OPTICAL METHODS IN ENGINEERING MEASUREMENTS

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Introduction

We can commemorate this year the 25th anniversary of the laser and the 20th anniversary of holographic interferometry.

At first holography and holographic interferometry were thought to be the answer to almost every optical problem. The lack of success was primarily attributed to the lack of fringe readout and subsequent quantitative analysis of holographic data. Even today, 20 years later, there is not yet a general method available, that can be used reliably to interpret holographic fringe patterns to obtain information on displacements, vibrations and deformations of arbitrary objects. However, a number of methods and systems based on techniques used in interferometry have been developed for specific applications. It seems that a combination of different methods can lead to powerful solutions to problems in industry. Furthermore, speckle photography and especially speckle interferometry are becoming useful tools in metrology. Shape and defect analysis arebecoming important in modern manufacturing; new sensors together with robotics will be developed.

Interferometry and holographic interferometry are becoming useful tools for precision measurements in research and for industrial applications.

Computer analysis is increasingly important in interferometry. The use of solid state detector-arrays, image memory boards together with microprocessors and computers for the extraction of the information from the interferograms and high resolution graphic boards find important application in optical metrology.

Automated quantitative evaluation of interferograms require accurate interference phase measurement, independent of fringe position and intensity variations superposed onto the interferograms. In many interferometric arrangements, phase shifting or heterodyne techniques have been introduced for resolution fringe analysis.

In the phase shifting technique or quasi-heterodyne technique the relative phase is changed continuously or stepwise, using at least three phase shifts of 90 or 120 degrees. The phase of the interference patterns can then be computed from the different measured intensity values. The phase shifting technique is very appropriate for digital processing and TV techniques. Interferometry and two reference beam holography together with video electronic processing lead to a sensitivity of 1/100 of a fringe at any point of the fringe pattern in the TV image. Heterodyne techniques lead to sensitivities of $\lambda/1000$.

Fringe analysis will be discussed together with the influence of adjustment errors when measuring the macro- and micro-structure of components using interferometry as well as computer generated holograms /2/. In addition, deformation and vibration can be studied using fringe analysis techniques.

In heterodyne methods the relative phase increases linearly in time and the reference phase is measured electronically at the beat frequency of the reconstructed wavefields. Heterodyne holographic interferometry offers high spatial resolution and interpolation up to 1/1000 of a fringe. It requires, however, sophisticated electronic equipment and mechanical scanning of the fringe pattern /1/.

Digital extraction of interference contours

Solide state detectors, image memory boards together with the development of computers are mostly responsable for the progress made in interferometric testing. Digital extraction of the phase in interferometry provides means of obtaining very precise measurements at rapid rates. It provides an opportunity to extract valuable information from interferograms.

For the fringe analysis in interferometry for testing optical components the different methods can be classified into static and dynamic methods.

For static methods, closed fringes should be avoided, hence a tilt needs frequently to be introduced. Fringe contours can be extracted manually or by digitizing fringe centers with a manual digitizer or densitometer. Video-techniques and image processing can be obtained by symmetrically coding fringes to a skeleton in a thresholded version of the interferogram. Furthermore, a phase detection technique in the spatial domain using Fourier transformation /3/ or Fourier analysis in connection with video technique can be used.

The interferogram fringes must be oriented normal to the line along which the FFT is to be calculated so that the true period, rather than an x-axis projection of the period is computed. The use of 1D-FFT makes the program simple and fast. 2-D processing of large image fields takes longer.

In the dynamic algorithm the relative phase between the reference beam and the test beam in a two beam-arrangement is varied at constant, controlled rate or in steps of $\pi/2$ for instance. Figure 1. shows an example of fringe analysis when testing an aspherical Ge surface using a c.generated hologram/2/ where 3-D and 2-D plots are shown.

Figure 1d. shows a quasi micro-structure analysis by subtracting the shape factor.

Interferometry in meterology

Interferometric techniques with automatic fringe analysis become useful tools for testing optical components as well as for macro- and micro-structure and geometry.

Useful applications of interferometry are found in accurate separation and distance measurements as well as for displacement and vibration analysis. For high precision measurements heterodyne techniques /1/ are very useful. For noise and vibration analysis at one or more points the amplitude of oscillation, together with the frequency, can be obtained when heterodyne techniques are applied. Furthermore, the range of application of interferometry can be extended by using 2-wavelength techniques. Subsurface material analysis will be described as another example of the application of interferometry.

Photothermal interferometry for non-destructive subsurface defect detection

For non-destructive material analysis by optically generated thermal waves opto-acoustical and photo-thermal methods can be used. Measuring the optical path length difference resulting from thermal expansion is an alternative method to detect the propagation of the thermal wave through the sample.

The thermal wave generated by a modulated Laser beam focussed onto the sample for instance, propagates through the material. This leads to a locally varying phase difference between chopper- and interferometer signal. Characteristical changes in phase difference and amplitude lead to the detection of subsurface defects.

An interferometric arrangement used to measure the surface expansion in transmission is shown in Figure 2. where the chopped Ar^+-Laser is focussed onto the probe to generate the heat wave. For the fringe analysis the phase of the reference is shifted automatically using a piezo transducer for each surface element to be analysed. For high sensitive detection it was found useful to work at the steepest slope of the fringe.

In Figure 3. the intensity variation of the fringe is plotted against the optical path variation resulting from the thermal wave. The path difference is of the order of a few nm. The intensity at the photodiodes I is

$$I = I_o \left(1 + m \cos \frac{4\pi}{\lambda} \delta\right)$$

where $I_o = \frac{I\ max + I\ min}{2}$

and $m = \frac{I\ max - I\ min}{2\ I_o}$

and the optical path difference $\delta = \delta_R + \delta_P + \delta_T$

The phase variations δ_T result from thermal expansion, δ_R from the surface roughness, and δ_p from the piezo induced phase variation with

$$\delta_p = \frac{\lambda}{2} \left(\frac{3}{4} + n \right) - \delta_R \qquad n = 0,1,2....$$

$$I \simeq I_o \left(1 + m \frac{4\pi}{\lambda} \delta_T \right)$$

The variation of the phase and amplitudes due to the two holes are shown in Figure 4. where the modulation frequencies in Figure 4a. are 140 Hz and in Figure 4b. 180 Hz.

Holographic non-destructive testing

The application of holographic techniques to routine inspection of products or components by manufacturers is rather limited. Wide industrial acceptance for non-destructive testing (NDT) was found by testing new and retreated tires. Most commercial aircraft tire manufacturers use the holographic techniques today. There is reason for optimism regarding holographic NTD.

Factors which have led to slow industrial acceptance of the technique include:

- time-consuming wet processing of holograms on silverhalide emulsions together with the requirement of high operator skill
- time-consuming processing of the fringe patterns
- relatively fixed sensitivity of holographic interferometry
- requirement of reliable rugged computer controlled lasers easy to field service for CW and dual pulsed holography.

There is reason for optimism regarding holographic NDT because many of the above difficulties are and will be taken care of in the near future. New fringe analysis procedures have been introduced and will be further improved. The availability of convenient and reliable photoconductor-thermoplastic cameras allowing exposure, development and viewing of holograms on films or on a reusable plate in a matter of a few seconds has great potential impact on the industrial viability of holographic NDT. Other quasi real time storage materials such as photorefractive electrooptical crystals will be developed.

Research will continue on the application of digital and electronic technology for automated readout and analysis of fringe patterns. Computational methods of the results will be further improved.

Different techniques can be combined with holography to lead to powerful system for NDT. Speckle photography and digital speckle pattern interferometry improve the non-destructive testing. Digital speckle interferometry (DSPI) is a variation of electronic speckle interferometry developed by combining holography and speckle interferometry. In DSPI the speckle patterns are processed digitally, instead of using analog electronics.

Vibration-analysis of rotating objects

Image derotation is the most promising approach for the study of rotating objects with holographic or speckle techniques. Image plane holograms are most convenient where the image of the rotating object is passed through or reflected by a prism rotating at half the rotational speed of the object, thus cancelling out the rotational motion. A Q-switch double-pulsed ruby laser is then used to produce a double exposure hologram of the rotating object /5/. New laser will be developed.

Laser Doppler velocimeter measure flow velocities of gases and liquids using the light scattered from small particles suspended in the flowing medium. The speed of optically rough surfaces can be determined by similar methods or by speckle velocity measurements.

The heterodyne interference and speckle techniques can be applied for in-plane and out of plane displacements and vibrations of objects with diffusely scattered surfaces at high local and temporal resolution. In the heterodyne techniques the optical frequencies are chosen to differ by say 0,1 to 40 MHz for ease of electronic analysis.

Figure 5. shows a result of an application of the combination of heterodyne interferometry and holographic interferometry applied to noise analysis and reduction of rotating car tires.

Holographic and speckle pattern contouring

A hologram or speckle interferometric recording of the object is made at a wavelength λ_1 and compared, under suitable viewing conditions with the corresponding recording made at a second wavelength λ_2. Holographic fringes of constant height or, in case of speckle interferometry, difference fringes of contour spacing Λ are observed where

$$\Lambda = \frac{\lambda_1 \lambda_2}{\lambda_1 - \lambda_2}$$

Holographic elements have been used for contouring but are only practical for relatively small objects and curvatures of object surfaces. The spacing of contour lines depends on the available laser lines of the required coherence and output power. The minimum practical value of Λ is typically 2 µm when operating with an Argon-ion laser or Krypton laser. An example of a quasi real time contour line when using a photorefractive crystal,BSO /6/ as storage material is shown in Figure 6. The contour lines are 13,9 µm. A reduced sensitivity is obtained when Moiré techniques are used but the field can be much larger.

Phase shifting in holographic interferometry

The availability of solid state detector arrays and microprocessors lead to powerful fringe analysis methods in holography. Phase shifting techniques used in interferometry can be used. For phase shifting a plane parallel plate can be tilted, alternatively a reference mirror can be mounted on a piezoelectric transducer.

In real-time holographic interferometry a phase shift ψ is introduced into the reconstructed reference wave leading to a resulting instantaneous irradiance of the hologram. The phase shifting will be described briefly in the double exposure technique where two reference waves are useful.

Holographic interferometry using two reference beams

a) Phase-shifting technique in double exposure holography

The use of two reference beams when recording the holograms leads to a simple implementation of the phase-shifting technique for the fringe analysis. The holograms are reconstructed with the two reference waves where one is phaseshifted relative to the other by means of a piezo transducer or by tilting a plane parallel-plate as in two-beam interferometry. Phase shifts of 90 or 120 degrees can be introduced.

For the double exposure technique the first hologram is recorded with the first reference wave shown in Figure 7. The second exposure of the deformed object caused by loads, pressure, temperature variation follows with the slightly tilted second reference wave. The reconstruction of the double exposed hologram with the two refence waves phaseshifted by steps of $\pi/2$ for instance leads to four wavefronts not counting the four complex conjugate wavefronts. Two are spatially separated due to the tilt of the reference waves, the two other form the interference fringes, namely

$$I = c \, |U_O|^2 \, \{ 1 + m \cos \left[(\phi - \bar{\phi}) + \psi_K \right] \}$$

where U_O is the reconstructed object wavefront and ψ_K with $K = 1,2,3$, are the phase steps, $(\phi - \bar{\phi})$ the phase difference of the deformed wavefront to be measured. The data are read into the image processor by means of a TV technique (diode arrays). The analysis of the interference pattern is similar to the technique discussed by the two-beam interferometry. The computer aided evaluation of the data allows a precise analysis of the deformation of the objects under load. The data can be presented as a 3-D-plot or as contour lines as shown in Figure 8a. and 8b. respectively or as a colour graphic /7/.

The concept of computer holographic analysis with the appropriate optoelectronic preprocessing assures high accuracy in the evaluation of holographic measurement data. Therefore, the determination of deformation and stress of components can easier be obtained from the holographic deformation data.

b) Heterodyne holographic interferometry

The principle was discussed in heterodyne interferometry /1/. The frequency difference of a few hundred KHz can be introduced by a rotating grating when using the direct and diffracted waves or by two acousto-optical modulators arranged in cascade to give opposite frequency shifts. During recording both modulators are driven with 40 MHz. In the reconstruction one is driven with 40,1 MHz leading to a frequency shift of 100 KHz. Scanning the image of the objects with a fringe pattern using a stationary reference and a scanning detector leads to the phase difference $(\phi - \bar{\phi})$.

To obtain the phase difference in orthogonal directions three detectors are used. The phase differences can be measured with two zero crossing phase meters, which interpolate the phase angle to $0{,}1^\circ$. Heterodyne holographic interferometry requires sophisticated electronic equipment and mechanical scanning of the image by photo-detectors. It is well suited when high sensitivity is required. By contrast the two reference beam phase shifting technique with TV-detection is simpler and requires a video-electronic data aquisition system.

Summary and conclusions

The optical precision measurement methods described in this paper have resolutions in the range from Å to a few microns. To extend the range structured light techniques or optical triangulation, can be used in metrology.

The application of interferometry and holography will be extended because of the progress made in the fringe analysis. New coherent light sources together with real-time storage devices will lead to further progress in the application of optical techniques in industry.

References

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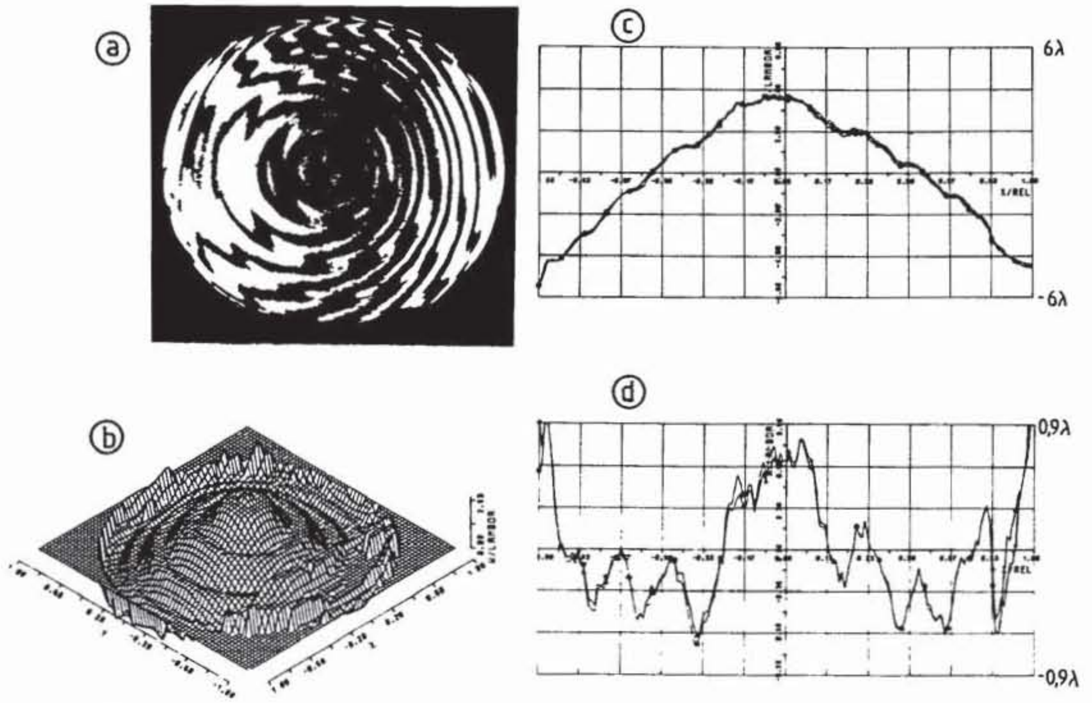

Figure 1:

Fringe analysis of an aspherical Ge surface.

a) Interferogram

b) Two dimensional fringe analysis

c) One dimensional fringe analysis

d) Deviation from best fitting aspheric surface

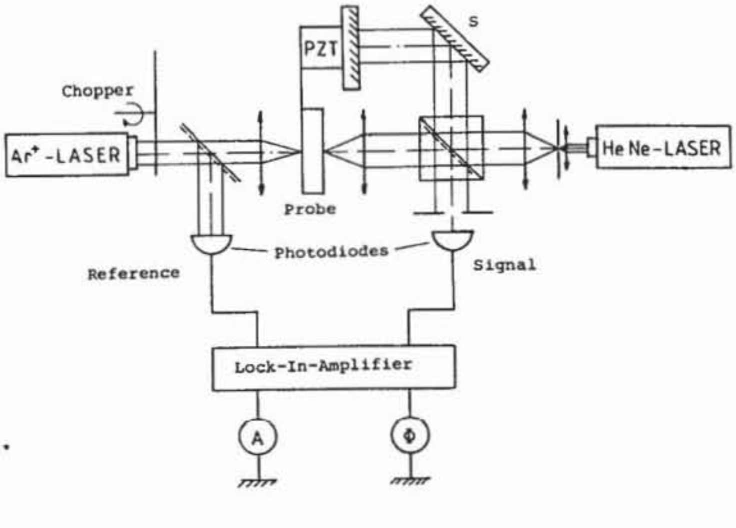

Figure 2:

Interferometer for heat-wave detection.

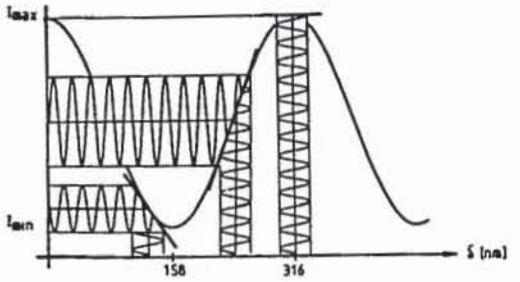

Figure 3:

Fringe analysis for heat-wave detection.

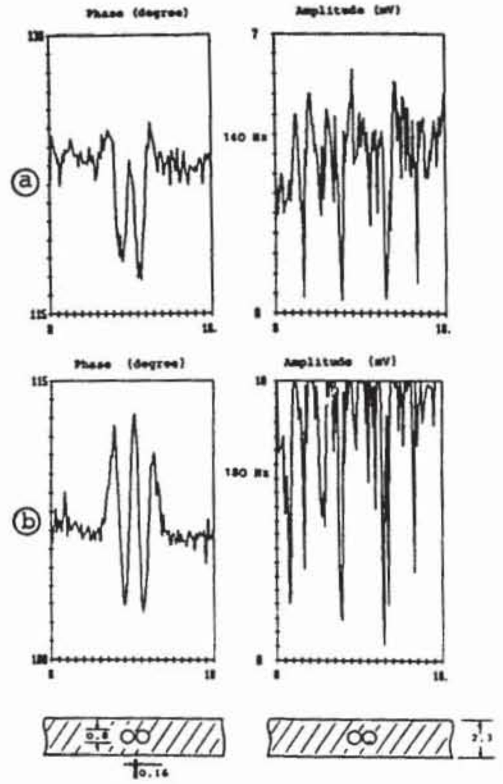

Figure 4:

Subsurface interferometric material testing.

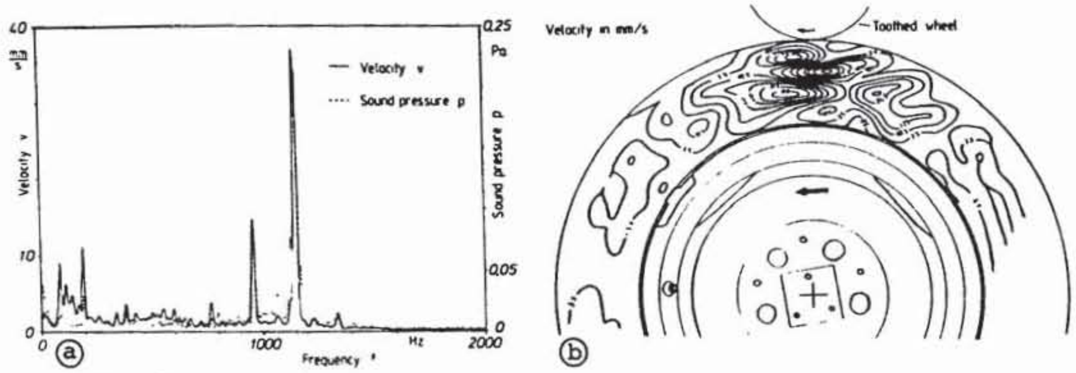

Figure 5:

Noise and vibration analysis of rotating car tires by combining:
5a) heterodyne interferometry with 5b) double pulse holography together with an image derotator.

Figure 6:

Real time contour lines separation 13,9 µm of a metallic surface using BSO as photorefractive storage material.

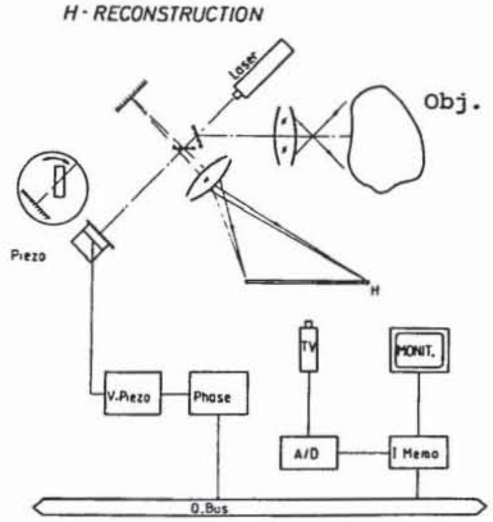

Figure 7:

Arrangement for double exposure holographic technique using two reference beams.

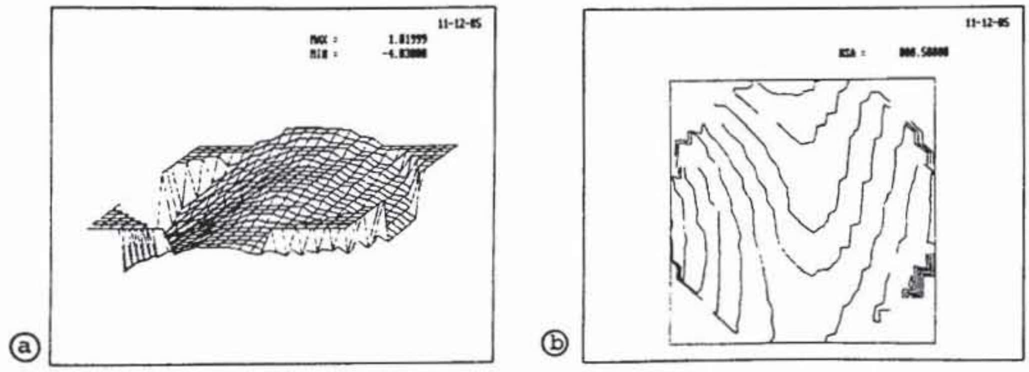

Figure 8:

Result of fringe analysis with two-reference-beam-technique.

8a) 3D-plot

8b) contour lines