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APPLICATIONS OF THE DIFFERENCE HOLOGRAM INTERFEROMETRY*

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1. Introduction

The aptitude of hologram interferometry for measurement of quantities being of industrial importance has undoubtedly been proved. Hologram interferometry can be used to produce a fringe pattern which represents the field of surface displacement of an opaque object in response to an arbitrary type of loading. It has successfully been applied for investigating phase object as well where the change in refractive index distribution is stored by an interference pattern. Among numerous applications of holography the contouring has also to be mentioned.

There are different techniques for quantitative evaluation of interferograms. Nevertheless, the main difficulty in applying hologram interferometry stems from the numerical evaluation of interferograms. First, the extraction of the tremendous data set from the requires a considerable amount of time. Second, the lack of the zero order fringe (unmoved points within the illuminated area) can introduce ambiguity at the interpretation of interferograms and lead to decrease of accuracy.

Frequently, there is no need to determine the total three-dimensional deformation to specify the shape of an object, or to calculate the temperature and mass distributions. The main interest can only lie in the differences (e.g. in shapes) of two objects. One of them can be referred to as the master one, the other as the test object at large scale production sampling.

The comparison can be done by the difference hologram interferometry [1]. As its inherent property a new object being compared is illuminated holographically by reconstructing the real images of the first object. The idea of the holographic illumination was proposed by D. Denby at al. [2], its potentiality to compare two objects by hologram interferometric techniques was formulated by D. B. Neumann [3]. In the following a short discussion of its principles will be given and selected applications will be presented.

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2. Basic considerations

Let us survey the steps of making difference interferogram, i.e. pattern displaying the difference in characteristic quantities.

In the first step, the conventional hologram interferometry is used to record an interference pattern which contains information concerning deformation, shape, or refractive index changes of the master object. This interferogram is considered as a way of recording and storing two wavefronts with a given phase difference.

For a while let us think in terms of the conventional hologram interferometry, keeping in mind the task of comparision. Then, the second step would be recording another double exposure interferogram related to a new (test) object. Its fringe system would contain information about deformation, shape or refractive index change of the test object. So, the test interferogram would also store two wavefronts with definite phase difference.

Determining differences between the two objects both interferograms are to be evaluated, because numerical results are comparable, only.

If the difference hologram interferometry is applied, there is no need for separate recording and evaluation of the interferograms. The test object is illuminated by the rea images of the master objects. As it was stated above the phases of the illuminating wavefronts were determined by the states of the master object. The states of the new object, due to the applied illumination, modify those phases and their subtruction/addition is realized by recording a new interferogram. Bearing the subtruction of the phases in mind, the difference in the states of the two objects is recorded by the new holographic interferogram.

With computer aided evaluation the difference interference pattern provides a very quick, easy to handle, optical measuring tool for the comparison of two objects with interferometric precision. Using fast recording material, the technique in this realization can be used as an on-line measuring device.

The quantitative representation of what has been said above is as follows [4]. For the sake of simplicity we restrict ourselves to the phase object considerations. Naturally, the analysis is also valid for opaque object investigations.

Let the test object in its initial state be illuminated by the first real image of the master object. The complex amplitude $\tilde{U}_1$ of the light arriving at the plate can be expressed as:

$$\tilde{U}_1 = U_0 \exp[-j\Phi_0],$$

where U_0 and Φ_0 are both functions of the spatial coordinates at the plate. The quantities U_0 and Φ_0 contain all the informations related to the wavefield which is determined by the refractive index distributions of the master and as well as test objects in their initial states.

The complex amplitude $\tilde{U}_2$ arriving at the plate during the second exposure, when the test object is subjected to a given load, e.g. heating, can be expressed as:

$$\tilde{U}_2 = U_0 \exp[-j(\Phi_0 + \Delta\Phi - \Delta\Phi')],$$

where U_0 and Φ_0 are as before, $\Delta\Phi$ is the phase difference caused by the refractive index change in the master object and $\Delta\Phi'$ is that of the test object. Because of the phase reversal of the master wavefronts the phase differences $\Delta\Phi$ and $\Delta\Phi'$ should be taken of opposite sign when both of them belong to the object change of the same character, e.g. increasing the refractive indices in transparent object case.

At the reconstruction of the holograms the irradiance of the object will be proportional to:

$$J = |\tilde{U}_1 + \tilde{U}_2|^2 = 2U_0[1 + \cos(\Delta\Phi' - \Delta\Phi)].$$

The number of fringes in the difference interference pattern is determined by the sum of $\Delta\Phi'$ and $(-\Delta\Phi)$.

3. Realization of the difference hologram interferometry

The analysis discussed above has been carried out in terms of separate uses of the master object wavefronts for illumination, and can be realized by dual reference beam method which permits dynamic control of the reconstructed real images of the master object and adds flexibility to the adjustment of the holographic illumination.

The master wavefronts can be recorded on a single plate with single reference beam, too [5]. The pecularities of the experimental set up are as follows:

Two-reference beam method: the two master holograms are recorded by two reference beams. The simplified experimental set up without beam expanding elements is shown in Fig. 1. The laser light coming from the right hand upper corner is devided into two beams.

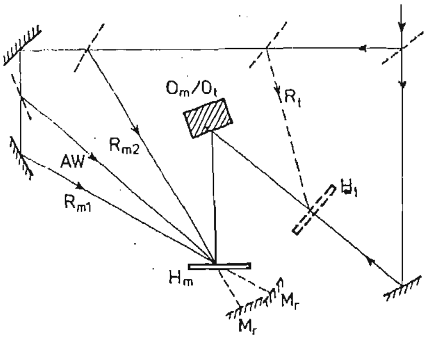

Fig. 1. Experimental arrangement: two-reference beam method

The beam passing through the first beamsplitter is the master object beam. The reflected light after consecutive splitting produces reference beam R_t for recording the difference pattern during the second step on the plate H_t; reference beams R_{m1} and R_{m2} for recording the master holograms on the plate H_m and the adjusting beam AW. Symbols O_m and O_t denote master and test objects, respectively. Mirrors M_r reverse the reference beams R_{m1} and R_{m2} for the illumination of the test object.

The two states of the master object are recorded on the same plate (H_m) by the two reference R_{m1} and R_{m2} coming from different directions. For fine alignment of the mirrors M_r, reversing the reference beams, an additional spherical wavefront AW is recorded by both reference beams. Reconstructing it by both conjugate reference beams simultaneously, its fringe free image indicates the correct alignment of the reversing mirrors.

Single reference beam method 1. (without beam splitting the object beams). The corresponding arrangement is the simpliest one because one reference beam is used, only, as in conventional double exposure holography. When the master hologram is illuminated by the reversed reference beam, both master object wavefronts are reconstructed and used in both illuminations. A double exposure interferogram is made for test object. When the test interferogram is reconstructed interference of four wavefronts can be observed. They are the difference interference pattern, and disturbing interference fringe systems: sum of the displacements and twice the actual displacement of the test object.

If the displacement of the master and test objects is to large that their frings systems are unresolvable, the difference interference pattern will be the only visible fringe system. The disturbing interference patterns result in a decrease in the visibility of the difference interference pattern.

The schematic drawing of the corresponding experimental arrangement is shown in Fig. 2 with main notations as in Fig. 1.

Single reference beam method 2 (with beamsplitting of object beams). An intermediate arrangement between the two reference beam technique and a single reference beam method 1 is shown in Fig. 3. A single reference beam is used for recording master wavefronts on a single plate. The significant element of the experimental set up in Fig. 3 is the beamsplitter *BS* separating the master object wavefronts on their way toward the hologram plate H_m. As a result of the beamsplitting they arrive on the hologram plate from different directions. During the wavefront reversal the appropriate path is open only while the alternate one is blocked.

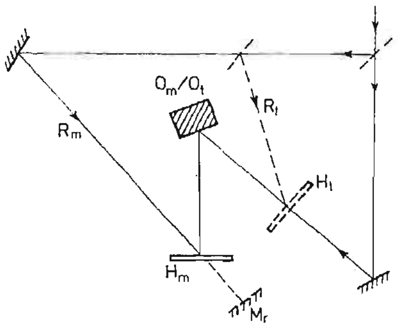

Fig. 2. Experimental arrangement: single reference beam method; no beamsplitting the object beam

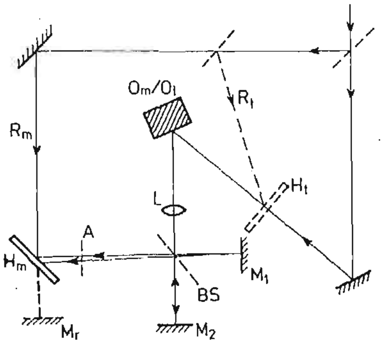

Fig. 3. Experimental arrangement: single reference beam method; beam splitting the object beam

All the other steps in producing difference interference pattern are the same as those discussed above. It is worth mentioning that there are another ways to split the object beams, e.g. using a michelson interferometr type beamsplitting.

4. Applications

4.1. Displacement difference measurement. In the case of displacement measurement the master object surface under study was the bottom of a pressure chamber. Between the two exposures the pressure was increased in it causing a bulging of the bottom and producing concentric fringe system.

For the sake of simplicity the same chamber was used for the test object as well, but in the latter case the bottom was repainted and the chamber position changed a little to simulate the different microstructure.

The first step is the recording a double exposure interferogram, corresponding to the two states of the bottom before and after the load. The developed plate H_m (Fig. 1) is placed back (with interferometric precision), the master object O_m taken away and the test object O_t placed as shown in the figure. A new holographic plate H_t is placed in the direction where the master object had been illuminated from.

The reference beams R_{m1} and R_{m2} were plane waves, their reversal is simply realized by the mirrors M_r. The test object O_t is illuminated by reconstructed real images of the master chamber in turn, corresponding to the sequence at the recording of the master holograms. If the pressure change between the two exposures in the master and test chambers is different, the bulging of the bottom will be different. This difference can be recorded in the form of interference pattern by the plate H_t.

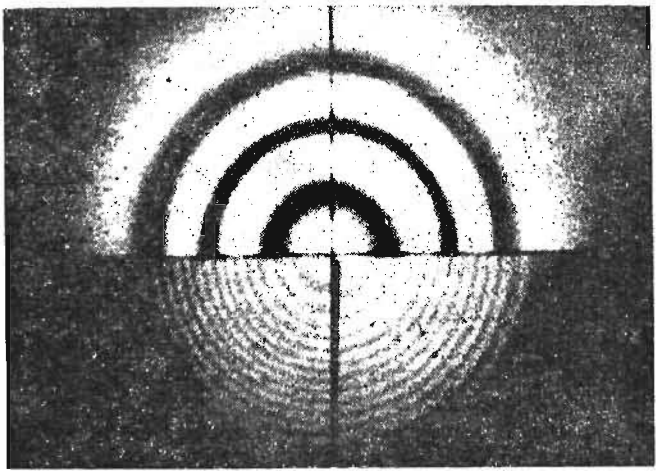

Fig. 4. Deformation measurement with two-reference beam method: composite interferogram (I)

The working of *DHI* can be demonstrated quantitatively on a composite interferogram in Fig. 4. The lower left quarter shows a quarter of the fringe system of the master object the upper half shows the half of the fringe system of the test object and the lower right quarter shows the essence: a quarter of the fringe system displaying the difference between the master and test object bulging. The bulging of the master object results in 15 (light) fringes, that of the test object only 3 fringes and their difference is really 12 fringes.

The composite interferogram of Fig. 4 is not composed by phototechnics but the holographic recording of the test object itself is composite: it was made in three steps and with different coverings of the test object. The coverings marked with lines and the illuminations belonging to them are explained in Fig. 5. First the lower half of the test object is illuminated with the image of the master object in its undeformed state (I_{m1}). In the second step the test object, in its undeformed state yet, is illuminated with the image of the master object in its deformed state (I_{m2}) and the lower right quarter is covered. After that the deformation of the test object follows. Then the last step is the illumination of the test object with the image of the master object in its deformed state (I_{m2}) while the lower left quarter of the test object is covered.

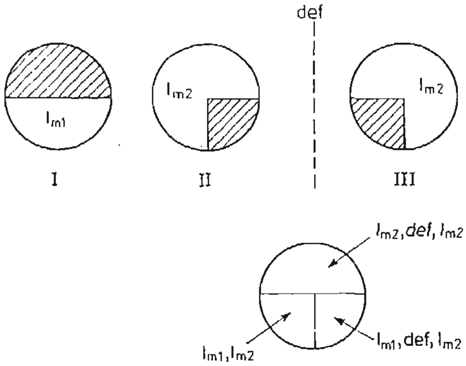

Fig. 5. Deformation measurement with two-reference beam method: steps of making the composite interferogram

Summarizing the three steps, the following has happened on the different parts of the test object (Fig. 5, lower part). The lower left quarter of the test object was illuminated only in the undeformed state of the test object by I_{m1} and I_{m2}, thus the interferometric fringe system of the master object arose. The upper half of the test object was illuminated before and after its deformation with the same wavefront, with the image of the master object in its deformed state (I_{m2}), thus the interferometric fringe system of the deformation of the master object arose. Finally, the lower right quarter of the test object was illuminated before and after its deformation with different images of the master object and in the right order (I_{m2} after I_{m1}), thus the required difference arose.

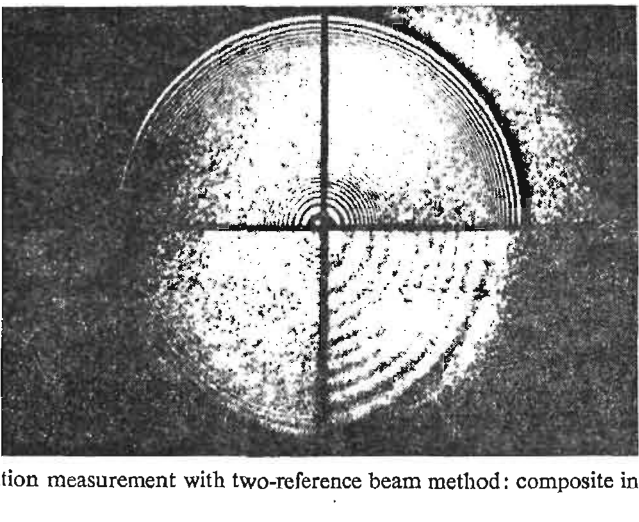

Fig. 6. Deformation measurement with two-reference beam method: composite interferogram (II)

The advantage of all of this is that the fringe system of the deformation of the test object and the difference fringe system could be recorded from nearly the same viewing directions at the same deformation, happening once, of the test object. Thus the source of error that the repeated deformation of the test object may be a bit different is omitted. (Of course, the recording of the two fringe systems at the same deformation, happening once, of the test object could be done without covering as well. One should put a beamsplitter in the path of the test object wavefront and use two hologram plates. However, this would have increased the already very dangerous light poverty of the set up.)

Fig. 6 is very similar to Fig. 4, only the fringe systems to be subtracted are too dense to be observed by the naked eye. Nevertheless their small difference can be seen in unchanged quality. Thus DHI works in the case of invisible dense fringes as well.

4.2. Shape difference measurement. As the second example of application a two-refractive index contouring will be presented [5]. As for the first step in *DHI* contouring, the quality of difference holograms and their reproducibility were the main aspects at the choise of the proper *DHI* method. They had been found quite problematic at the authors previous deformation measurements as well. The lower quality may be connected with the diffuse holographic illumination itself although simple interferograms of good quality could be produced by using the same holographic illumination in both steps. The reproducibility, however, must depend upon the disturbing effects of the surroundings only.

The two-refractive-index contouring has got the special requirement that at least the observation of the object has to be perpendicular to the window of the container [6]. At *DHI* contouring, where the observation and illumination change their role at producing the difference, this means that in any case both have to be perpendicular to the window of the container. A beamsplitter can ensure this but with significant loss of light power only. Therefore, a compromise was chosen and the beamsplitter was replaced by a pair of mirrors cemented on the faces of a prism close to each other. Through this pair of mirrors, the observation of the master object (and the illumination of the test object) was perfectly perpendicular and the illumination of the master object (and the observation of test object) was only nearly perpendicular.

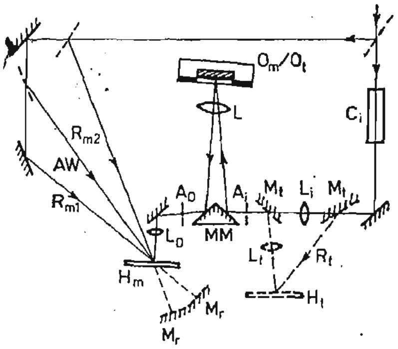

Fig. 7. Experimental arrangement for contouring

The sketch of the experimental setup is shown in Fig. 7, and the pair of mirrors is denoted by *MM*. The lens L_i focuses the beam of the collimator C_i onto the right mirror of the pair of mirrors *MM* and the lens *L* ensures the parallel object illumination. The observation from parallel directions is achieved through the lens L again and after the reflection on the left mirror of MM through the aperture A_0 and the lens L_0. The pair of mirrors MM is placed at the foci of the lenses L_i, L and L_0 that the illumination and observation directions could get quite close to each other R_{m1} and R_{m2} are the two plane reference waves and AW is the additional spherical wave for the master hologram H_m. (The beam expanding elements are not shown.)

The changes required to the production of the difference interferogram of the test object are shown by dotted lines in the figure. The mirrors M_r reverse the reference beams R_{m1} and R_{m2} and the mirrors M_t reflect the reference beam R_t and the test object beam onto the hologram plate H_t. The lens L_t makes a very reduced image of the test object on the hologram plate to increase the intensity of the weak object beam.

The object is an aluminium membrane of 60 mm diameter, the middle of which can be loaded with a micrometer screw to change its shape in a controlled way. Its surface was machined by surface grinder and was corroded by NaOH to get a plane and diffuse surface which could be contoured with 10 μm sensitivity. It is placed in a container with an optically flat planparallel window.

To get 10 μm sensitivity, alcohol and water are used in the container in the two steps of contouring at the argon laser line $\lambda = 488$ nm. First the contour image of the master

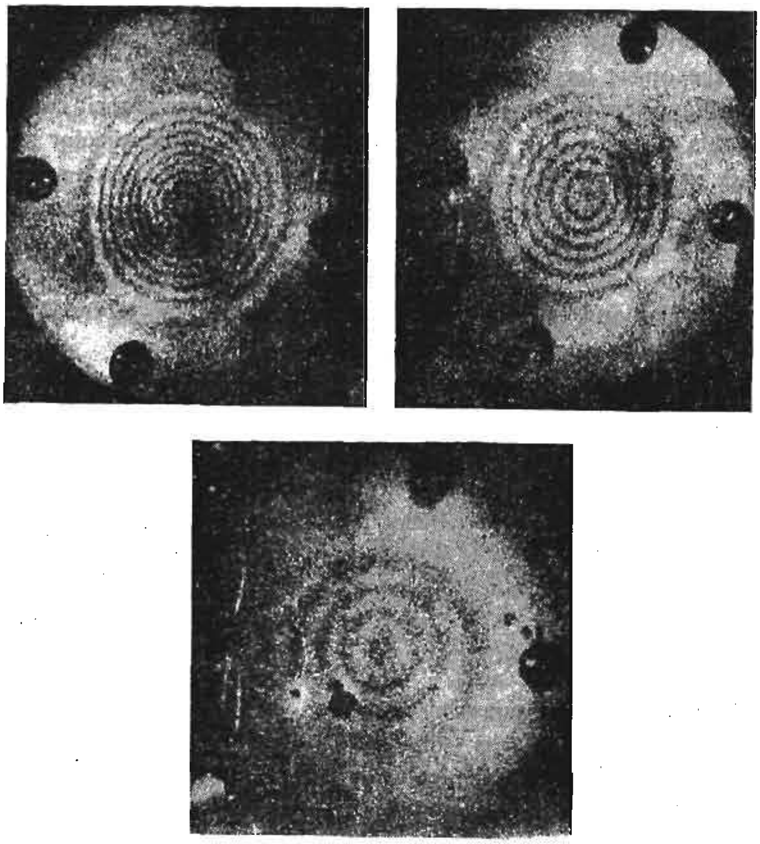

Fig. 8. Master-, test and difference contour fringes

object is produced. The two exposures of the master hologram H_m are taken with the reference beams R_{m1} and R_{m2} separately while the additional wave AW remains always present. At the reconstruction of the master hologram H_m, the reference beams R_{m1} and R_{m2} are reversed to produce real images. Their coincidence is achieved by observing and eliminating the interference fringes of the two real images of the additional wave AW. Then the contour fringes of the master object appear. These images are used separately for the illumination of the test object in the second step at the recording of the test hologram H_t. The liquids and reference beams R_{m1} and R_{m2} are used in the same order as before. Thus the difference contour image of the two objects is produced by the test hologram H_t.

In Fig. 8 the evidence of difference making is illustrated numerically. The arrangement used was the predecessor of the arrangement outlined above. The illumination and observation directions subtended wider angle and the lens L was put quite obliquely in the light path to avoid the disturbing reflections. The concentric fringe system of the approx. 65 μm bulging at the centre is shown in Fig. 8 in the case of the master object. The test object was simulated by changing the shape of the same object to approx. 100 μm bulging. Its fringe system is shown in Fig. 8. The fringe system of the difference bulging (approx. 35 μm) of the centre is displayed in Fig. 8 within half a fringe accuracy.

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Резюме

ПРИМЕНЕНИЯ РАЗНОСТНОЙ ГОЛОГРАФИЧЕСКОЙ ИНТЕРФЕРОМЕТРИИ

В работе представлено методы разностной голографической интерферометри. Преимущество метода состоится в возможности сравнения между двумя объектами и пригоден когда нет необходимости вычисления всех компонент перемещения или формы объекта, а мы заинтересованы опеределением разницы перемещений или изменения формы объекта.

Streszczenie

ZASTOSOWANIE RÓŻNICOWEJ INTERFEROMETRII HOLOGRAFICZNEJ

Praca przedstawia krótki opis zasad różnicowej interferencji holograficznej. Jej istotna zaleta polega na możliwości porównywania (znajdowania różnic) pomiędzy dwoma obiektami. Metoda jest przydatna gdy nie ma konieczności wyznaczania wszystkich składowych przemieszczenia, lub wyznaczania kształtu obiektu a wówczas gdy interesuje nas różnica kształtu lub zmiana kształtu obiektu.

Praca wpłynęła do Redakcji dnia 1 czerwca 1987 roku.