METHODS OF HOLOGRAPHIC INTERFEROMETRY FOR INDUSTRIAL MEASUREMENTS

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1. Introduction

Experimental techniques are of a great importance in studying the stress/ /strain state of machine parts and of different construction elements. The difficulties of analytical solution according to theories of elasticity and plasticity in many practical problems make the experimental methods unavoidable in practice. The traditional techniques, such as dial gauges, strain gauges, suffer from the drawback that they provide information at specific points and hence require prior knowledge of the location of critical areas. Optical methods have the double advantage to be full field means of measuring displacements and to be nondestructive.

The optical methods under consideration are always costly to establish because of the high intellectual and economic capacity absorbed. With automatic data processing, costs may rise to three or four times those of purely holographic methods. In this case, however, both measuring possibilities and accuracy will be considerably increased. It is worth mentioning that only fully automated holographic measuring systems will be a match for traditional techniques from metrology points of view, especially when measurements are carried out outside the laboratory, in factory environment.

In the case of a three-dimensional displacement field, the applicability of holographic interferometry is determined by its aptitude to measure all components of the displacement vector with the required accuracy.

In this paper the basic double-exposure techniques of holographic interferometry [1, 2, 3, 4, 5, 6] will be presented from the point of view mentioned above and a short description will be given of an improved technique suggested by the author for the measurement of the three-dimensional displacement field by holographic interferometry [7].

2. Methods of holographic interferometry

In general, the great many proposed schemes for the interpretation of holographic interferograms can be classified according to four main groups of techniques, called, after Briers [8], the fringe localization (FL), fringe counting (FC), zero order fringe (ZF) and hologram fringe (HF) techniques. Among the double-exposure techniques there are also a few other ones, of lesser interest, which do not fall into any of these groups.

2.1. *The fringe localization method* [1, 2] was historically the first reported technique for interpreting holographic interferograms. The technique utilizes the fact that, for certain types of object motion the fringes are localized at some distance from the image. In calculation, this distance is used as a parameter. The method is powerful in determining the in-plane component of motion (the component in the plane perpendicular to the line of sight). The other components of displacement can be found, in principle, by repetitive measurements of fringe spacing and localization from different observation directions. Nevertheless, the effectiveness of this procedure is limited by the normally small size of typical interferograms. So the components of motion, with exception of the in-plane one, are very difficult to measure with some accuracy. Another disadvantage of the FL technique is the difficulty to locate the plane of the fringes to some accuracy. Several works have been done to overcome these problems (e.g. [9]), without any success.

2.2. *The fringe counting technique* [3] also makes use of the fact that the fringes are, in general, located at some distance from the surface of the reconstructed image. The optical system used for viewing the fringes is focused on the image and is stopped down until the fringes are clearly visible. The surface point under consideration is viewed continuously from different directions and then the displacement component is determined by counting the number of fringes passing across the image point. The method gives the component of translation of the point in a direction perpendicular to the bisector of the two extreme lines of sight and in the plane containing these lines of sight. Other components of motion can be measured to a limited accuracy as in the case of the FL method. In spite of its rather convenient application in determining a complex object motion, the FC method does not suit measurement of the three-dimensional motion to the accuracy required by the industry. Due to its relative simplicity the FC technique remains a very useful holographic method even in its original form and the more so with improvements and developments especially for the rapid, semi-quantitive interpretation of interferograms.

2.3. *The hologram fringe technique* [5, 6]. This interpretation method is based on the formation of interferometric fringes arisen from each pair of identical points of object surface. Two displaced point sources are known to result in an interferometric pattern in space easy to handle analitically and permitting to determine the displacement. In general, this interpretation method uses a limiting aperture through which to view the fringes. Basic relations have been presented and nomograms constructed [10] for determining the displacement direction and magnitude of surface points from the shape of fringes, on the basis of their spacing and bend without numerical analysis. Since the method investigates the absolute displacement of a single point, there is no need to worry about whether the motion is due to translation, rotation or deformation. The major disadvantages of the method are the poor visibility of fringes, the high level of noise, the limited accuracy, the very time-consuming work to realize the motion of the whole object. This objection could be overcome to some extent by automatic data processing, nevertheless the HF method is likely to a rather complicated technique for determining three-dimensional displacement fields.

2.4. *The zero-order fringe technique* [4] overcame the limitations of the previously mentioned FL and FC methods by utilizing multiple holograms. In this method the change in optical path from the source to the observer is determined for each point of the surface. In order to measure all the displacement vector components, in this generalized approach, three separate interferograms will be required. Each from these interferograms measures the displacement component along the bisector of the illumination and viewing directions. In other words, the measurement sensitivity is maximum along the bisector determining the sensitivity vector. In this way all three components of displacement can be measured to the required accuracy.

Unfortunately the multiple hologram technique which involves the observation of fringes through interferograms made at different viewing positions has a serious practical drawback. In reducing the fringe patterns, it is necessary to reproject all the fringe patterns to the normal view.

Recording three interferograms on a single photographic plate with three different sensitivity vectors can be performed by turning the object [11]. In this case the experimental setup consists of three reference beams and a single object beam. Application of the method is, however, hampered by difficulties in precise mechanical adjustment: during the first exposure the object changes its position three times. After that the load is applied and the second exposure follows, where the object positions must be just the same as during the first exposure. In addition, the investigation of static displacements by this technique is restricted to the elastic load range, where presumably the deformations are reversible in practice too.

This method eliminates the main disadvantage of multihologram technique: the object being photographed from the same direction, its shape and dimensions are the same on different holographic images. This leads to the simplification of interpretation procedure and what is more important, leads to an increased accuracy.

Hung proposed a method [12] that has offset the drawback of multihologram technique in general and in particular the disadvantages of Sampson's technique [11]. The method applies three object and reference beams each, while the three double-exposure interferograms are recorded on the same plate.

Hence the fringe patterns required for calculating displacement components can be photographed from the same direction.

In this technique the plate is first exposed consecutively to three pairs of object and reference beams. The surface is then deformed and a second set of exposures is made again on the plate. After processing, the plate is reconstructed by the reference beams separately, and each interferogram is photographed.

So the necessity of fringe reprojection and of the identification of surface points on different holograms as in the case of Sampson's single hologram technique is eliminated.

Nevertheless, recording such a sixfold-exposed hologram is time consuming so that the time required for measurements is greater than the period of disturbances. So in the case of this measuring system the accuracy and reliability of measurements are decreasing with increasing the exposure time. On account of the disadvantages mentioned above this technique does not meet the requirements for investigating dynamic processes in factory environment.

In order to avoid the disadvantages of the previous multihologram techniques we have proposed an improved method for measuring three-dimensional displacement fields. The experimental setup is similar to that by Hung et al. In this technique, however, the three illumination and the three reference beams work simultaneously. In order to guarantee the interference of one of the three object beams with its reference beam only the other beams must be uncorrelated. Beams not belonging together are brought out of correlation by properly chosen optical path of each beam: the geometrical path difference between object and reference beams belonging together is less than the coherence length of the laser used for measurements, while the path difference between other beams exceeds the coherence length. Such an arrangement is very simple to realize in the case of ruby lasers due to their limited coherence length.

So in this technique the plate is first exposed to the three independent uncorrelated object beams which create three independent holograms on a single plate with the proper reference beam. The surface is then displaced or deformed and the three new holograms are recorded simultaneously on the plate in the same ways.

The reconstruction process results in three independent interferograms without cross-talk among them. Then the interferograms can be photographed separately.

3. Experimental demonstration

The effectiveness of the suggested technique was demonstrated in our laboratory by measuring the displacement of membrane surface points. The membrane was clamped at three points along its perimeter and loaded at the center.

Recording of interferograms was accomplished by cw He—Ne laser with two illuminating and two reference beams. Optical path difference between branches was 0.65 m. The scheme of interpretation of the interferograms is shown in Fig. 1. A rectangular co-ordinate system with origin at the point of loading is assigned to the measured surface. The beams are in the plane x, y. The displacements of the surface points are measured in the plane x, y. The figure presents the sensitivity vectors S_1 and S_2, the two objects beams and the direction of observation.

The two interference patterns corresponding to the two sensitivity vectors are shown in Fig. 2. On the right-hand side there are twenty fringes of different order and on the second interferogram there are eighteen ones.

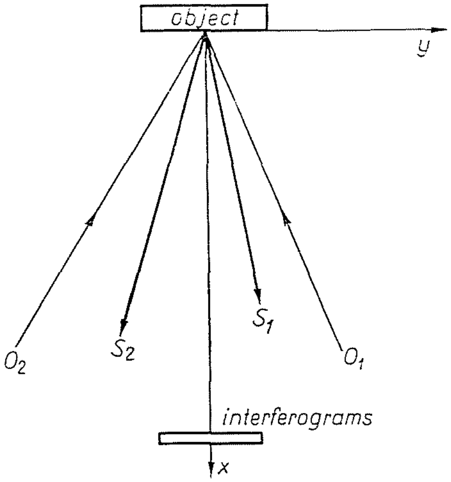

Fig. 1. Scheme of interpretation of interferograms

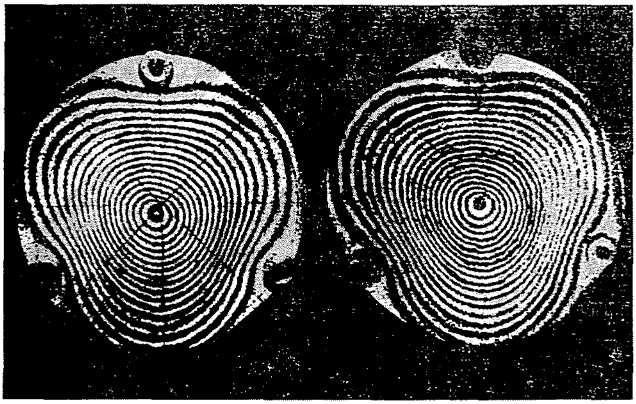

Fig. 2. Interference pattern with two different sensitivity vectors

The actual displacement component at the membrane center was measured by a micrometer screw. The values of the displacement components d_x and d_y measured holographically are shown in Fig. 3 as a function of the distance from the center. The scatter of the component d_y around its average value shows that the accuracy of the measurement is within the limit of error. The value of the displacement component d_x at the membrane center was estimated within 7%.

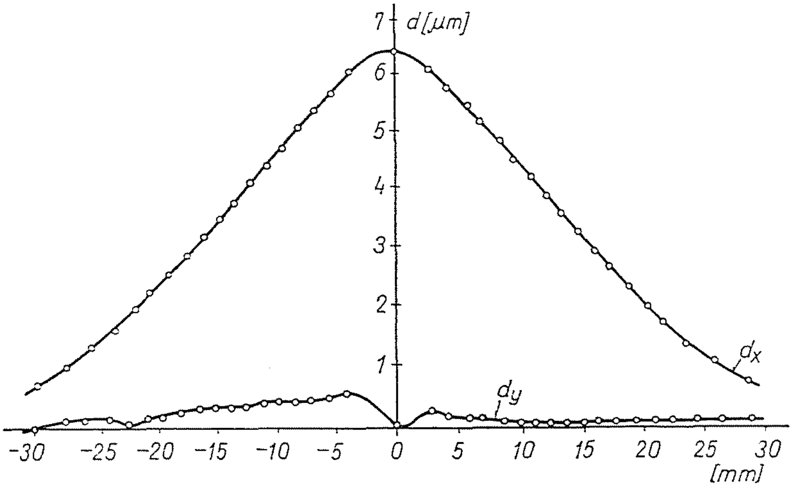

Fig. 3. Displacement components d_x and d_y *vs.* distance from membrane center

4. Conclusion

The demand to measure three-dimensional motion raises concrete requirements for the optical scheme of holographic interferometer.

A holographic interferometer has to measure all three Cartesian components of the displacement vector to the required accuracy.

The difficulties of identifying the surface points in multihologram technique can be eliminated by recording three interferograms on a single plate with different sensitivity vectors.

Applicability of the proposed technique of measuring three-dimensional motion in factory environment has a stipulation, that of simultaneous recording. At the same time, the three interferograms must be independent of each other.

The independence of the interferograms can be achieved by properly choosen path difference between beams.

The relative complexity of optical scheme is a disadvantage of the technique.

The expediency of the method is illustrated by the measurement of the displacement of membrane surface points.

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Summary

Applicability of holographic interferometry for measuring three-dimensional displacement fields is determined by the suitability for measuring all the displacement vector components to the required accuracy. The most important methods of double-exposure techniques are analyzed from the point of view mentioned above. The simultaneous recording of three independent interferograms on a single plate as an improved method of measurement of three dimensional motion is also described. An experimental demonstration is presented which utilizes the improved technique.

References

1. Hildebrand, B. P.—Haines, K. A.: Appl. Opt. **5** (1966) pp. 172—173
2. Haines, K. A.—Hildebrand, B. P.: Appl. Opt. **5** (1966) pp. 595—602
3. Александров, Е. Б.—Бонч-Бруевич., А. М.: ЖТФ, **37** (1967) pp. 360—369
4. Ennos, A. E.: J. Phys. E (Sci. Instrum.) **1** (1968) pp. 731—734
5. Tsujiuchi, J.—Takeya, N.—Matsuda, K.: Optica Acta, **16** (1969) pp. 709—722
6. Gates, J. W. C.: Opt. Technol. **1** (1969) pp. 247—250
7. Füzessy, Z.—Szarvas, G.: Preprints of the International Conf. on Opt. Comp. in Research and Develop. Visegrád (1977) pp. 73—82
8. Briers, J. D.: Opt. and Quant. Electr. **8** (1976) pp. 469—501
9. Boone, P. M.—Verbiest, R.: Optica Acta, **16** (1969) pp. 555—567
10. Boone, P. M.—De Backer, L. C.: Optik, **37** (1973) pp. 61—81
11. Sampson, R. C.: Exp. Mech. **10** (1970) pp. 313—320
12. Hung, Y. Y.—Hu, C. P.—Henley, D. R.—Taylor, C. E.: Opt. Commun. **8** (1973) pp. 48—51

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