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Experimental Stress Analysis

Optical Methods in Experimental Mechanics

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Abstract: The paper deals with optical experimental methods used in experimental mechanics, especially in experimental stress analysis. High attention is given to optical methods – classical and modern optical methods and its future in mechanics, i.e. classical optical interferometry based on optical interference and superposition, stereometry, stereophotogrammetry, photoplasticity, heterodyne interference, moiré, holography and holographic interferometry, speckle photography and speckle correlation methods etc.

Keywords: Experimental mechanics, Experimental stress analysis, Optical methods, Interferometry, Holography, Holographic interferometry, Moiré, Speckle.

1. Introduction

Interference, diffraction and other phenomena with participation of light electromagnetic waves are age-long optical problems inspiring generations of physicists and engineers to precise their characterisation and to develop technology for new and often unconventional applications in large scientific and technical areas, especially in mechanics. In recent decades there has been observed a methodological and application shift from traditional methods, using conventional optical interferometry and mechanical superposition (moiré method) or polarisation in transmission photoelasticimetry for solving planar or spatial tasks to their modern modifications (shadow moiré and reflexive photoelasticimetry). A certain application area, but relatively little used, is photoplasticity. An advent of lasers, new optoelectronic devices, advanced computer technology and evaluation methods in engineering practice have opened new possibilities of optical methods (holography, holographic interferometry, speckle interferometry, quantum optics and others).

Classical optics describes the interference and diffraction phenomena using concepts of *perfectly coherent* and *perfectly incoherent light beams*, more recently using the concept of *partially coherent* light beams. Superposition of ideally coherent or partially coherent light beams allows to observe, for example on the screen, the interference pattern, in the latter case with the contrast of interference fringes lower than the contrast of interference fringes formed by coherent beams. The interference image usually requires time stationarity and the same frequency of interfering beams, what can be relatively easy satisfied using a single primary source of coherent radiation. In the case of the use of incoherent light beams an interference pattern cannot be observed, but it is possible to see and thus technically utilise the phenomena resulting from superposition of light fields.

Generally, the large number of optical techniques and their technical variants, with emphasis on their use in mechanics, can be perhaps divided on the physical principle, what also fairly well describes their historical development.

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2. Classical optical methods

The period before the appearance of a phenomenal source of coherent light – laser, by that time a radiation source of unimaginable parameters, was characterised by the following groups of methods.

2.1. Optical interferometry

Classical optical interferometers are usually classified as follows:

- *two-beam interferometers*, for instance Michelson, Mach-Zehnder, Sagnac interferometers et al. Various technical types of interferometers satisfying numerous applications were derived from these basic types.
- *multi-beam interferometers,*
- *heterodyne interferometers,*
- *others*; to this group we count either conventional interferometers to some extent of a particular type (such as Newton interferometer, etc.) or interferometers developed later (e.g. laser interference anemometer known under the name LDA etc.) and white-light interferometers.

Two-beam interferometers are devices using two beams of radiation propagating to the place of their superposition (interference) along the different optical paths, one beam is usually called the reference beam and the second object beam. The difference of optical paths of these two interfering wavefronts is $\Delta p = p_1 - p_2 = \sum n_1 d_1 - \sum n_2 d_2$, where n_i is index of refraction and d_i is the geometrical length of beam trajectories, $i = 1, 2$.

The interference pattern usually requires time stationarity and the same frequency of interfering beams, what can be relatively easy fulfilled providing a primary source of coherent radiation. We discern between two basic methods for obtaining two beams from the same source, the *method of wavefront division* and the *method of amplitude division*.

The principle of wavefront division uses, for example, *Rayleigh interferometer* [5, 6], which employs two separated parallel collimated beams. One beam passes through the investigated material and the second one through the reference material, while the geometrical lengths of the two beam trajectories are the same.

The method of amplitude division uses some optical elements for division of the primary beam. These are optical elements based on the semi-reflective thin optical layers, reflective or transmissive diffractive optical grid, generating one or more diffracted beams and polarising prism producing two orthogonally polarised beams [5]. On the principle of amplitude division there are based, for example*, Michelson (Twyman-Green) interferometer, Mach-Zehnder interferometers* (both with a plenty of engineering applications*), Newton, Fizeau, Haidinger, Sagnac interferometers*, etc.

The principle of the Michelson interferometer is shown in Fig. 1, where the source beam is divided by the semi-transparent thin film deposited on the plane parallel substrate and the same film is used for grouping beams reflected from mirrors M1 and M2. The compensation plate is used for matching the optical paths in both interferometer arms. The interference pattern is created as a consequence of the difference of optical paths in both arms, and in practice it can be described in terms of technical design of the interferometer or applied principle of source, such as: (a) – interference using point sources, (b) – interference using sources of finite dimensions, (c) – interference using collimated beams - so called Twyman-Green interferometer. Michelson interferometer is one of the most frequently used interferometers in practice for highly precise distance measurement, testing of optical components in the production [6], [7], [8] etc.

The principle of Mach-Zehnder interferometer is shown in Figure 2 with two beams propagating through different optical paths. The interferometer is in practice quite difficult to be aligned and stabilised, in spite of that it is often used especially to study the flow, heat transfer, temperature fields in different optically transparent media (such as water, air, plasma), for measuring the flow velocity, vibration etc. [9], [10], [11], [12].

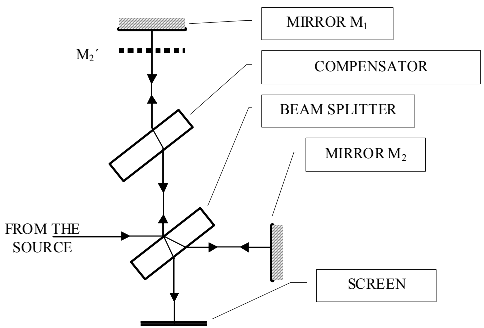


Fig. 1. Michelson interferometer

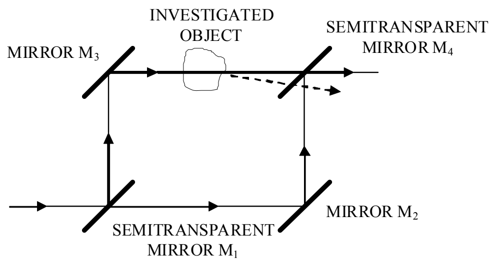


Fig. 2. Mach–Zehnder interferometer

Multi-beam interferometry relies on a thin plane parallel layer of thickness d and refractive index n and a plane wave with unit amplitude incident the plane at an angle θ_1. Multiple reflections at boundaries and transmissions through thin layer cause a rapid decrease of wave amplitude. The phase shift of wave (trasmitted or reflected) after one passage through the layer is $\varphi = \frac{4\pi}{\lambda}\frac{nd}{\cos\theta_2}$. Intensity of interference fringes after trasmission is $I_T(\varphi) = |A_T(\varphi)|^2 = \frac{T^2}{1+R^2-2R\cos\varphi}$, where $R = r^2$ is reflectivity and $T = t^2$ transmissivity. Intensity of interference fringes after reflection is $I_R(\varphi) = \frac{2R(1-\cos\varphi)}{1+R^2-2R\cos\varphi}$. Interference fringes obtained by multiple reflection from plane thin layer are complementary to the fringes of transmitted light, ie. if $R \to 1$ then we obtain a very narrow dark fringes (minimum), see Figure 4b. It is therefore obvious that the multiple interference on a thin layer allows much narrow interference maxima in comparison with two-beam interferometry, what is practically advantageous. Based on multiple interference with partially transparent and highly reflecting surfaces we can use Fabry-Perot interferometer in laser technology, spectrometry, etc.

Today, already quite extensive and an independent method is *white-light interferometry* [30] with its many technical modifications, when a classical type of interferometer is used together with a kvazicoherent light source, such as a laser diode.

2.2. Stereometric and stereophotogrammetric methods

These methods are historically the oldest, they are based on the principle of stereoscopic sight or the record [1]. Their using is traditional, usually for measuring curvature, strain, stress etc. The relatively low sensitivity of these methods constraints their application for relatively macroscopic measuring. These methods with use of advanced technical features and assessment procedures can expect their renaissance, namely most likely in non-traditional areas.

2.3. Moiré

From an optical point of view it is a description of the interference object generated by superposition of two or more geometric elements, mostly grids. Mutual rotating of grids may create two types of moiré fringes. The first type is called *moiré subtractive fringes*, the second type is called *moiré additive fringes*.

Shadow moiré method, for example, a topography is realised in projection of reference grid lines to the surface of examined object, such a grid is called objective. By superposition of both grids we gets field of moiré fringes, which describe the topography of the investigated shape. Basically, we can distinguish two basic methods, the shadow moiré method with collimated light and observation and the shadow moiré method with "spot" lighting and observation (light source and observation place are in a finite distance from the investigated surface). Optical arrangement of the shadow method for the latter case is in Fig. 3a, the principle of its technical realisation can be seen in Fig. 3b. From this it is clear that the obtained result is surface contour of an object relative to the chosen defined (imaginary) reference plane (the plane OD in Fig. 3a).

Relatively low real sensitivity (resolution) of these methods somewhat delimits their usage when the resolution of tenth millimetres or better is required. This problem can be successfully addressed by modifying the applied moiré topography, i.e. introducing a *supplementary stage* in the imaging moiré process [13], and in this way to relatively increase the number of moiré fringes and enhance the method to be more sensitive. Current possibilities of technical use of CCD technology, computing (data-processing) etc., then show unexpected possibilities in the use of moiré methods and we can speak about a significant revival of this classic method.

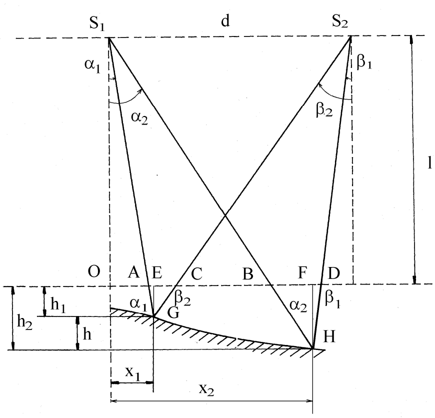


Fig. 3a. Shadow moiré topography; principle of the method with two lightening sources in finite distance from the examined surface.; OD – reference plane, S_1, S_2 – light sources, GH – examined surface

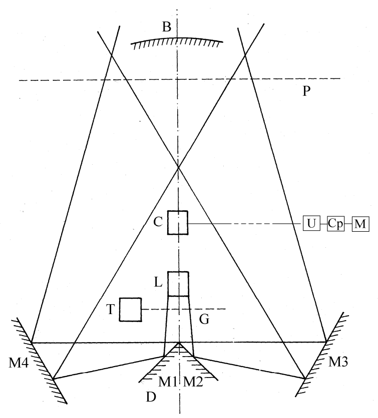


Fig. 3b. Shadow moiré topography; scheme of technical realisation; L – slide projector with moiré grid, M – mirrors, C – camera, B – examined surface

2.4. Photoelasticimetry

Photoelasticimetry is a traditional set of methods based on the principle of birefringence of some materials occurring when the stress is applied [1] [2] [3] [4] etc. The effect and the intensity of birefringence phenomenon is a criterion of stress in the material. According to the applied method and the choice of material (there are often used model materials) we recognise *transmission photoelasticimetry* or *reflective photoelasticimetry*, *temperature* *photoelasticimetry* etc. This widely used method, especially as a model one, was all the time technically improved by their users (they often talk about schools) and in particular by professional manufacturer of these measuring devices, so we can talk about the classical method technically operated at the highest technical level in its time, both for 2D and 3D tasks. However, currently these methods does not attract the previous attention for various reasons.

The previously mentioned methods are based on the superposition of the interfering waves or other phenomena (polarisation etc.), not strictly requiring highly coherent light sources. Especially the classical optical interferometry was dependent on at that time available monochromatic light sources, but their nature confines unambiguously range of their applications. After all we can trace applications of these methods in the top quality even from the today point of view. The invention of laser and its technical application in the measuring field has revived also the old methods. In combination with methodology of subsequent discoveries (for instance holography) and development of new opto-electronic elements, computers and mathematical algorithms for processing measured data, the possibility of new application quality and quantity has emerged. From various reasons methods recently constrained in their application capabilities were (and still are) significantly improved and employed at unexpected quality level regardless the known trends in mechanics accompanying the progress of numerical methods. The following methods are based wholly on the coherent optical waves interferometry.

3. Holography and holographic interferometry

Many known ways divided holography and holographic interferometry methods are mostly based on their two basic applications [14], [15], [16], [17], they are real time method and double exposition. Other specialised methods derived from them are time-average method, stroboscopic method, hyperbolic method etc. Expectations promised by holography as a real revolutionary method have been largely met. In combination with classical interference methods (for instance holographic methods combined with Mach-Zehnder interferometer), new holographic methodology and other new procedures brought unprecedented simplifications of experimental load and advancement of applications in mechanics. It can be stated that the holographic interferometry is a part of classical interferometric methods demanding the good laboratory background and highly qualified personnel.

Holographic interferometry or equivalently *differential holographic interferometry* is based on the interference of reconstructed wave with another coherent wave. In the case of small differences between these two waves it is possible to determine the demanded changes quantitatively from the macroscopic interference pattern and it does not matter whether the waves come from two different objects or from single object located subsequently in two positions, or absorbing or phase object. According to nature of interfering waves we can recognise two basic methods.

Single hologram method (*real time method*) is implemented in such a way that the object image is recorded at the photographic plate (hologram). After its development the plate is located exactly in the original position keeping the experimental setup unchanged. Exposing the hologram by the original reference wave, now a reconstruction wave, we have a reconstructed image of the object in the original position. The intensity of resulting interference field of this image is in the form

$$I_I = \left(a_P + a_1'\right)\left(a_P + a_1'\right)^* = \overline{I_I} + 2A_0^2 A_1 A_1' \cos\left(\phi_1 - \phi_1'\right),$$

and obviously it is modulated by cosine function.

Two hologram method (*double exposition method*) usually records the same object in two different states at the same photographic plate creating two holographic pictures. In special case, when the reference wave is advantageously used also as a reconstruction wave, the intensity of the image of the object located in the original position and the same size and without aberration is expressed by the relation $I_I = \overline{I_I} + 2A_0^4 A_1 A_1' \cos(\phi_1 - \phi_1')$, again modulated by the cosine function.

In both cases we obtain the interference field in the form of dark and light fringes at the non-vanishing background, and the fringe contrast is in general higher when using two hologram method than with single hologram method.

Quantitative evaluation of holographic interferograms is basically focused on determination of the optical path difference charactesizing the process under consideration. In the case of objects with diffuse reflective surfaces the variances in optical paths characterise the position change of points at the examined surface. In the case of phase objects we determine the change of index of refraction, which is a measure of the examined variable. In the case of objects with diffuse reflective surface the method according to A. E. Ennose or E. B. Aleksandrov and A. M. Bonch-Brujevich [14] is generally used for the evaluation of the interferogram.

Experimental *analysis of the deformation state* of the object surface is required application in elasticity and strength of solid and elastic bodies. Quantitative evaluation of holograms and holographic interferograms is usually constrained to the determination of the shift vector $\Delta\mathbf{r}$ or its elements. The known shift vector $\Delta\mathbf{r}$ does not solve the shift quality. Generally we have to take into account the following shift vector components:

- object translation as a solid body,
- object rotation as a solid body,
- inherent deformation of the object because of force action (elasticity area).

In general it is not possible to distinguish unambiguously the individual components from the shift vector. Experimental determination of the deformation tensor was proposed in general case by W. Schumann a M. Dubas [18], [19], [20], [21], with experimental *localisation of interference fringes*, what can be experimentally considerably demanding.

4. Speckle methods

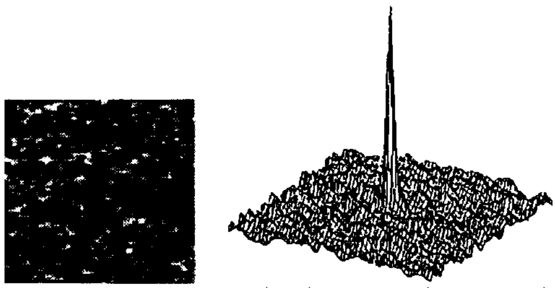
The recent progress of holographic methods, especially employing the *speckle holography* and its variants, already overcome this imaginary frontier, in no case due to its principle but in particular due to the possibility to apply the modern technical and optoelectronic elements.

Now the speckle holographic methods (on the base of their principle and description) are included into the group in summary called ***coherent interferometric methods***, also **coherent speckle methods** or **speckle methods.** These methods employ statistical properties of optical coherent speckle fields and they are probably the representatives of new targets and applications in mechanics.

From this point of view we can divide these methods as follows:

- **speckle interferometry** (**speckle photography**) employs the interference of coherent speckle fields resulting in simple interference fringes with profound speckle structure. Today used method **EPSI** could be included in this group.
- **statistical correlated speckle method**; characteristic interference fringes are not the result of this method, two or more speckle fields are evaluated statistically. The shift between speckle fields is retrieved from shifting of maximal value of mutual correlation function

due fluctuations of speckle field intensities before and after the object deformation or its translation [22-29]. In Fig. 4 we see the photo of typical speckle field and its calculated two-dimensional auto-correlation function, it is evident that the maximum always occurs in zero point. In Figure 5 we have the photos of speckle fields for two object locations, for instance before and after its deformation with corresponding function of mutual correlation. When the object changes its position the maximum of correlation function is not in zero point and this shift measures the object translation under examination (correlation function exhibits its maximum at the zero point with no object shift – it is translation, deformation, rotation etc.). At the same time the maximal value of correlation function decreases, as a consequence of mutual field shifting and partial changes in speckle structure, this state is indicated as *decorrelation.*



$I(X,Y)$ $\qquad$ $C(\overline{X},\overline{Y}) = \langle I(X,Y) I(X+\overline{X}, Y+\overline{Y}) \rangle$

Fig. 4. Speckle field and auto-correlation function

$I_1(X,Y)$ $\qquad$ $I_2(X,Y)$ $\qquad$ $C_{12}(\overline{X},\overline{Y}) = \langle I_1(X,Y) I_2(X+\overline{X}, Y+\overline{Y}) \rangle$

Fig. 5. Two speckle fields before and after object deformation or translation and calculated mutual correlation function

5. Conclusion

Progress in light sources, detectors and computers allow new insight to the application possibilities, especially in traditional technical areas. We can speak about application revival of classical optical measuring methods in its technical parameters both qualitatively and quantitatively.

Today application of optical experimental methods in mechanics is generally obvious emphasising their advantages as variability, contact-less measurement and possible high automation level of measured data processing.

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References

[1] Kolektiv: Experimentální pružnost. SNTL, Bratislava, 1970.
[2] MILBAUER M.: Fotoelasticimetrie. SNTL, Praha, 1953.
[3] BREPTA R., PROKOPEC M.: Šíření napěťových vln a rázy v tělesech. Academia, Praha, 1972.
[4] JAVORNICKÝ J.: Photoplasticity. Academia, Praha, 1974.
[5] BORN M., WOLF E.: Principles of Optics. Pergamon Press, Oxford, 1980.
[6] HARIHARAN P.: Optical Interferometry. Academic Press, Sydney, 1985.
[7] HECHT E.: Optics. Addison Wesley, Reading, 1987.
[8] SALEH B.E.A, TEICH M.C.: Fundamentals of Photonics. John Wiley & Sons Inc., New York, 1991.
[9] MALACARA D.: Optical Shop Testing. John Wiley & Sons Inc., New York, 1992.
[10] SCHRODER G.: Technická optika. SNTL, Praha, 1981.
[11] DURST R., MELLING A., WHITELAW J. H.: Principles and Practice of Laser Doppler Anemometry. Academic Press, London, 1981.
[12] Ed. by CHA S. S., BRYANSTON-CROSS P. J., MERCER C. R.: Optical Diagnostic for Fluid, Heat, Combustion and Photomechanics for Solids. Proc. SPIE, Vol. 3783, 1999.
[13] KEPRT J., HRABOVSKÝ M., BARTONĚK L., TŮMA J.: Projekční moiré topografie. Jemná mechanika a optika 1 (2000) 4-10.
[14] WEST Ch. M.: Holographic Interferometry. John Wiley & Sons Inc., New York, 1979.
[15] Ed. by RASTOGI P. K.: Holographic Interferometry. Principles and Methods. Springer-Verlag, Berlin, 1994.
[16] MEHTA P. C., RAMPAL V. V.: Lasers and Holography. World Scientific, London, 1993.
[17] ABRAMSON N.: Light in Flight on the Holodiagram. SPIE Opt. Eng. Press, SPIE – Belingham, Washington, 1996.
[18] DUBAS M., SCHUMANN W.: Sur la détermination holographique de l`état de défomation a la surface dun corps non transparent. Optice Acta 21 (1974) 547.
[19] DUBAS M., SCHUMANN W.: On Direct Measurements of Strain and Rotation in Holographic Interferometry Using the Line of Complete Lokalization. Optica Acta 22 (1975) 807.
[20] SCHUMANN W., DUBAS M.: On the Holographic Interferometry Used for Deformation Analysis with One Fixed and One Movable Reconstruction Source. Optik 47 (1977) 391.
[21] HRABOVSKÝ M.: Experimentální analýza rozložení napětí na lopatce regulačního diagonálního čerpadla. Sborník referátů z 18. mez. konf. o experimentální analýze napětí EAN´80, 20.-22.51980, Tále, Čs. Společnost pro mechaniku při ČSAV a DT Banská Bystryca, 1980, 73-92.
[22] YAMAGUCHI I.: Fringe Formation in Deformation and Vibration Measurement Using Laser Light. Ed. by Wolf E., Progress in Optics 22 (1985) 271.
[23] ARCHBOLD E., BURCH J. M., ENNOS A. E.: Recording of in-Plane Surface Displacement by Double-Exposure Speckle Photography. Opt. Acta 17 (1970) 883.
[24] TIZIANI H. J.: Application of Speckling for in-Plane Vibration Analysis. Opt. Acta 18 (1971) 891.
[25] TIZIANI H. J.: A Study of the Use of Laser Speckles to Measure Small Tilts of Optically Rough Surface. Opt. Commun. 5 (1972) 271.
[26] ARCHBOLD E., BURCH J. M., ENNOS A. E.: Displacement Measurement from Double-Exposure Lasers Photography. Opt. Acta 19 (1972) 253.
[27] YAMAGUCHI I.: Real-Time Measurement of in-Plane Translation and Tilt by Electronic Speckle Correlation. Jpn. J. Appl. Phys. 19 (1980) L131.
[28] PETERS W. H., RANSON W. F.: Digital Imaging Techniques in Experimental Stress Analysis. Opt. Eng. 21, 3(1982) 427.
[29] HRABOVSKÝ M., BAČA Z., HORVÁTH P.: Koherenční zrnitost v optice. UP Olomouc, 2001.
[30] PAVLÍČEK P.: Měření profilu předmětu pomocí interferometrie v bílém světle. Jemná mechanika a optika 3 (2002) 83-85.