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STATE AND PROSPECTS OF COMPUTERIZED SYSTEMS MONITORING THE TOPOLOGY OF SURFACES, BASED ON WHITE LIGHT INTERFEROMERTRY

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Abstract: This paper describes a computerized system for object topology control based on a white light interferometer. The theoretical fundamentals of white light interferometry and mathematical model of an interferogram are presented. An overview and comparative analysis of methods for the reconstruction of the topology of surfaces based on a white light interferogram are performed, their main advantages and disadvantages are defined, and the objectives for the development of computerized systems are formulated.

Key words: surface topology reconstruction, white light interferometry, computerized systems, signal processing, phase detection.

1. Introduction

There are many tasks in science and engineering connected with analysing the topology of surfaces. Thus, the dimensions and characteristics of a surface are the important parameters in the manufacturing of elements for micro-electro-mechanical systems, semiconductor components, in the control of quality of transparent films of monitors, LCD displays, etc [1, 2]. There are many techniques both contact and noncontact providing such measurements. First of all, it is contact stylus scanning, atomic force microscopy, scanning tunneling microscopy, vertical scanning interferometry, confocal microscopy, phase shifting interferometry, etc. [2, 3, 4].

However, the undeniable benefits go to optical methods, in particular interferometers [1]. The lack of physical contact with a testing surface, high resolution and scanning speed, and the ability to study objects with large geometric dimensions - this is an incomplete list of the advantages of interferometers taken when studying the surfaces topology.

For more than a century, the interferometers have passed a long way of the development and improvement [2, 5, 6]. Nowadays a great variety of such optical devices is known. They are focused on the efficient solution of specific scientific and technological problems (issues). In particular, recently lots of attention is paid to the development and application of low-coherent interferometers or white light interferometers. They have several advantages in analyzing the topology of complex surfaces [1, 6, 8].

In practice, white light interferometers work in the computerized systems, which are responsible for obtaining a high-quality interferometric pattern of the object under measurement and reconstructing on its basis the topology of a surface. Due to the low coherence of white light (in contrast to the monochromatic), it is more difficult to achieve wave interference and to register a stable and high-quality interferometric pattern [8]. In addition, the fast attenuation of an interferogram makes the algorithms for the reconstruction of the topology of a surface more complicated.

Nowadays, a lot of methods and algorithms for the surface reconstruction based on the white light interferogram have been developed [2, 5, 9, 10]. However, in some cases, these algorithms do not provide the accuracy and efficiency required by practice. The aim of this paper is overview of white light interferometry applications and identification the ways to improve characteristics of computerized systems for topology control of nonlinear dynamic surfaces, and also, reviewing and comparing the existing methods and algorithms for surface reconstruction based on the white light interferogram, which are used in modern computerized systems designed for the control of the topology of surfaces, as well as identifying their advantages and limitations.

2. Characteristics and areas of white light interferometry application

Optical interferometry is a non-contact measurement method, which is based on light interference. The phenomenon of superposition of two or more electromagnetic waves is called interference. As a result, the strengthening (maximum) and weakening (minimum) areas of the resultant wave can be observed.

With the help of optical interferometry, the measurements in the range from a few centimeters to a few micrometers can be performed. In addition, the lateral resolution (along the x and y axes) reaches the order of several micrometers and a resolution of height measurements (along the axis *z*) to a few nanometers. The resolution of the interferometer is determined by the light wave length [6].

Conventional monochromatic interferometry is a common technique of surface testing as the monochromatic light can produce high quality interference fringes, which can be easily stored and processed. Despite a large number of advantages, the monochromatic interferometry also has some disadvantages, in particular the ambiguity of the reconstruction of surface topology with differences/steps larger than the wavelength [11]. The usage of white light interferometry (WLI) helps to overcome the problem of phase ambiguity. Therefore, WLI enables the measurement of rough and "step"surfaces, as well as surfaces with a sharp slope [5, 7, 12].

Another advantage of white light interferometry, in contrast to monochromatic, is a lower noise level due to the lack of spurious interference fringes [7, 8, 13]. Almost in every optical device or system, which contains optical components, spurious reflections appear. By using high-coherence light sources (e.g., lasers), these reflections create spurious fringes and add accordingly noise to the measurement. Low-coherence systems (with a white light source) also produce spurious reflections, but they appear when the optical path difference is less than a few micrometers.

When testing a micro-surface structure by an optical profiler, it is extremely important for the sample to be in focus. For smooth surfaces, it is sometimes difficult to determine the focus [7]. Using a low-coherence light source, the interference fringes are obtained only when the path lengths of two beams are nearly matched. The maximum interference fringes contrast is obtained when the path lengths of the beams from a reference mirror and a testing object are exactly matched. Thus, moving the testing surface and finding the maximum contrast of the interferogram, we can determine the focus.

Given all these advantages, WLI is widely used for different applications not only for precise measurement of distances, topology and surface roughness, but also for movement, vibration, homogeneity or thickness control, for pressure and temperature measurement, for testing optical systems, etc [5, 6, 14].

The micro-electro-mechanical systems (MEMS), which consist of microelectronic and micromechanical components, are widely used in manufacturing of different sensors. An important issue for the MEMS technology is miniaturization of micro components. The typical dimensions of micromechanical elements can range from one to one hundred micrometers, while the size of the MEMS chip crystal is from 20 micrometers to a few millimeters. In order to determine the static and dynamic characteristics of the microelectromechanical system, it is essential to know their parameters such as size, surface quality, etc. [12, 15]. These tasks can be accomplished by using WLI.

WLI is also used to measure pressure, including blood pressure [16, 17]. In medical examination and treatment, pressure measurement is an important parameter for monitoring the condition of human health. The measurement of dynamic blood pressure changes in the rat's carotid artery has been successfully carried out with the help of 125-mkm diameter fiber-optic pressure sensor. The sensor consists of two mirrors. One of the mirrors serves as a membrane. The deformation of the membrane under pressure alters the length of the resonator. The combination with WLI enabled to determine the change in length and avoid the noise caused by curvature of optical fibers and fluctuations of a light source. Quite a small size of the sensors makes it possible to apply them in interventing medical instruments (e.g., catheter, guide wire). The sensor provides the pressure measurement in the range of 50-400 mmHg with the resolution of 3.8 mmHg.

When using WLI for analyzing the surfaces coated with transparent films, in the interference pattern appear two peaks caused by the reflection from the front and back surfaces [18]. These peaks enable to determine the thickness and profile of the film. A profilometer created on the white light interferometer allows measurements in the range from 0 to 100 mkm. This profilometer is used in the manufacturing of semiconductors and LCD displays.

WLI is used to control the quality of wedges in the process of ultrasonic bonding [19]. The ultrasonic bonding is important in microelectronics manufacturing. It is used to make mechanical and electrical interconnections. So, it is important that the work surface of the wedge under ultrasound should clearly meet the specifications to ensure a durable wires connection. Due to the high-speed measurement and high vertical resolution (a few nanometers), these tasks are effectively performed by the white light interferometers.

WLI can also be used to measure absolute temperatures [14]. Such a system consists of three white light interferometers (two Fabry-Perot interferometers and a Mach-Zehnder interferometer). One of the Fabry-Perot interferometers serves as a sensing one and is heated to the environmental temperature. The other Fabry-Perot interferometer works as a reference interferometer, which is protected from environmental disturbances. It is heated (exposed) to the known reference temperature T_p. The Mach-Zehnder interferometer is a processing interferometer. It is adjusted to match the interference pattern of the sensing interferometer. The two arms of the processing interferometer are connected to piezoelectric transducers. Their voltage directly depends on the path difference between the two arms of the interferometer. The path difference and reference temperature being known, the absolute temperature of the sensing interferometer can be determined.

The white light interferometer is the basis for a sensor system intended for the simultaneous determination of temperature and pressure [20]. Such a system can contain up to four pressure and temperature sensors and allows the pressure measurement in the range from 0 to 20 MPa, and the temperature measurement in the range of ± 50 °C.

In addition, the white light interferometer works as part of a system for surface roughness measurement with high resolution [21]. The rough surface to be tested is inserted in one arm of the interferometer, in the other one, there is a reference mirror. A sensing fiber serves as a reference mirror. Using this system, it is possible to measure rough surfaces, the roughness depth of which varies from 2 to 4.5 mm with an accuracy of ± 450 nm.

Despite the wide range of the tasks and different areas of application, in white light interferometers, in fact, the reconstruction of the profile of a working surface of the respective sensors is performed based on the registered interference pattern. Further, using the known dependences of the value $z\,(x,\,y)$ of the sensor surface, the controlled parameter or physical quantity (pressure, temperature, etc.) is determined. The peculiarity of such tasks is the need for reconstruction of nonlinear surface topology of sensors, that change their parameters depending on the value of the measured physical quantity. Therefore, it makes sense to eximine the principle of formation of a interference pattern and its relation to the topology of a surface.

3. The structure and operation of a computerized system to control the topology of a surface based on white light interferometry

Nowadays, interferometers work as a part of computerized systems. They provide an automatic search for high quality interferograms, their registration with reference to surface coordinates and topology reconstruction. A generalized block diagram of a computerized system for surface topology control based on white light interferometry is shown in Fig. 1. Various modifications of the WLI computerized system (e.g., with a moving measured object, two-beam, etc.) are known.

The Michelson interferometer is used to illustrate the principle of interferometer operation. A beam splitter divides a light source wave into two waves W1 and W2, which are directed to a reference mirror and a measured object respectively. The waves are reflected from the objects and return to the beam splitter, where they overlap. The result of the waves' superposition is recorded with a CCD-camera. To improve the quality of an interference pattern, a number of additional elements, such as polarizers, lenses, collimators, light pipes, etc. are used.

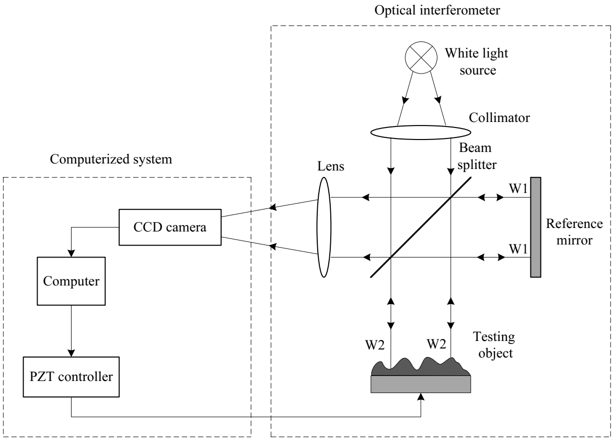

Fig. 1. Generalized block diagram of computerized system

At present, the optical part of computerized systems of WLI satisfies the needs of practice. But the development of efficient algorithms for the real time reconstruction of different surfaces and their implementation on modern computing platforms are the topical objectives.

The mathematical model of a white light interferogram is described as follows [22]:

$$I(T) = I_0 + E(T)\cdot C(T) \qquad (1)$$

$$E(T) = I_M \cdot \exp - \left(\frac{4\cdot \Delta\lambda^2 \cdot T^2}{\lambda_0^4} \right) \qquad (2)$$

$$C(T) = \cos\left(\frac{4\cdot \pi}{\lambda_0} \cdot T \right) \qquad (3)$$

where I_0 is the constant component of the interferogram signal; $E(T)$ represents the interferogram envelope; $C(T)$ denotes the interferogram carrier; I_M stands for the modulation amplitude; T is the optical phase difference; λ_0 represents the central wavelength; $\Delta\lambda$ is the spectral bandwidth of the light source.

The signal of a white light interferogtam is shown in Fig. 2.

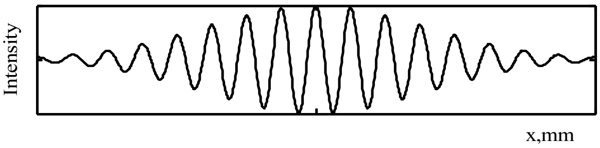

Fig. 2. White light interferogram

The task of the topology reconstruction is to determine from nonlinear equations (1)–(3) the optical path difference *T*, that is directly associated with the relative height *z* of the surface at the point (*x*, *y*).

At the present time, many techniques for analysing a white light interference pattern and determining an optical path difference are proposed. The most common of them are discussed below, in particular, the analysis of their suitability for the reconstruction of nonlinear dynamical surfaces.

4. Overview of existing white light interferogram-based methods for surface topology reconstruction

The optical phase difference *T* can be determined from both envelope (2) and carrier (3) of an interferogram signal. Therefore, the existing methods for the surface topology reconstruction in white light interferometry can be conditionally divided into two classes, which mean the definition of the informative parameter *T* from the envelope and carrier respectively.

There are several **methods for the detection of an envelope** from an interferogram signal and calculation on its basis the optical path difference, in particular, bucket, sliding average, weighted sliding average, the Fourier or Hilbert transform methods [12, 23]. For example, the method of sliding average in its content provides low frequency filtering in order to suppress a carrier. Theoretically, the most accurate results for the detection of an envelope can be obtained using the Hilbert transform.

A method for the maximum intensity detection also relates to the first class methods and is intended to find the point of maximum intensity. This point corresponds to the relative surface hight [12]. This method needs less storage space, so it is suitable for high-speed or real-time measurements. In this method, for each surface point only four buffers are required to store the recorded intensities of *i*-th scan positions during the measurement. The detected maximum value represents the relative height of the corresponding point on the measured surface. It is obvious that the resolution of this method is limited to the step increment. For higher accuracy, the scanning increment should be decreased. However, this increases the measurement time and significantly increases the impact of noise on the results.

Higher sensitivity and accuracy can be achieved by a phase analysis of the carrier (3) rather than by an amplitude analysis of the envelope (2). In addition, a frequency or a phase as an informative parameter (in contrast to an amplitude) is more resistant to noise. Thus, it is reasonable for the surface topology to be determined from the phase of an interferogram carrier. So, the following methods belong to the second class.

A method of the direct phase demodulation provides determining the phase from the ratio of real and imaginary components of an interferogram. For the quadrature component detection, an adaptive method of the frequency demodulation [24] or Hilbert transform is used [25]. However, this method causes the problem concerning the reconstruction of a non-linear surface, since in that case the carrier has quasisinusoidal character.

A phase-shifting method is based on the analysis of several phase-shifted interferogram [4, 9, 12]. For an unambiguous determination of the phase at each point of the interferogram, at least 3 measurements with the known phase shift should be performed. Phase shift methods have been developed for monochromatic interferometry, not for the white light one, i.e. the interferogram intensity was assumed to be constant. Therefore, the use of a classical phase shift algorithm for WLI leads to significant reconstruction errors. To reduce their impact, the intensity changes of a white light interferogram should be taken into account. One of the methods based on the assumption that the envelope of a white light interferogram is locally linear, i.e. it can be approximated by a piecewise linear curve [26]. For the method to be implemented, the registration of 7 interferograms with phase shift $k\pi/2$ (k =-3…+3) is required. However, the practical application of this method has some problems. The assumption on local linearity of the envelope introduces errors in the final results. Also for precise measurement, the exact change of the vertical scanning step $k\pi/2$ is required but it is difficult to implement in practice. In addition, the need for a large number of interferograms makes it impossible to carry out real-time measurements.

The fringe tracing method is based on the assumption that the local intensity extrema correspond to the extrema of the assumed harmonic function of the detected interference signal [9]. In this case, the phase difference at each point of the interference pattern, where the intensity maximum or minimum is located, is multiple of π. The main problem of this method is to determine the points located in the fringe centers where the phase difference is known. Then from these points the phase value can be calculated.

The Fourier transform method is based on the transfer and analysis of signal intensity in a frequency domain [9]. An amplitude spectrum is symmetric with respect to a constant component. A spectral peak at zero frequencies represents low frequency spectral components resulting from the modulation of background intensity. Two symmetric spectral sidelobes carry the same information about the phase value $\Delta\varphi$. Applying appropriate adaptive bandpass filters in the spatial frequency domain we can extract one of the sidelobes. The value of an unwrapped phase can then be calculated by the inverse Fourier transform of the filtered spectrum. Discontinuities of the phase values must be properly unwrapped by appropriate mathematical techniques.

The disadvantage of this method, as well as the fringe tracing method is the sign ambiguity of the calculated phase. Bandpass filtering of the Fourier spectrum is the major step of the method described.

Using an appropriate filter allows us to practically eliminate noises and uninformative components in the interferogram. However, a badly chosen filter may cause a great disturbance of the resulting data.

Since recently, wavelet transform has been widely used for the phase demodulation of interference patterns. This is a well-known theory of digital signal processing, which is more suitable for the analysis of non-stationary signals, in particular the signals with time change frequencies [24]. An analysis using the continuous wavelet transform has been carried out [12]. These algorithms determine the phase of pattern and can be divided into two approaches - the phase or frequency estimation. The results of the comparison between the reconstruction methods are shown in Table 1.

Table 1

Comparative analysis of techniques for surface topology reconstruction based on white light interferogram

Method **Parametrs**	Number of pattern required	Analysis domain	Computational complexity	Resistance to noise	Possibility of dynamic measurements	Coping with discontinuous	Difficulty of automation
Envelope detection	one	s	m	l	yes	no	l
Maximum intensity detection	few	s	l	l	no	no	h
Direct phase demodulation	one	s	m	m	yes	yes	l
Phase shifting	few	s	l	m	no	yes	h
Fourier transform	one	f	h	h	yes	no	l
Fringe tracing method	one	f	h	m	no	no	l
Wavelet transform	one	s /f	v	h	yes	no	m

s – spatial, f – frequency, m – medium, l – low, h – high, v – very high

Reconstruction of dynamic surfaces implies an increase in the speed of measurements. That is why, the methods that can enable the reconstruction based on one interferogram are analyzed. Another problem for many WLI applications is the reconstruction of nonlinear surfaces. The reconstruction methods described are not accurate enough, because there appear computational errors due to the complex dependence of the optical path difference T in nonlinear equations (2)–(3). It seems that the potentially most suitable methods for the reconstruction of nonlinear dynamic surfaces may be the wavelet transform and fringe tracing methods. Since these methods are computationally difficult even for linear surfaces, search for the ways of increasing the accuracy of nonlinear surfaces reconstruction requires additional computational capability (cost). In this regard, to study the ways of their implementation on different computing platforms to ensure high performance is the topical objective.

5. Conclusion

In the last decade, white light interferometry has attracted great interest in researchers. Numerous publications in WLI have proved it. Due to a number of advantages, the areas of its application are constantly expanding. This is facilitated by the performance of the interferometers in computerized systems.

Many tasks require the surface topology reconstruction of different sensors based on the registered white light interferograms. At the same time, additional requirements may be nominated to limit the overall dimensions of computerized systems, which include optical and computer parts. Given the rapid development of computer technology, first of all, it is reasonable to perfect the characteristics of such systems by improving the computational part. Therefore, at present, the research is focused on the improvement of the known and search for new methods of surfaces reconstruction. In comparison with monochromatic interferometry, the surface reconstruction based on the white light interferograms gets more complicated on account of attenuation of the intensity moving away from the center of the interferogram. This generates the reconstruction errors. The known methods solve this problem effectively for smooth surfaces or surfaces with small curvatures. However, several applications of WLI are associated with the reconstruction of so-called dynamic nonlinear surfaces. For such tasks, the known methods do not provide the required accuracy (reconstruction error grows with increasing the curvature of the surface). In addition, the need of dynamic surfaces reconstruction (surfaces, wich parameters change over time) makes high demands on the computational efficiency.

Thus, the search for new algorithms for the reconstruction of nonlinear dynamical surfaces and their implementation on different computing platforms is topical. It includes the implementation in embedded systems, which will expand the scope of applications of computerized systems based on white light interferometry.

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СТАН ТА ПЕРСПЕКТИВИ РОЗВИТКУ КОМП’ЮТЕРИЗОВАНИХ СИСТЕМ КОНТРОЛЮ ТОПОЛОГІЇ ПОВЕРХНІ

Богдан Стадник, Ебергард Манске, Анна Хома

Описано комп’ютеризовану систему контролю топології об’єкта на базі інтерферометра білого світла. Подано основні теоретичні відомості оптичної інтерферометрії та наведено математичну модель інтерферограми. Проведено огляд та порівняльний аналіз методів реконструкції топології поверхні із інтерферограми білого світла, визначено їх основні переваги та недоліки, а також сформульовано завдання щодо розвитку комп’ютеризованих систем.

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Anna Khoma – Graduated from the Lviv Polytechnic National University, Ukraine and the TU Ilmenau, Germany. Currently, she is pursuing her Ph. D. course at Lviv Polytechnic National University. The research deals with the improvement of methods for the analysis of a white light interferogram.