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J.W.C. Gates and O.C. Jones

(*1)

National Physical Laboratory
Teddington, Middlesex, TW11 OLW
United Kingdom

"Non-conventional measuring techniques for industry"
Some recently developed optical measurement techniques

Abstract

The National Physical Laboratory, at Teddington, near London, is the focal point for measurement of all kinds in the United Kingdom. Whilst primary responsibility is to provide fundamental standards of measurement, new techniques are constantly being developed and evaluated in order to maintain an adequate lead over the demands of developing technology. In the application of optical methods of measurement to problems in industry, and especially in the engineering field, some of the innovations have relevance to photogrammetry. This paper reports on some of the recent measuring applications of lasers, speckle photography, moire recording and holography. Three dimensional measurement from recorded images such as interferograms is also discussed.

(*1) including work by K.G. Birch, J.M. Burch, G.D.Dew, C. Forno, P.W. Harrison and D.C. Williams

1. Introduction

The main responsibility of a national standardising laboratory such as the National Physical Laboratory is to provide fundamental standards of measurement and this necessarily involves maintaining a considerable breadth of experience in the measurement technology current at any time. It is also necessary to carry out research in order to anticipate future demands for improved standards or for different types of measurement. Because fundamental measurement work calls for greater accuracy than that required to meet normal industrial needs, this often leads naturally to the development of more powerful, specialized measurement techniques, or to the investigation of alternative approaches to particular measurement tasks. At the same time, NPL has close contact with a wide variety of industries and this often prompts the exploitation of research into new and unconventional measuring techniques. There are many examples of such activities leading to the development of new instruments and components, as well as to the provision of reference standards for industrial calibration measurements. One example of the first is the development of digital linear measurement techniques based on moire effects between optical diffraction gratings. (Palmer et al 1975) An example of the second kind (arising from the same field of research) is the use of crossed diffraction gratings (Fig. 1) as dimensional calibration standards in electron microscopy. (Clapham and Hutley 1973) Many other less familiar examples could be cited.

There seems to be an increasing interest in the photogrammetric world in improving awareness of, and liaison with, other fields of optical measurement technology. Conversely, the highly developed techniques currently used for mapping from air photographs, together with the more recent analytical approach to the combination of observations from optical records, appears to have great potential for application to a wide range of industrial measurements in three dimensions.

In this paper, a number of examples of current measurement technology at NPL which appear to have potential for exploitation in photogrammetry and related fields are put forward for consideration.

2. Contouring of nearly flat surfaces

Two important classes of measurement undertaken are concerned with the verification of surfaces of nominally flat form. In each case optical interference is used to provide a pattern of interference bands that constitute a visible and recordable set of height contours, and it is useful to arrange that the contours are in the form of an ordered, nearly parallel set with no loops. The departure from flatness is then accurately proportional to the transverse displacement of the contour-interference fringe from a straight line; this is analogous to the information provided by the parallax in a pair of stereo photographs.

2.1 Flatness of optical surfaces

The Fizeau interferometer, (Fizeau 1862), is still the most widely used instrument for evaluating the flatness of optical components. It employs interference between wavefronts reflected from two surfaces which are separated by a small air-space (Fig. 2). If one surface (the proof plane) is perfectly flat, then the interferogram maps directly the errors of flatness of the second or test surface. A small inclination is usually introduced between the two surfaces so that the departure from straightness of any particular fringe can readily be assessed visually in terms of the fringe spacing. The contour interval is equal to half the wavelength of the monochromatic light used. Circumstances may arise however in which the errors of the proof plane are not negligible or in which the accuracy obtainable by visual estimation is inadequate. It is then necessary to record the fringe pattern photographically and to extract the required information by some method such as that briefly described here.

A series of ordinates at convenient unit separations is constructed perpendicular to the fringes (figure 2, $x = 1$ to 13), and the distance from an arbitrary origin at which each fringe intercepts these ordinates is measured. The fringes are numbered sequentially and the numerical value corresponding to each of a series of points at unit separations along each ordinate is determined by a process of interpolation. This establishes the magnitude of the air-gap (less an arbitrary constant) at a network of points uniformly distributed over the surface. It is subsequently a straight-forward matter to apply corrections for the known errors of the proof plane to remove the angle of tilt arithmetically so that the results represent departures of the height of the test surface from an appropriate mean plane.

The most difficult part of this procedure is to locate the position of the fringes since they are not sharply defined but have an intensity distribution which follows a \cos^2 curve. A common procedure, but one which has severe limitations is to trace the fringes from an enlarged print or projected image of the negative. A number of more refined techniques which give the necessary precision have been described. A visual stereoscopic method devised by Gates (1954a, 1954b) relies on the use of two interferograms in which the angle between the interfering surfaces is of opposite sign, but in which the spacing and position of the fringes are, as far as the irregularities of the surfaces will allow, the same. A photoelectric technique, but one which involves considerable elaboration of both mechanics and electronics, has been described by Ryner and Halliday (1950). The limit of discrimination is typically $\lambda/100$.

2.2 Flatness of engineering surfaces

In the normal processes of engineering metrology, the flatness of a surface is evaluated from the combination of a number of observations of the departure from straightness of lines on the surface. Comparative measurements are made at many points along each line relative to some reference straight line provided by a straight edge or a stretched wire. An alternative procedure is to observe the tilts

of elements of the surface from point to point using a level or autocollimator. The data collected along each line on the surface are then assembled and combined so as to provide a contour map over the areas considered. Of necessity these measurements are done in a series of steps and consequently questions arise over whether one has missed isolated surface irregularities, and the validity of interpolation between measurements taken at a limited number of points. In addition, the feet attached to the stepping base of a level are of finite size and therefore cannot resolve the detailed surface topography.

A recently developed instrument which avoids these doubts is the oblique incidence interferometer (Birch 1973). It has the property, resulting from the obliquity of the incident wavefront on the surface under test, of producing interference fringes with usable contrast from such surfaces as black granite and fine ground or lapped steel. It also provides a desensitized fringe contouring interval of $2.5\mu\text{m}$ or 0.0001 in. It presents in a single interferogram information as to the micro- and macro-topography of a surface area up to 750 mm long by 75 mm wide. A schematic diagram of the oblique incidence interferometer is shown in figure 3. It uses a low power He-Ne laser source and transmitting diffraction gratings as beam-splitters. The transmitted zero-order wavefront from the first beam-splitter acts as the reference wavefront, while the first order diffracted wavefront is incident on the surface under examination. After reflection from the surface this wavefront is distorted in proportion to the surface's departure from flatness. The two wavefronts recombine at the second beam-splitter and produce an interferogram indicating the form of the test surface.

If it is required to assess the flatness of larger surface areas then a series of interferograms must be recorded from which observations are taken for subsequent assembly. From each interferogram the departures from flatness are determined at selected measurement stations along a straight surface generator, the selected stations corresponding to the intersections of the surface generators and forming a regular array. The choice of the size and form of the array is important, being dependent on several factors including the shape of the surface and the mode of operation of the measuring instrument. By selecting a few preferred arrays that are applicable to the majority of measuring instruments and related to surface shape but not size, it has been found possible to write generalized computer programs that are able to assemble any chosen set of observations. For example, hexagonal arrays are preferable for use with instruments that have a fixed stepping length.

3. Deformation measurement by recording with coherent light

The use of lasers in specialised applications in measurement and recording is increasingly common. The first technique described here has a very high sensitivity to distortion of surfaces in the direction of viewing, revealing changes of $0.01\mu\text{m}$. The second technique is more akin to conventional photography and has particular usefulness in measuring the in-plane distortion of surfaces.

3.1

Holography is a two-stage photographic process using laser light that records the wave-pattern from an object, and not its image as formed by a lens. The photographic plate receives light scattered from the object at the same time as an off-axis 'reference' beam direct from the laser. (Fig 4). When the processed plate (the hologram) is illuminated by the reference beam only, a 3D virtual image is generated behind the hologram, by diffraction. This image can be viewed by looking through the hologram, or photographed with a camera directed through it.

Interferometry using holograms is carried out in two ways:

(i) 'Live fringe' method. The processed hologram plate is replaced in its holder in the system so that the reconstructed image is superimposed exactly on the object. If the object is deformed, interference fringes are seen on its surface, increasing in number as the displacement becomes greater. The deformation contours may be viewed or photographed as the deformation takes place.

(ii) Double exposure method. The hologram plate is exposed twice, once before and once after the object is deformed. The reconstructed image then has a 'built-in' fringe pattern related to the deformation that has taken place between the two exposures. The fringes can thus be photographed and measured at any convenient time subsequent to the hologram being recorded.

Both methods allow surface deformation to be visualised and measured, independently of the nature of the surface. Engineering structures may therefore be examined directly. The magnitude of the displacement d at any point on the surface to the fringe pattern is given by the relation (Fig 5)

$$2d \cos \theta \cos \alpha = n\lambda$$

where n is the fringe order number, λ is the wavelength. θ is the angle of bisection between illuminating and viewing direction, and α the angle between the bisector and the displacement vector. Thus for any unknown surface displacement the fringe contours are a measure of the resolved part of the displacement vector in the direction of the bisector of the viewing and illuminating directions. For near-normal incidence and viewing, the displacement in the out-of-plane direction will be measured, with a contour spacing of half a wavelength.

Holographic interferometry may be used quantitatively eg. for measuring the dilatation of a cylinder under pressure, or qualitatively, as in the detection of poor adhesion of laminates in a composite structure (Fig. 6). Deformation measurement is limited to a few tens of fringes ($\sim 25/\mu\text{m}$ displacement) but with a sensitivity $\sim 0.1 \mu\text{m}$.

3.2

Speckle photography is a simpler technique, applicable to the measurement of in-plane surface displacement. Local tilt may be measured by making a slight change in technique.

The image of a laser-illuminated surface formed by a lens is modulated by bright and dark speckles, the diameter of which are given by the approximate formula

$$\sigma \sim \lambda F.$$

Where F is the aperture ratio of the lens (the 'f-number'). Thus a camera lens working at $f/4$ generates speckles of about $3\mu\text{m}$ diameter.

If a double-exposure photograph is recorded on fine grain film, with deformation of the object between exposures, the speckles become doubled. Their separation depends upon the local in-plane component of displacement and the magnification m of the system (Fig 7). The speckle separation, and thus the corresponding surface movement, can be measured by directing a narrow laser beam through the developed negative. A pattern of parallel equi-spaced fringes is formed by diffraction at the doubled speckles. The in-plane surface displacement d is obtained from the fringe spacing g and the wavelength by applying the relation

$$d = \lambda l/mg$$

The direction of displacement lies at right angles to the fringes.

The technique is insensitive to line-of-sight displacement, and stability requirements are much less than those needed for interferometry. Ultimate sensitivity for imaging at 1:1 magnification is $\sim 0.1\text{ m}$. Strain values over a 2D field may be obtained by differentiating displacements. A detailed review of these techniques has been given by Ennos (1978).

4. Deformation Measurement By High Resolution Moire Photography

Optical techniques for measuring deformation and strain offer the advantages over conventional techniques of being non-contacting and of recording information from the complete surface of the structure. Areas of high strain can be analysed quickly and the propagation of cracks that are visually undetectable can be studied

The conventional moire-grid technique (whereby small changes in a grid pattern applied to the object are recorded photographically) has been adapted so that a standard 35 mm camera can be used to record the deformation and still provide an increased sensitivity. The new system, which is capable of measuring movements as small as 1 part in 10^5 of the width of the structure, uses a 4-slotted mask inside the lens of a good quality camera. (Burch & Forno, 1975) This modification 'tunes' the lens to resolve 300 lines per mm over the whole field of the image plane and the depth of focus is increased to approximately three times that achieved with the conventional circular aperture. (Fig. 8).

The camera is used to record a fine pattern applied to the engineering structure. In some cases this may be random but more usually it is a regular pattern of dots running horizontally and vertically across the surface. When the camera is set at a predetermined distance the demagnified image of the pattern will appear as 300 resolved elements per mm in the image. Then, using electronic flash illumination, double exposure photographs are made on the same film frame before and after the object is deformed. After the film has been processed the fine pattern detail in the image behaves as two orthogonal diffraction gratings. A beam of light directed onto the negative will be diffracted into four first-order directions. By viewing the negative in one of these diffracted beams a moire fringe pattern, or displacement map, is seen, in which dark fringes correspond to movements of one half the pitch of the object pattern. From the one negative two such displacement maps are generated representing either the vertical or horizontal displacements depending on which diffracted beam is being examined. From these maps the various features of material behaviour, such as cracking and slipping, are identified and quantitatively evaluated.

One example of the application of the technique involved the measurement of deformation during loading of a 3.6 m wide brick arch. Sheets of paper, printed with 65 dots/inch, were pasted onto both the brick surface and a central reference girder. The modified camera was positioned 6.15 m away so that the pattern appeared demagnified as 300 lines/mm detail in the image. The arch was progressively loaded from above and photographed at intervals. Visual inspection of the fringes revealed a great deal of information concerning the local deformations that occurred such as cracking in the span, separation of the piers and the compression of mortar in the top courses. The fringes were closely spaced where the strain level was high and it was possible to instrument these these regions with strain gauges so that more accurate values could be obtained as the test proceeded.

Other studies of large structures have included concrete buildings, a pressure vessel and textile materials. A recent development has extended the application of the technique to high temperatures, up to 600 °C in air. (Forno, 1978). Strain at high temperatures was successfully measured in a mild steel block containing a welded fillet of stainless steel running across its centre. The fine dot pattern was prepared by spraying a dispersion of titanium dioxide pigment in water through a 40 holes/mm grid fixed to the surface. The block was then mounted on to a hot plate and a modified camera was used to record the effects of different thermal and mechanical conditions with the block heated to 450 °C. The resulting fringe maps (Fig. 9) showed the influence of temperature on the localised thermal expansion mismatch. Such localised behaviour would not have been detected by conventional high temperature strain gauge techniques.

5. Laser techniques for alignment levelling and plummeting

Many problems of engineering alignment and deflection measurement in the range 10m-1km can be solved by observing the relative alignment of three points. The system adopted, developed and used by NPL for

many years is well suited to this need (Harrison, 1978). In this the optical axis is defined by two well-spaced points, the laser source and the centre of an imaging unit. The third point of reference is the centre of the image so formed. By receiving it on a grid screen and attaching the three units of the system in known relationship to the points to be measured, the alignment of those points can be monitored by observing image position with respect to the screen origin. Depending upon range and application the imaging unit may be a simple glass lens, or a Fresnel zone plate or grating. Photoelectric recording techniques have also been developed. For establishing a vertical reference in the form of a laser beam several laser-based instruments are available. (Tolman, 1976).

The precision of all such optical alignment techniques is usually limited by the atmosphere. Despite much theoretical work on perturbing effects in the open atmosphere (3), the calculation of corrections to be applied in engineering situations is still rather uncertain. However, a transverse temperature gradient of 1°C/m may produce a bending of about $d/5$ arc seconds ($d \mu\text{rad}$). In principle, the amount of bending can be directly measured by observing the separation between light beams of two different wavelengths, since blue light is bent about 1.5 per cent more than red. A "dispersometer" based on this principle is being developed (Williams, 1978) primarily for the longer ranges of interest to surveyors and geodesists.

6. Developments in progress

This paper has presented some examples of measuring technology that may influence the practice of photogrammetry in the future, especially in engineering applications and in the control of dimensional measurement during mapping. Development is also continuing at NPL of new ways of making three dimensional measurement in engineering, in addition to the improvement of calibration methods for the verification of established 3-axis measuring techniques.

It is hoped to apply recent developments in stereophotogrammetry to provide independent support for this three dimensional calibration, and for mapping the three dimensional surface form of components of critical importance in optical systems. Other applications may arise in X-ray imaging, and in mechanical engineering and testing. One challenging problem is the measurement of the form of very small components, such as the diamond indenters used in Rockwell C-scale hardness testers. Automatic interpretation of interferograms/contour patterns, a problem area common to several of the foregoing techniques is currently receiving considerable attention, with a view to reducing the labour involved in data reduction. There seems little prospect, however of completely removing the need for the intervention of a skilled human interpreter at present.

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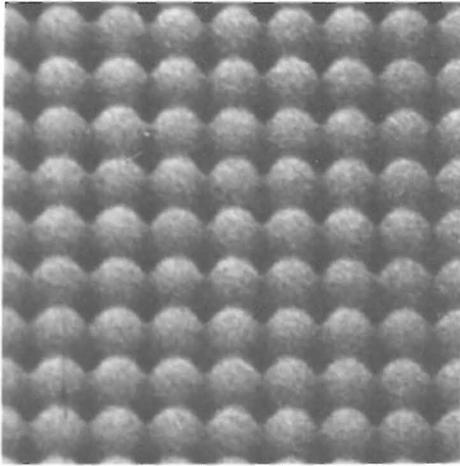


Fig 1 Scanning electron micrograph of crossed diffraction gratings. Spacing 300 nm.

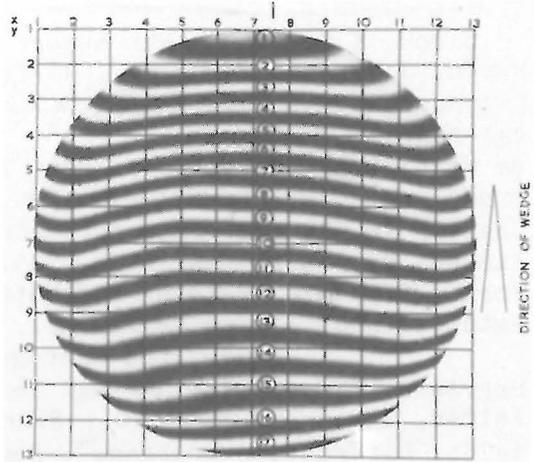


Fig 2 Specimen Fizeau interferogram. System of measurement.

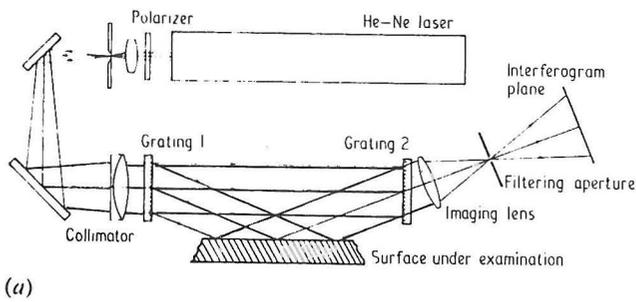


Fig 3 Schematic diagrams of oblique incidence interferometer employing diffraction gratings as beamsplitters.

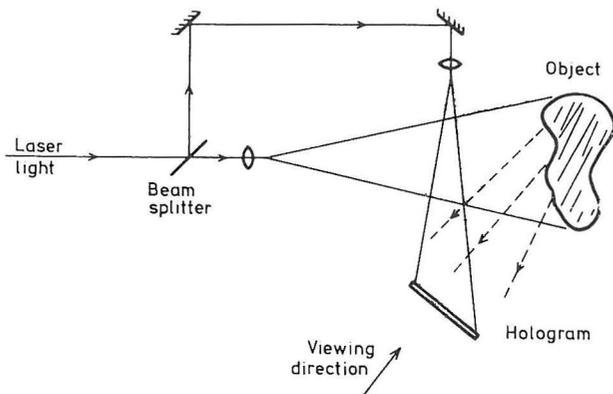
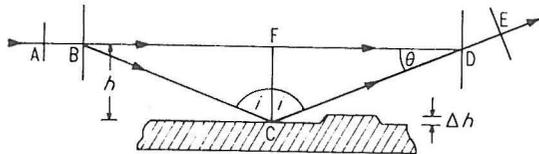


Fig 4 Recording and viewing a hologram

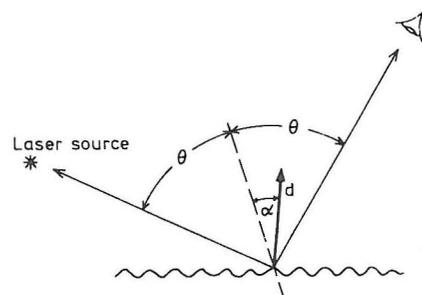


Fig 5 Angles of incidence viewing, and component of displacement d .

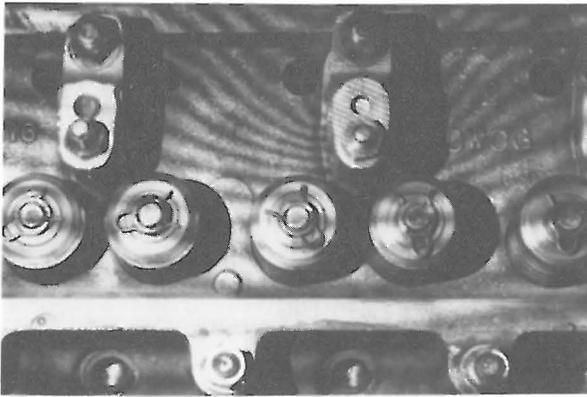


Fig 6 Holographically formed interference fringes on cylinder head of motorcar engine resulting from overtightening one nut.

Double exposure speckle photograph

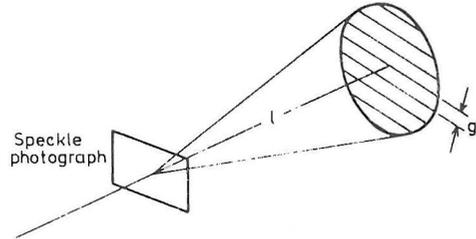
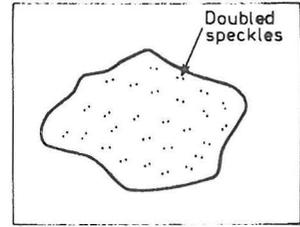


Fig 7 Doubling of speckles by in-plane displacement. Resulting interference pattern after recording.

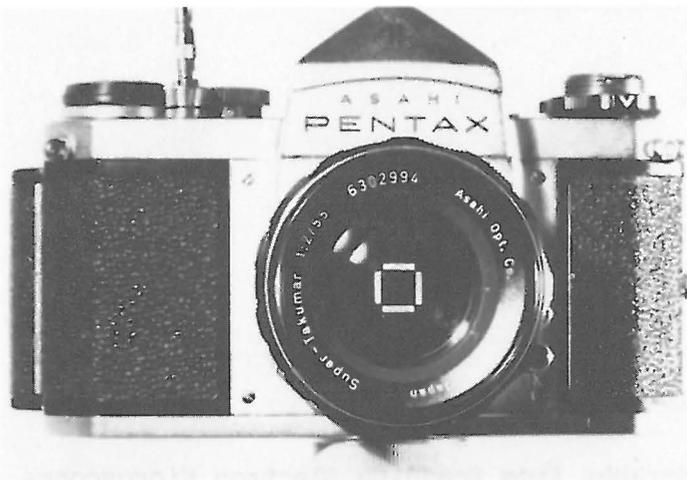


Fig 8 The modified 35 mm camera.

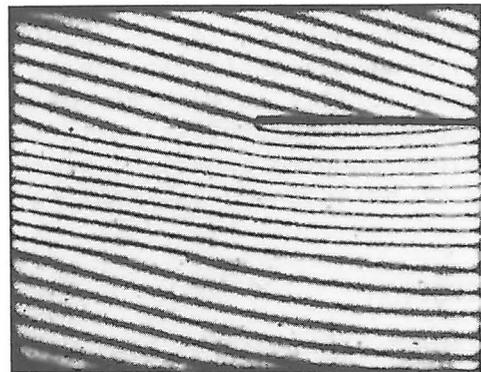
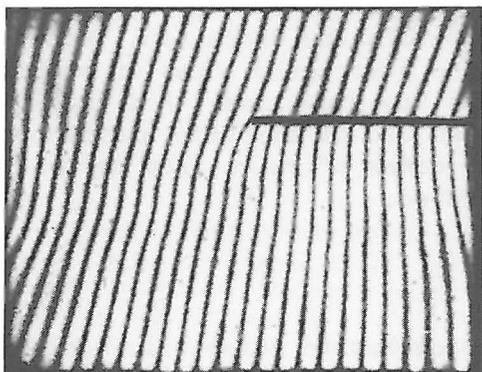


Fig 9 Moiré fringe maps resulting from cutting into a welded steel block and heating to 450 °C. Movements in (a) the x direction and (b) the y direction. Sensitivity 25 $\mu\text{m}/\text{fringe}$