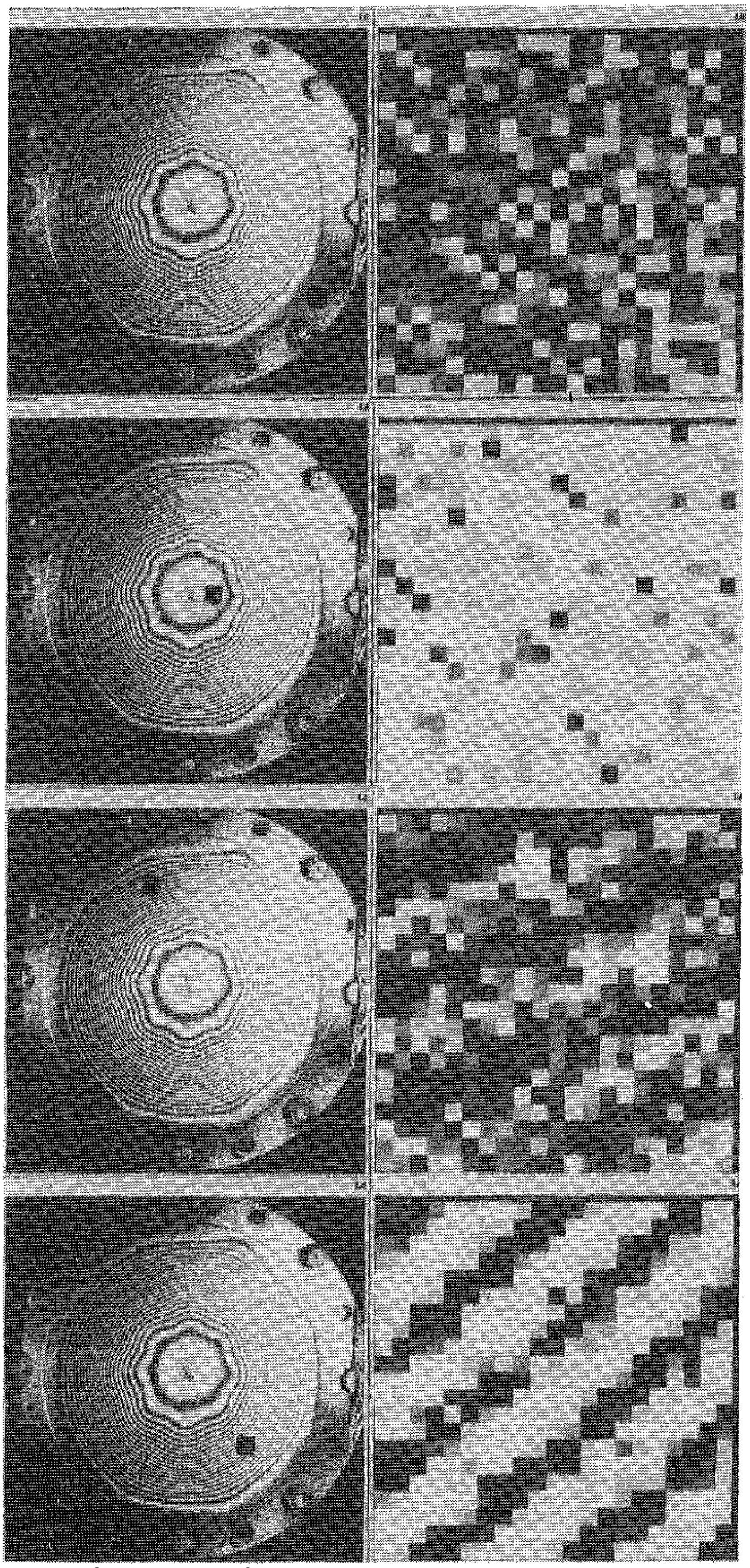


Fig. 5 Holographic interferometric fringe pattern

a. Given a point (i,j) and the search direction ALFA against the horizontal line, three different paths, ALFA, ALFA+45, ALFA-45, are taken into account.
b. For each direction and given span DEPTH, the weighted sum of light intensity is calculated. In fact, to give more importance to nearest points, light intensity is multiplied by a weight value function of the distance from the point (i,j). To avoid, or at least to limit, noise problems it is more efficient to assign to each point the mean intensity of the boundary points than to sum the light intensity of single points.
c. Having chosen the brightest path, both the search angle and point (i,j) are updated.
d. When the point is included in the point-array of fringes, the program stops.
e. If the light intensity of the chosen point is quite low, the DIP program asks the man-superviser for specific permission to go ahead. In the case of a positive answer the analysis goes to step a. Bright intensity is defined as too low when it is lower than the average intensity around the point plus the standard deviation.
f. When the algorithm cannot read one fringe-line, the superviser can stop the procedure. To obtain a complete 3D reconstruction, it is unnecessary to store the whole array of analyzed points. One function of mesh density allows us to choose from among those which are sufficient for spatial representation.

When the examined domain is not convex the editor can set the boundary points.

5.3 Triangular mesh representation

About the algorithm used in this paper, the following features can be pointed out:

1. It sets up a model by means of a triangular mesh, using the points of the array mentioned above as vertex points [9,10];
2. it performs a realistic representation of the surface [11,12].

Once the surface has been obtained it is very easy to calculate its derivative (either along x or y).

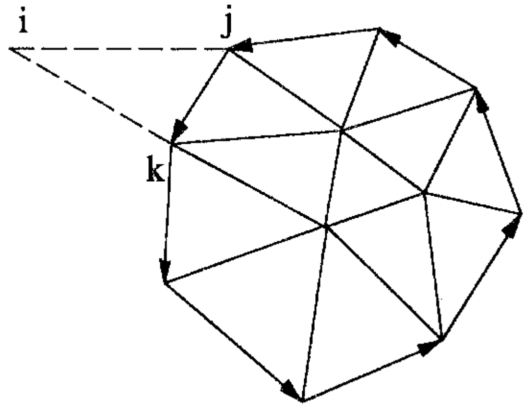
Consider a point-domain with coordinates x(i), y(i), z(i) where i=1,...N. We must look for, and graphically represent, a function f(x,y) which must agree with the interpolation condition

$$z(i) = f(x(i), y(i)) \qquad i = 1,.....N$$

$$(x(i), y(i)) = (x(j),y(j)) \text{ only for } i=j$$

The mesh is thus drawn according to the following points:

a. one coordinate system is chosen and the points of the domain are reordered according to the distance from the origin;
b. the first triangle is made by linking the first three unaligned points;
c. about the next points it is important to establish their position with respect to the mesh just drawn. This goal is achieved by means of the determinant (fig. 6) D which is positive only when i is in the right position. A counterclockwise condition for the vectors has been adopted.
d. The final step is to up-date the boundary conditions.
e. At last an optimization method, based on the minimum angle, is used.



$$D_{jk}(x,y) = \begin{vmatrix} X_j & Y_j & 1 \\ X_k & Y_k & 1 \\ X & Y & 1 \end{vmatrix}$$

Fig. 6 Mesh generation

5.4 Realistic representation

At present, two versions of the DIP code exist, one working on a 3550 Apollo workstation and the other on a Silicon graphics workstation. On this latter machine many graphic subroutines specialized in realistic representation are available and for them the only necessary data are the array of triangle vertexes. On the Apollo version, instead, these subroutines need to be set up. This is why this version of the program runs more slowly.
Realistic representation requires the presence of a light source and a knowledge of the optical properties of surfaces. With a light source very far from the object, light-rays can be assumed to be parallel, and the aspect of the surface depends on its physical properties and the orientation (angle) with reference to the rays' direction. The light intensity on a surface depends on the inner product between vector $\underline{n}$, perpendicular to the examined surface, and vector $\underline{l}$, parallel to the directionof the light. For a mirror's surface the brightness at each point is given by the fundamental law of reflectivity: the light is visible only from a specific direction. If we consider $\underline{e}$ as the observation vector and $\underline{l}$ as the illumination vector the amount of visible light is proportional to $(\underline{l} + \underline{e}) * \underline{n}$. This kind of reflection is known as specular reflection.
Indirect reflection calls for a different mathematical approach: light is equally reflected in each direction and the difference in brightness is due only to the different amount of incident light. For this reason indirect illumination is proportional to the inner product between $\underline{l}$ and $\underline{n}$. When the product is negative no reflection light exists. Only positive values must be taken into account. Now, considering I_s as specular reflection and I_i as indirect reflection, we have

$$I_s = \underline{e} * \underline{n} \qquad I_i = \underline{l} * \underline{n}$$

To obtain total illumination a weighted sum must be used. The formulation given below is very common:

$$I = m\, I_i + g\, I_s^k$$

where m is a coefficient proportional to opacity of surfaces while g is proportional to their luster, k is a constant roughly ranging from 0 to 10 (in our case it was 1-2). The practical application of these formulations requires the calculus of normal at each surface point. In the DIP program the Gouraud algorithm [11,12] can be summarized as follows:

1. in each vertex the normal is obtained by the average of normals in next triangles;
2. nodal intensity can be calculated with the above formula.
3. The illumination point inside the triangle is calculated by a linear interpolation between vertex values.

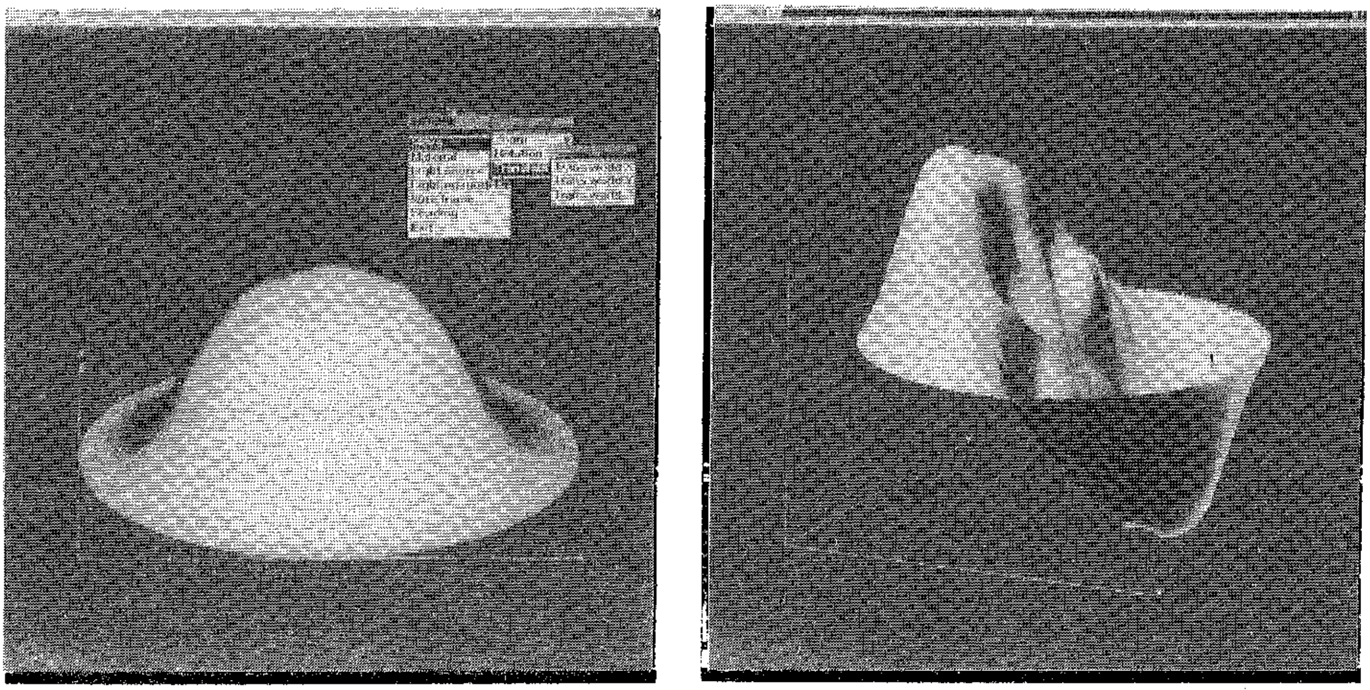
The problem of hidden lines has been solved with an algorithm Z-buffer: the triangle must be drawn starting from the farthest ones from the observer.

6. APPLICATIONS

All the above images were obtained by means of the DIP program running on the Silicon Graphics work-station. In this case the fringe pattern was recorded by a normal camera and was later digitized and transferred to the IRIS computer. All preliminary image enhancement has been done. The analysis of each image takes less than 10 minutes. Above fig. 5 shows the holo-interferometric fringe pattern of a reinforced disc-model loaded by a uniform pressure. The model simulated a flange with eight radial ribs [4]. Fig. 7a shows the 3D reconstruction of out-of-plane displacements given by the holographic fringe pattern shown above. Fig. 7b shows the derivative along x direction of the same function. From both picture the eight radial reinforcement, present in the structure at hand, are clearly visible.
Fig. 8 shows in a, a fringe pattern obtained by optical rotation of those shown in fig. 5, and in b, its spatial reconstruction. In this case the monotonicity of fringes is evident and from the reconstruction both radial and a central reinforcements are noticeable.

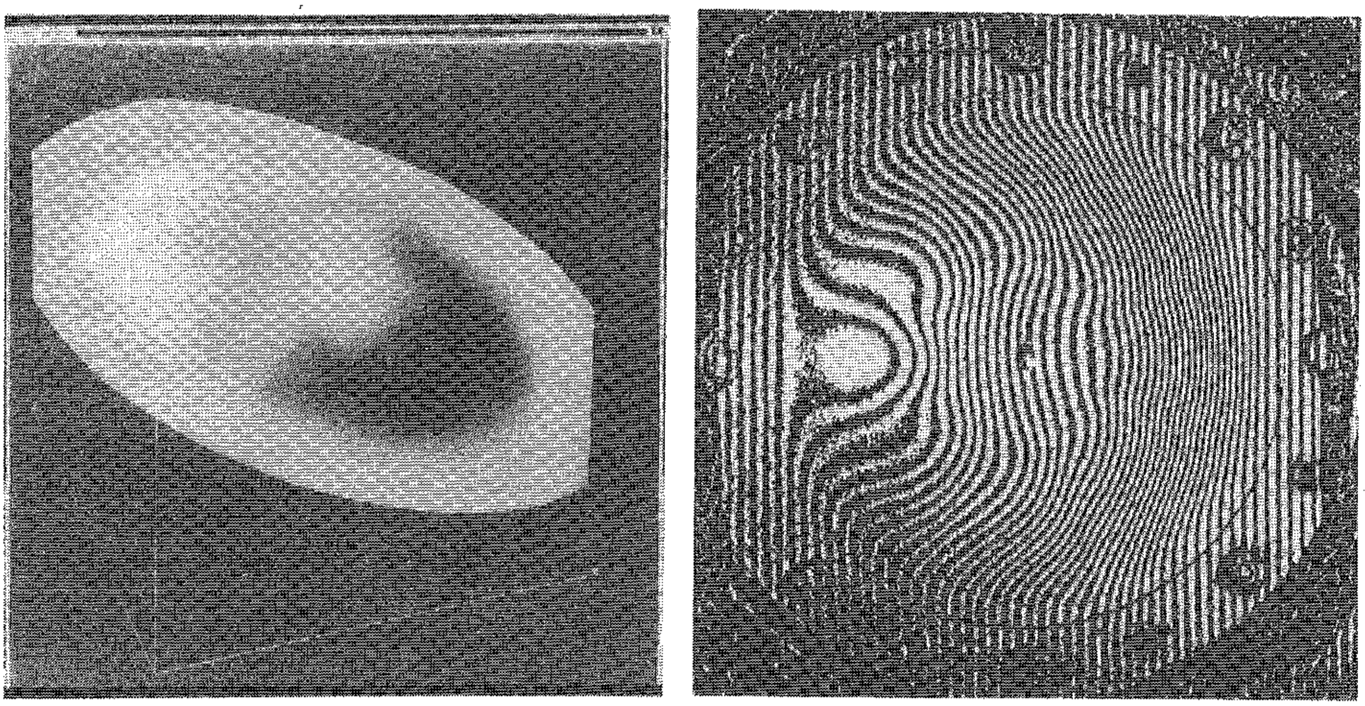
7. CONCLUSION

DIP code seems to be very useful and very easy to work with. In just a few minutes the 3D reconstruction of images of very poor quality is possible and this allows a more powerful analysis of results. Images which are particularly corrupted by noise or very dim can be pre-processed by classical image processing operators. Even these algorithms are present inside DIP. The authors have seen that the algorithm works much better on dark fringes than on bright ones because generally in the latter case the noise is higher. Of course, to apply the algorithm to dark fringes an image inversion can be applied.
The program can easily be linked to a FEM (finite element method) program to achieve the stress values: this procedure will facilitate the taking into account of the right boundary conditions of the structure. For automatic fringe searching another advancement can be obtained by an expert system capable of supporting a complete knowledge of the image object.



a b

Fig. 7 - 3D reconstruction of fringe pattern (a) and its derivative along x



a b

Fig. 8 - 3D reconstruction (a) of the fringe pattern with a carrier (b).

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